

Cenomanian–Campanian (Late Cretaceous) planktonic assemblages of the Crimea–Caucasus area: Palaeoceanography, palaeoclimate and sea level changes



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ABSTRACT

During the Cretaceous, the Crimea–Caucasus area occupied a position in the Peri-Tethys which was transitional between the Boreal and Tethyan realms. The evolution and stratigraphic distribution of planktonic foraminifera and radiolarians in the Upper Cretaceous sediments of the region are described. The specialized, morphologically complex keeled taxa evolved in the latest Albian and persisted until the end of the Cretaceous. These overall evolutionary trends are punctuated by a series of bioevents, one of the most important being the Cenomanian–Turonian boundary. This is marked by a series of organic-rich sediments, that are related to an Oceanic Anoxic Event. The Turonian–Coniacian interval was marked by a further development of keeled taxa. A major change in the assemblage is described near the Santonian–Campanian boundary, when marginotruncanids were replaced by globotruncanids.

The Albian is marked by the diversification of the radiolarian genus *Crolanium*, the last occurrence of which is typical of the Albian–Cenomanian boundary. The Upper Coniacian to Lower Santonian strata are characterized by the high taxonomic diversity of the Quinquecapsulariidae and the Neosciadiocapsidae. A marked change in the radiolarian assemblage occurred at the Santonian–Campanian boundary: the Late Santonian, warmer-water assemblage dominated by the Pseudoaulophacidae being replaced in the earliest Campanian by cooler-water assemblages characterized by the Prunobrachidae. The changes in the assemblages of planktonic foraminifera and radiolarians at the Santonian–Campanian boundary are attributed to changes in palaeoceanography and the influence of more Boreal-like conditions.

Three significant episodes of sea level change can be identified in the Cenomanian–Campanian of the Crimea–Caucasus area. The first is associated with the Albian–Cenomanian boundary, the second at the base of OAE2, and the third in the Mid–Early Late Turonian. This latter event had different durations in the Crimea and Caucasus regions and this could be related to more local tectonic processes.

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1. Introduction

The geodynamic evolution of the Crimea–Caucasus area was related to the opening of the Black Sea Basin, as well as to tectonic processes in the Pontides. The Cretaceous history of this area can be sub-divided into three phases: 1) Valanginian–Aptian transgressive phase; 2) Early–Middle Albian phase of rifting; and 3) a Late Albian–Maastrichtian phase of significant, often global, sea level changes (Nikishin et al., 2008). It is this third phase that is the focus of this research.

The Crimean and Caucasian regions have been investigated in terms of foraminifera and radiolarians for the first time, although some preliminary results have been published by Vishnevskaya (1991, 2001), Vishnevskaya and Kopaevich (2008, 2014), Korchagin et al. (2012), and Bragina et al. (2014). This investigation of the stratigraphic and quantitative abundance of the two groups provides important information on water depth, temperature, sea level fluctuations and changes in palaeoceanography (oligotrophic/eutrophic water regimes) that can be used to interpret significant Cretaceous palaeoceanographic changes (Bjorklund and Swanberg, 1987; Erbacher et al., 1996; Dubicka and Peryt, 2011, 2012a,b).

The Upper Cretaceous successions of the Crimea–Caucasus area considered in this investigation are shown in Fig. 1 (Crimea) and Fig. 2 (Caucasus). The formal sub-divisions of the investigated successions, based on foraminifera and radiolarians, and including the important biostratigraphical markers, are presented in Fig. 3.

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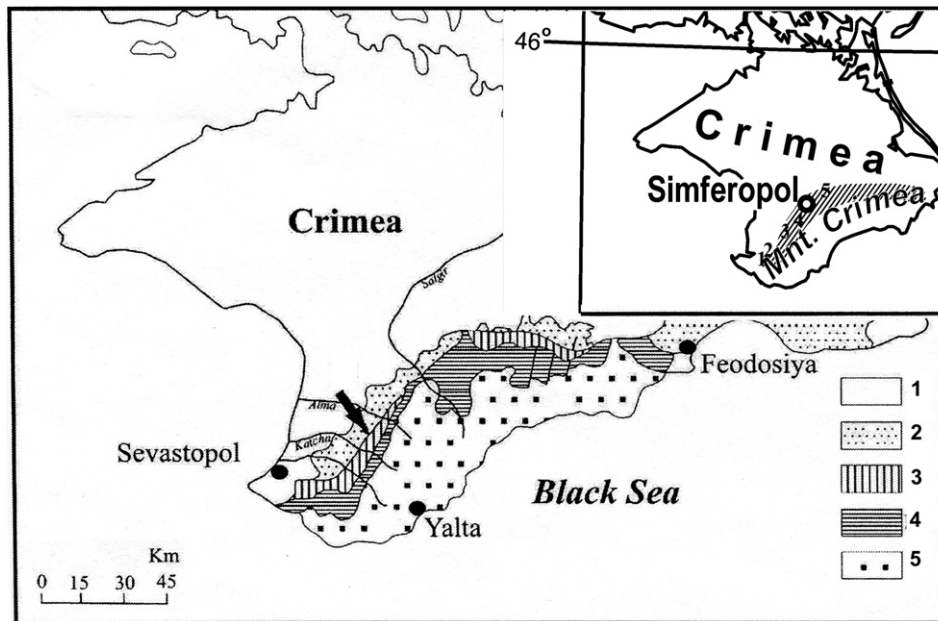


Fig. 1. Location and geological map of the study area in Crimea. The black arrow indicates the Upper Cretaceous outcrops [1, Neogene–Quaternary; 2, Paleogene; 3, Upper Cretaceous; 4, Lower-Cretaceous; 5, Triassic/Jurassic]. Localities are shown on insert: 1, Kudrino (Campanian); 2, Belaia Mountain (the Cenomanian–Turonian boundary interval); 3, Aksudere Valley (the Cenomanian–Turonian boundary interval); 4, Selbukhra Mountain (the Cenomanian–Turonian boundary interval); 5, Biuk-Karasu River (the Middle–Upper Turonian interval).

2. Geological setting

The Lower to Mid-Cenomanian of the Crimea (Fig. 1) is represented by limestones and marls (50–70 m) and the Upper Cenomanian (10–20 m) by white limestones with rare marl intercalations (0.5–1 m). An erosional boundary is present between the Albian and Cenomanian strata (Alekseev, 1989; Gorbachik et al., 2000; Kopaevich and Khotylev, 2014). This is particularly marked in the Bacsan section of the Caucasus region (Figs. 2, 4, 5) which has been described by Vishnevskaya et al. (2006) and Vishnevskaya and Kopaevich (2008).

The lower part of the Middle Cenomanian is missing as a result of a short, world-wide regressive event (Hart and Tarling, 1974; Gale et al., 1999; Nikishin et al., 2008). The top of the Lower Cenomanian is truncated by an erosion surface (the Mid-Cenomanian non-sequence) with small fragments of lower Jurassic rocks present in the overlying strata (Alekseev, 1989; Gale et al., 1999; Hart, 2004). This sharp drop in sea level, followed by recovery, is confined to the boundary of the Lower and Middle Cenomanian, as well as to the base of the bituminous claystones in which the clastic material is recorded (Figs. 6, 7).

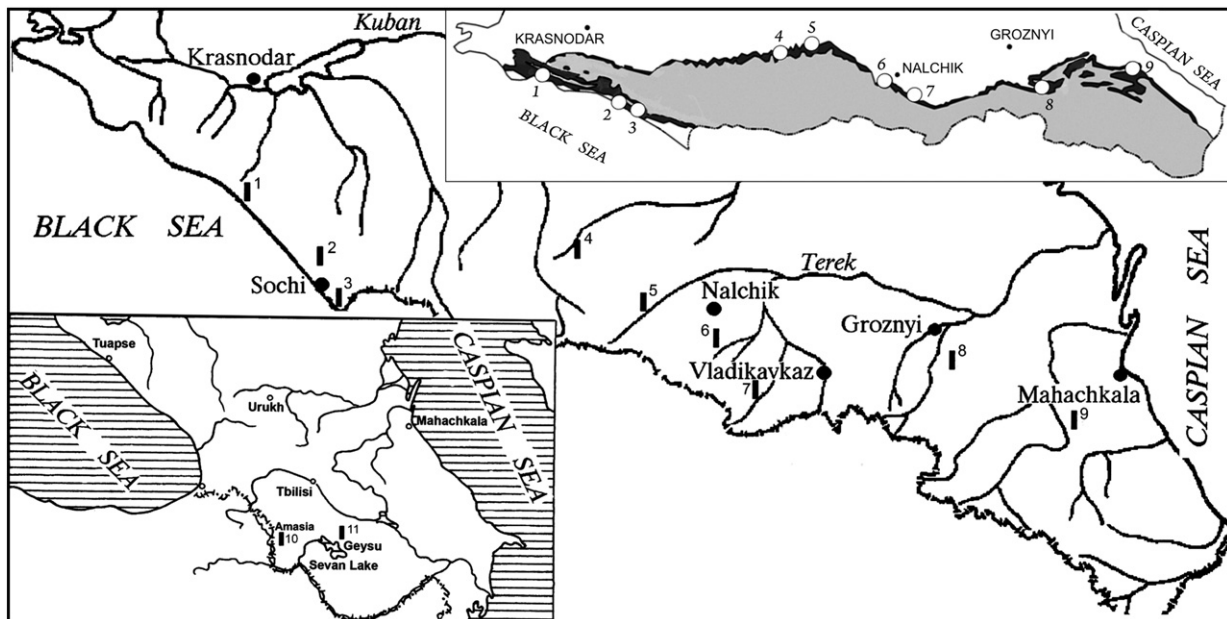


Fig. 2. Sketch map of the western Caucasus, showing location of Upper Cretaceous outcrops in the Great Caucasus (modified after Vishnevskaya and Agarkov, 1998) and in the Lesser Caucasus. 1, Tuapse; 2, Agura; 3, Hosta. Sections located in the western part of the Greater Caucasus: 4, Podkumok; 5, Bacsan; 6, Kheu; 7, Uruk; 8, Bass; 9, Aimaki. Sections located in the central and eastern part of the North Caucasus: 10, Amasia; 11, Geysu near Lake Sevan. Both sections are located in the Lesser Caucasus. The black color indicates the Upper Cretaceous outcrops on insert.

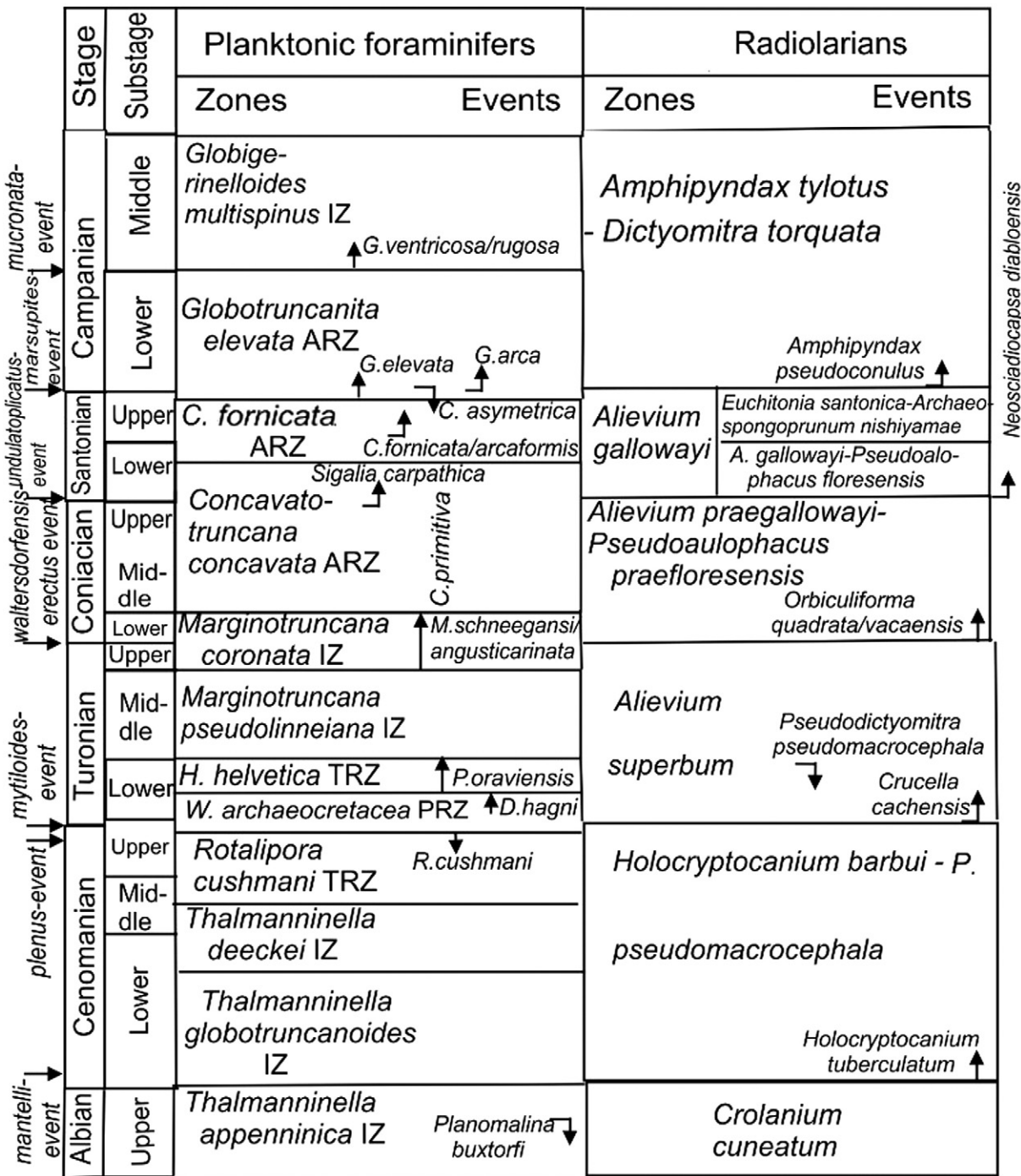


Fig. 3. The Upper Cretaceous zonal scheme for the study area (planktonic foraminifera and radiolarian zonations).

There is considerable variation in the succession overlying the Upper Cenomanian. In the most complete sections brown clay and organic-rich, brown and dark gray laminated marl (1–1.5 m) with quartz, glauconite and silt-grade volcanic material, fish remains and *Chondrites* bioturbation are present. Highly condensed, Lower Turonian glauconitic marl rests directly upon this erosional surface elsewhere (Alekseev, 1989; Alekseev et al., 1997, 2007; Baraboshkin et al., 2003). In the Belaya, Aksudere and Selbukhra successions (Figs. 1, 6), this interval represents the uppermost Cenomanian OAE 2 (Naidin and Kiyashko, 1994a,b; Gavrilov and Kopaevich, 1996; Kopaevich and Kuzmicheva, 2002; Fisher et al., 2005; Badulina and Kopaevich, 2007; Badulina et al., 2009).

The Cenomanian of the northern Caucasus comprises rhythmically bedded limestones and marls in the north slopes of the Great Caucasus and pelagic turbidites in the western part (Aliev and Mirkamalov, 1986; Baraboshkin et al., 2003). These sediments also include the Upper Cenomanian 'black shale' of the Ananur Formation and the famous uppermost Cenomanian–lowermost Turonian Ananur Chert Horizon which extends from Tuapse (Fig. 2) of the western slope of the Great Caucasus throughout Ananuri of Georgia to Zarat in Azerbaijan (Vishnevskaya and Sedaeva, 1988). Within the Upper Cenomanian succession in the eastern part of the northern Caucasus (at Uruk (7), Bass (8) and Aimaki (9) on Fig. 2 and in other sections), two units are distinguished: a gray marly limestone with bentonites and a light-colored

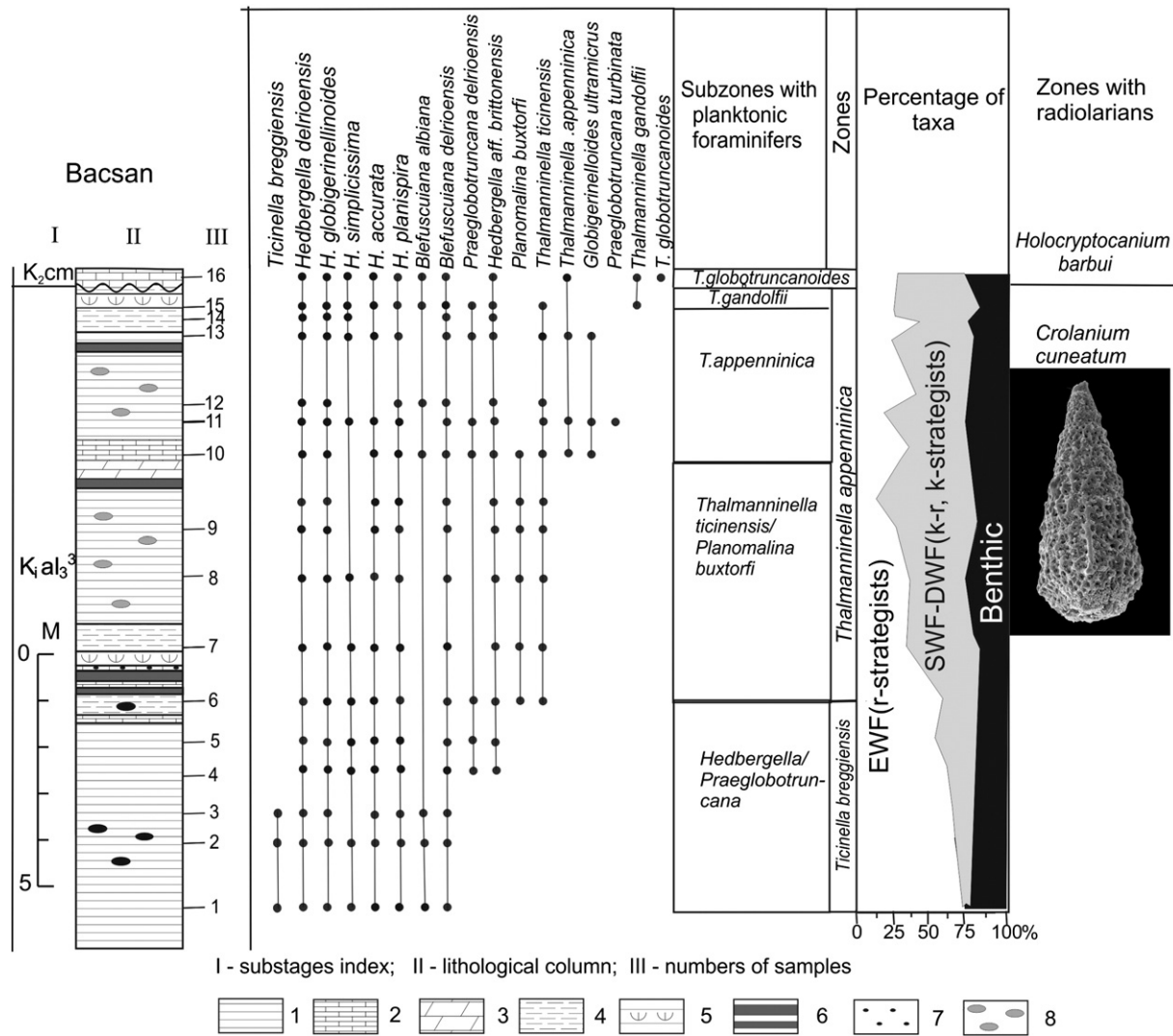


Fig. 4. Bacsan section (locality 5 on Fig. 2), and stratigraphic distribution of the most important planktonic foraminifera around the Upper Albian–Lower Cenomanian boundary. Lithological key: 1, carbonate clays; 2, limestones; 3, marls; 4, clayey marls; 5, tuffaceous layers; 6, bituminous layers; 7, phosphatic nodules; 8, siliceous nodules. Abbreviations for the assemblages of planktonic foraminifera: EWF – epicontinental water fauna; SWF – shallow water fauna; DWF – deep water fauna; BF – benthic foraminifers.

limestone with several layers of black or brown marl with chert concretions near the Cenomanian–Turonian boundary (Tur, 1996; Tur et al., 2001; Gavrilov et al., 2013). ‘Black shale’ sediments occur within pelagic turbidites in the western part of the Great Caucasus, as, for instance, in sections near Novorossiysk City and Andreevski Pass (Badulina et al., 2009).

The Cenomanian of the ophiolite belts of the Lesser Caucasus is represented by siliceous limestones with fragments of plagioclase, alkaline feldspar, quartz, and alternations of titanium-rich tholeiitic and alkaline basalts of an island arc type, associated with rich radiolarian assemblages. The latter are widely distributed within the Lesser Caucasus i.e., the village of Geysu near Lake Sevan, Shalva–Akeria Basin (villages of Pichaniz, Lyalyabagirlu, Ardushlu, Vagazin, Asrik, Kanakhend and Finga), Terter Basin (Chaban–Dag, Karadgalu, Levchay spring) and Vedi Basin (Kyusuz). At all localities, olistostromes and turbidites are associated with ophiolite-clastic and volcanic material and an increased proportion of trachyte tuffs, with continent-derived detritus (Zakariadze et al., 1983).

A new transgressive episode began during the earliest Turonian, with a maximum in the Mid-Turonian and – following a Mid-Late Turonian regressive phase – in the Coniacian (Baraboshkin et al., 2003; Kopaeich, 2010). All Turonian–Santonian deposits are represented by white, pink to gray limestones interbedded with greenish-

gray marls. In the Turonian succession, two members are defined, the lower one being represented by chalk-like limestones and calcareous-rich marls with chert concretions (up to 30 m) and rare macrofauna. The upper member consists of pure limestones with rare brachiopods, inoceramid bivalves and echinoids. These limestones are highly stylolitized. Between the Lower and Upper Santonian, a time of submarine erosion of the sedimentary cover took place in the south-western part of the Crimea Mountains. In the north, sediments of the Coniacian and part of the Turonian were eroded but in the south the extent of erosion was less. In the north, a new cycle of sedimentation began during the Early Campanian, but in the south during the Late Santonian (Nikishin et al., 2008). Upper Santonian sediments, including clay-rich limestones with glauconite, are dated by crinoids of the genus *Marsupites* (Alekseev, 1989; Nikishin et al., 2008). The Turonian–Santonian sequence in the study area is characterized by a significant content of siliceous material and cherty nodules (Fig. 6).

The Santonian succession in the northern Caucasus (Uruk, Bass and Aimaki sections; Figs. 2, 7) often contains blocks of pink limestone from the underlying Turonian and Coniacian that may also indicate tectonic movements. The light-colored Campanian limestones consist predominantly of chert nodules in the lower part (Vishnevskaya and Agarkov, 1998).

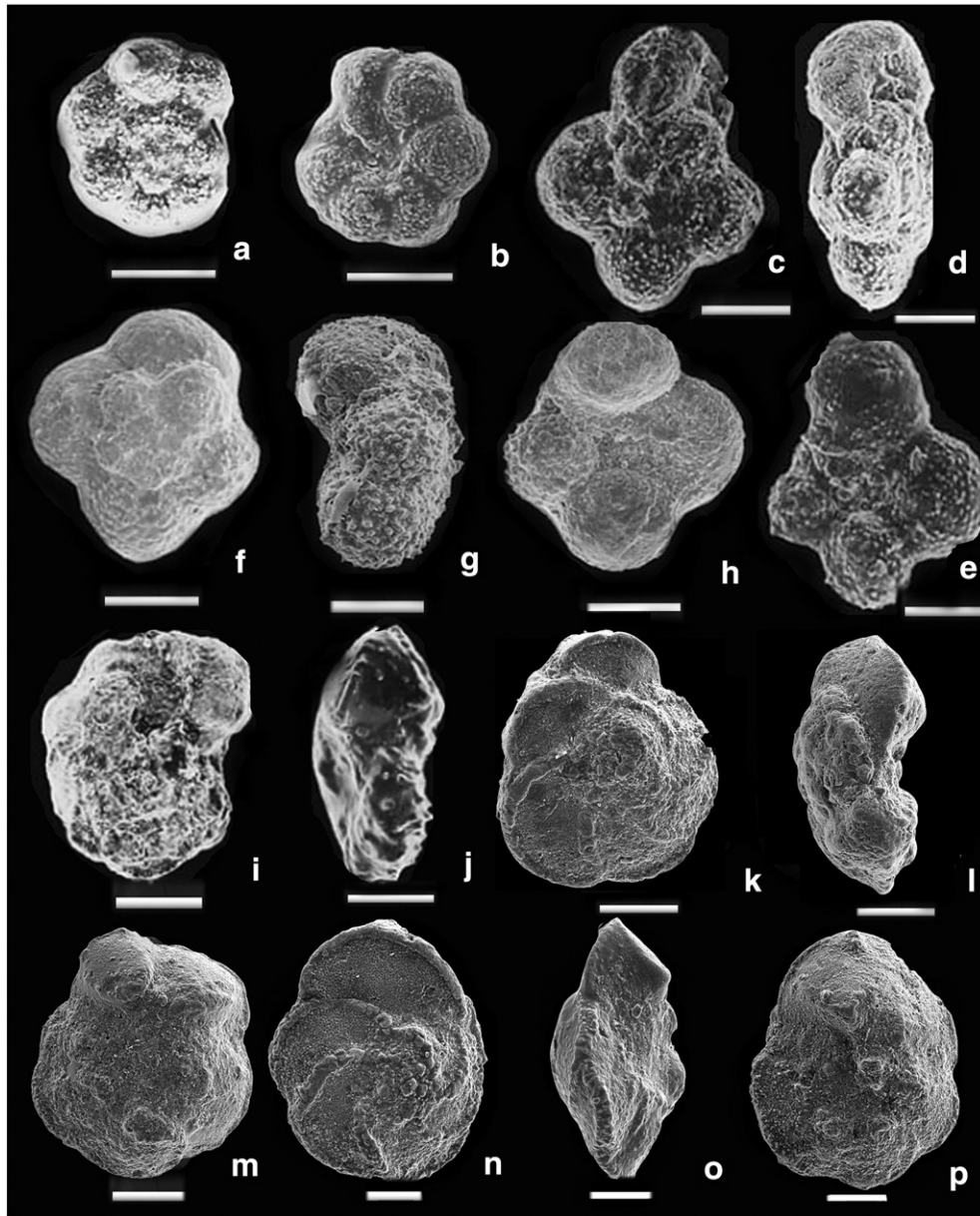


Fig. 5. Albian–Cenomanian planktonic foraminifera from the Bacsan section (northern Caucasus). a–b, *Hedbergella globigerinellinoides* (Subbotina); sample B-2, a – spiral side, b – umbilical side. c–e, *Hedbergella simplicissima* (Magne and Sigal); sample B-4, c – spiral side, d – axial side, e – umbilical side. f–h, *Hedbergella accurata* Gorbachik and Alexandrova; sample B-5; f – spiral side, g – axial side; h – umbilical side. i–j, *Planomalina buxtorfi* (Gandolfi); sample B-10; i – spiral side, j – axial side. k–m, *Thalmaninella appenninica* (Renz); sample B-13; k – spiral side, l – axial side; m – umbilical side. n–p, *Thalmaninella brotzeni* (Sigal); sample B-16; n – spiral side, o – axial side; p – umbilical side. All scale bars 100 μm .

The Campanian is widely distributed across the study area and represented by a transgressive series of carbonate sediments (Fig. 6). The base of the Campanian differs at different localities. It can be a sharp boundary, with a hiatus, or with a degree of condensation, or it can be represented by a continuous transition from the Upper Santonian (Baraboshkin et al., 2003). The Campanian sediments vary in thickness (from 80–90 m in the northwest up to 150–200 m in the southwest) across Crimea, consisting of gray marl, white chalky marl and cream clay-rich limestone. At the base of the Campanian, a few horizons of montmorillonite clays were formed, as a result of the submarine weathering of andesitic ashes (Alekseev, 1989; Nikishin et al., 2008).

The lowest Campanian beds transgressively overlie different horizons: from the Upper Albian to Upper Santonian. The Campanian of the northern Caucasus consists of an alternation of white limestones, gray or green–gray clayey limestones and marls. The total thickness is 350–400 m.

3. Material and methods

There are a number of key successions for the description of the distribution of planktonic foraminifera: Bacsan (Great Caucasus, Figs. 4, 5) and Selbuhra (South-Western Crimea, Kopaevich and Khotylev, 2014); see Table 1. The sediments are represented by sandstones and claystones with an admixture of carbonate and volcanic material (Table 1). From the same interval, 24 samples from the Podkumok River and Kheu sections (North Caucasus; Kopaevich and Khotylev, 2014) have been investigated. The Cenomanian–Turonian interval has been investigated in a number of successions in South-Western Crimea, including Aksudere, Belaia Mountain and Selbuhra (Table 1, Figs. 6–10). The rocks are calcareous and contain small beds of “black shale” of variable thickness (Fig. 6). This interval is also represented in the Uruk succession (Great Caucasus) by carbonate-rich sediments that contain

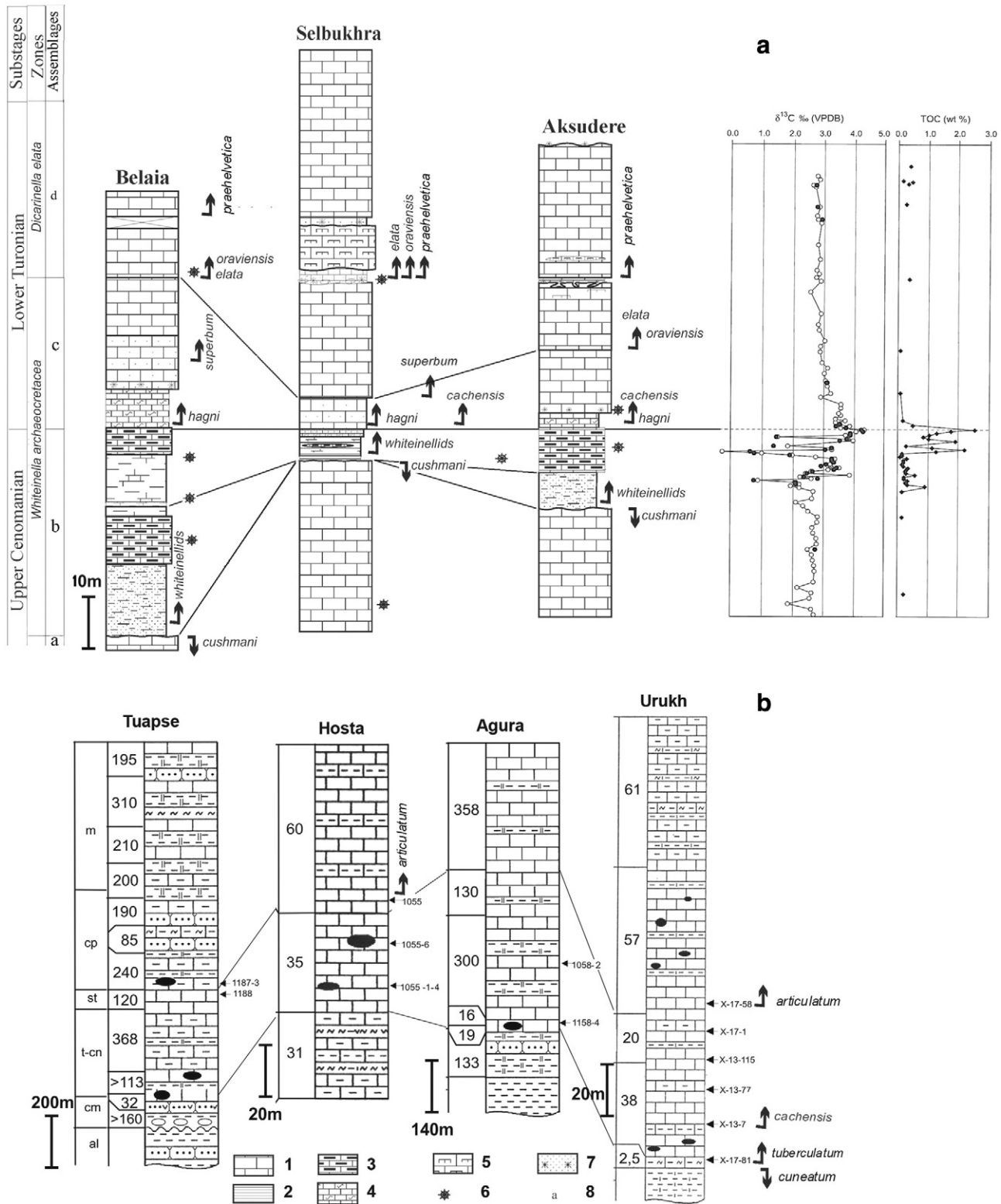


Fig. 6. Correlation of the Upper Cretaceous sections: A, correlation of Cenomanian–Lower Turonian sections in Crimea; B, correlation of Cenomanian–Maastrichtian sections in Great Caucasus. The localities are indicated in Figs. 1 and 2. Key: 1, rhythmically bedded marls and limestones; 2, clays; 3, siliceous limestones; 4, siliceous marls; 5, carbonate sands with glauconite; 6, bituminous layers; 7, radiolarian “bloom”; a, *Rotalipora cushmani* Zone with k/r strategists; b, *Dicarinella imbricata* Subzone with r-strategists; c, *Dicarinella hagni* Subzone with r and r/k strategists; d, *Dicarinella elata* Zone with r/k and k/r strategists. Black arrows indicate FAD and LAD of marker species. The graphs for $\delta^{13}\text{C}$ and TOC (wt.%) are adapted from Fisher et al. (2005).

an admixture of siliceous materials. The terminal Santonian–Campanian interval can be seen in the Kudrino succession in Crimea (see Table 1).

Five successions in the south-western part of Crimea were analyzed for foraminifera and, in part, also for radiolarians (Table 1). Eight successions in the Caucasus were investigated for radiolarians, and, in part,

also for foraminifera. In addition, radiolarians are abundant in the carbonate–siliceous successions of the northwest Caucasus (Vishnevskaya and Sedaeva, 1988; Vishnevskaya, 2001). Foraminiferal and radiolarian zonal schemes, with the age attributions shown in Fig. 3 (see also Vishnevskaya et al., 2013a,b; Vishnevskaya and

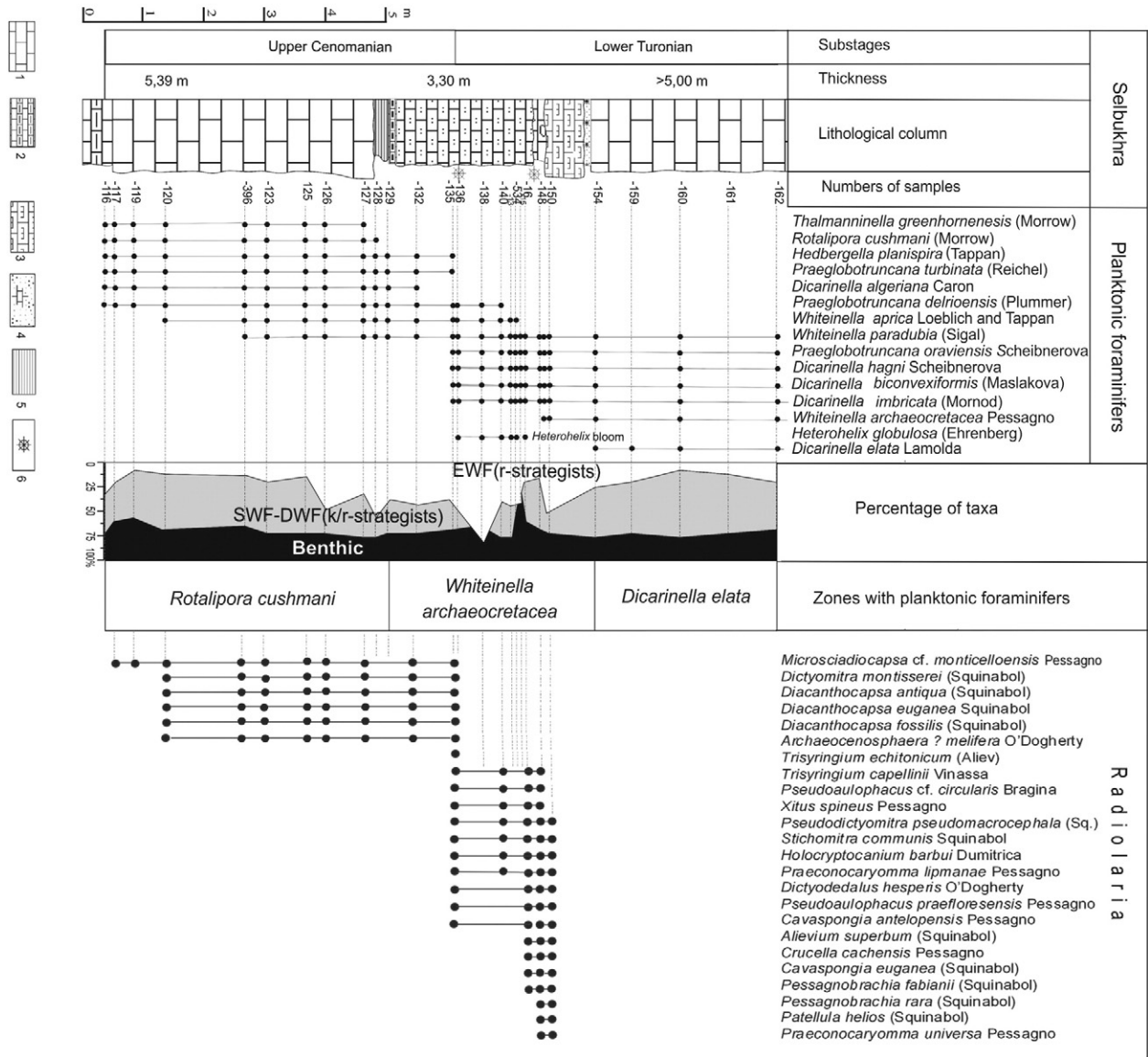


Fig. 7. The Selbukhra section and the most important foraminifera and radiolarians near the Cenomanian–Turonian boundary (for legend see Fig. 6).

Table 1

Overview on sample locations, numbers of samples and respective figures.

Region	Locality	Age	Number of samples	Microfossils	References and figures
Great Caucasus	Bacsan	Uppermost Albian	15	Foraminifera, Radiolaria	Figs. 2, 4
		Lower Cenomanian	1	Foraminifera, Radiolaria	Figs. 2, 4
	Uruk	Albian	1	Foraminifera, Radiolaria	Figs. 2, 6, 11
		Cenomanian	1	Foraminifera, Radiolaria	
		Turonian	1	Foraminifera, Radiolaria	
		Coniacian	2	Foraminifera, Radiolaria	
		Santonian	2	Foraminifera, Radiolaria	
	Lower Campanian	1	Foraminifera, Radiolaria		
		1	Radiolaria	Figs. 2, 6	
	Hosta	Turonian–Campanian	3	Radiolaria	Figs. 2, 6
		2	Radiolaria	Figs. 2, 6	
Lesser Caucasus	Bass	Cenomanian–Campanian	28	Foraminifera	Fig. 2, Kopaeovich and Khotylev, (2014)
		Uppermost Albian–Lowest Cenomanian	12	Foraminifera	
	Podkumok	Uppermost Albian–Lowest Cenomanian	8	Foraminifera, Radiolaria	
		Cenomanian	7	Radiolaria	Figs. 2, 12
Crimea	Kudrino	Lower Campanian	17	Foraminifera	Figs. 1, 14
		Upper Cenomanian	20	Foraminifera, Radiolaria	Figs. 1, 6

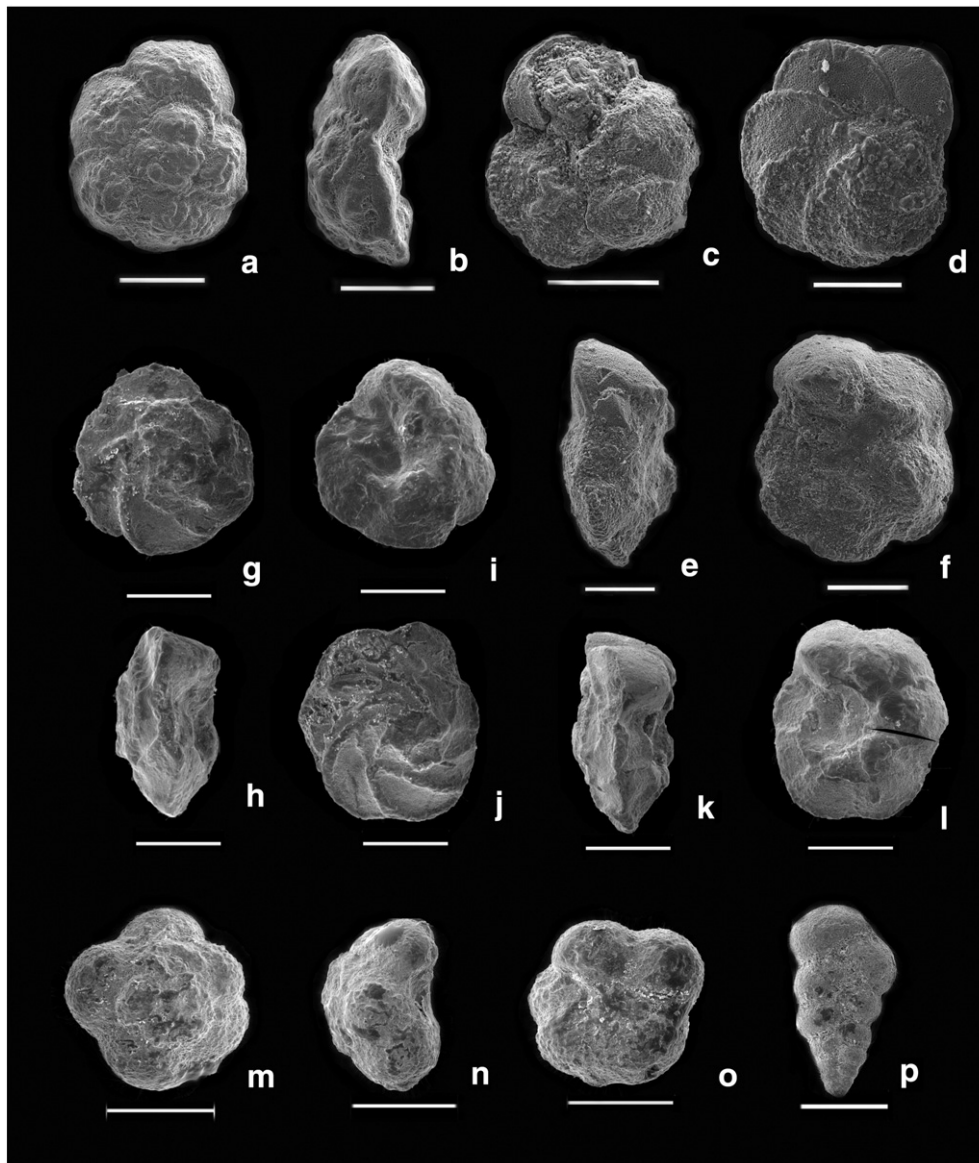


Fig. 8. Cenomanian planktonic foraminifera of sections in Crimea (Selbukhra Mountain) and the Caucasus (Bacsan River): a–c. *Rotalipora cushmani* (Mornod), Selbukhra Mountain, sample 132, a – spiral side, b – axial side, c – umbilical side; d–f. *Thalmaninella globotruncanoides* (Sigal), Bacsan River, sample B-16, d – spiral side, e – axial side, f – umbilical side; g–i. *Thalmaninella gandolfii* (Sigal), Bacsan River, sample B-16, g – spiral side, h – axial side, i – umbilical side; j–l. *Thalmaninella deeckeii* (Franke), Selbukhra Mountain, sample 129, j – spiral side, k – axial side, l – umbilical side; m–o. *Whiteinella paradubia* (Sigal), Selbukhra Mountain, sample 123, m – spiral side, n – axial side, o – umbilical side; p. *Heterohelix globulosa* Cushman, sample 132. Scale bar equals 200 μm .

Kopaevich, 2014) were used here. In this paper, the sea level changes and a water depth model have been constructed using the planktonic/benthic (P/B) ratio and an analysis of the planktonic foraminiferal assemblages. The P/B ratio can serve as an indication of relative depth and position to shoreline (Grimsdale and Van Morkhoven, 1955; Phleger, 1960, p. 257–259) but must be used with caution. Variations in the benthic community, caused by changes in the palaeoecology, can affect the P/B ratio. This indicator has, nevertheless, been used in many publications (e.g., Carter and Hart, 1977; Alekseev et al., 1997, 2007; Walaszczyk et al., 2010; Dubicka and Peryt, 2011, 2012a,b). The small serial planktonic foraminifers (heterohelicids and guembelitrids) are often considered to be the shallowest-water dwellers whereas the planispiral forms (globigerinelloidids) and trochospiral forms with globular chambers (hedbergellids, archaeoglobigerinids and rugoglobigerinids) may have lived slightly deeper. Keeled taxa and large biserial and multiserial heterohelicids are believed to have been the deepest-dwelling planktonic foraminifers. This bathymetric division

has been based on palaeobiogeographic distribution data, changes in distribution of foraminifers relative to eustatic changes, oxygen isotopic data and by analogy with the depth habitats of recent foraminifers (e.g., Bé, 1977; Hart and Bailey, 1979; Leckie, 1987; Premoli Silva and Sliter, 1995; Petrizzo, 2000, 2002; Dubicka and Peryt, 2011, 2012a,b; Wendler et al., 2013).

Foraminifera and radiolarians were extracted from relatively soft marls and clay-rich limestones (99 samples) using standard micropalaeontological techniques. This involved soaking dry samples (~200 g) in sodium bicarbonate and washing these through a 0.063 mm sieve. Relatively hard, silicified rocks from the siliceous marls and limestones (39 samples) were disintegrated by soaking crushed rock samples with sodium sulfate (Maslakova et al., 1995). The chert-rich clays (9 samples) were crushed and then boiled with 5% H_2O_2 , while chert and chert-rich limestones (13 samples) were treated with 0.5–3.0% HF, according to the methods described by Dumitrica (1970) and Pessagno (1976). Foraminiferal preservation is

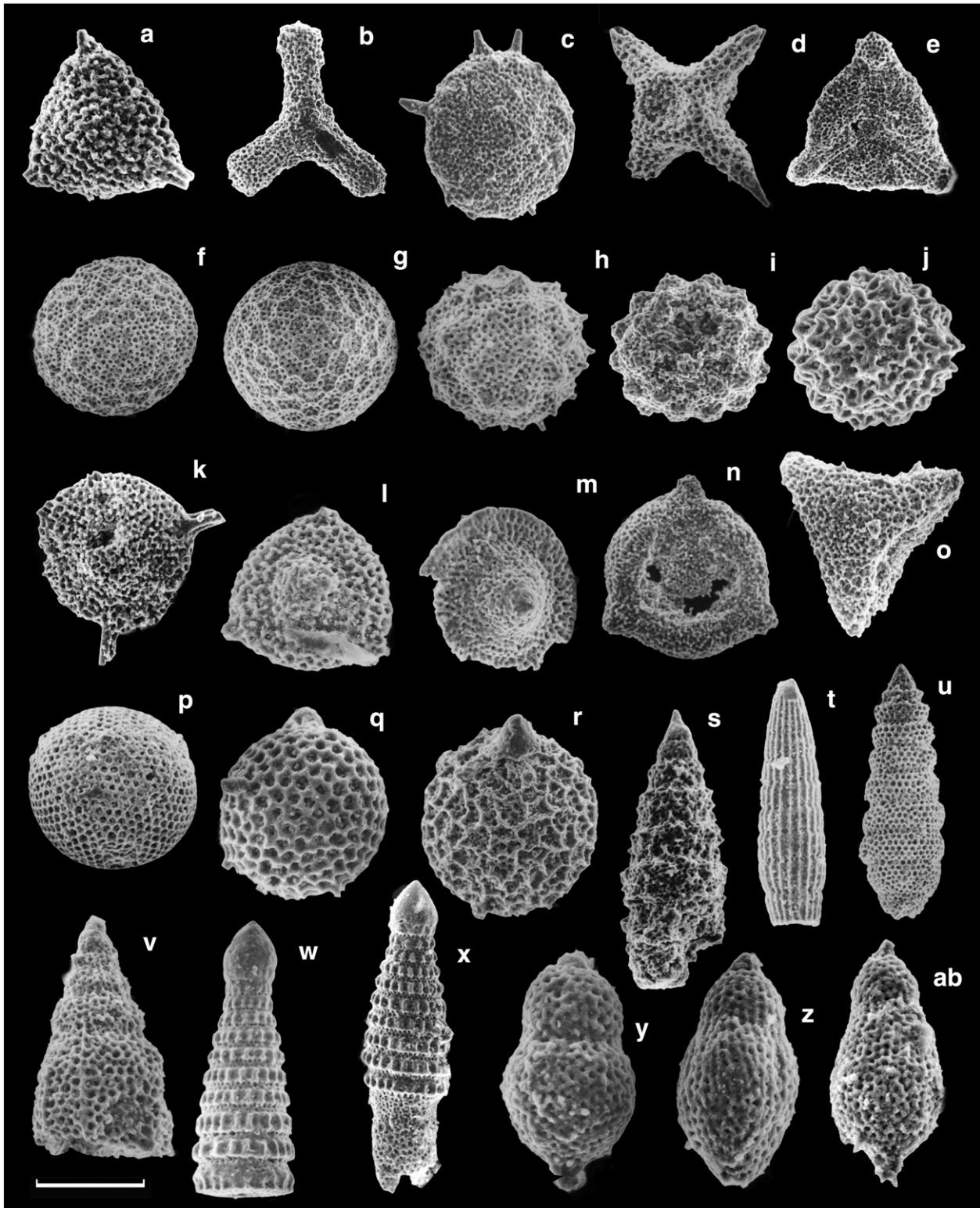


Fig. 9. Cenomanian–Turonian radiolarians of the Selbukhra Mountain section of Crimea: a. *Alievium superbum* (Squinabol); b. *Pessagnobrachia fabianii* (Squinabol); c. *Patellula helios* (Squinabol); d. *Crucella cachensis* Pessagno; e. *Pessagnobrachia rara* (Squinabol); f, g. *Archaeocenosphaera ? melifera* O'Dogherty; h, i. *Praeconocaryomma lipmanae* Pessagno; j. *P. universona* Pessagno; k. *Pseudoaulophacus cf. circularis* Bragina; l. *P. praefloresensis* Pessagno; m. *Microsciadiocapsa* sp. cf. *monticelloensis* Pessagno; n. *Cavaspongia euganea* (Squinabol); o. *C. antelopensis* Pessagno; p. *Holocryptocanium barbu* Dumitrica; q. *Trisyringium echitonicum* (Aliev); r. *T. capellinii* Vinassa; s. *Xitus spineus* Pessagno; t. *Dictyomitra montisserei* (Squinabol); u. *Stichomitra communis* Squinabol; v. *Dictyodetalus hesperis* O'Dogherty, w, z — *Pseudodictyomitra pseudomacrocephala* (Squinabol), y — *Diacanthocapsa fossilis* (Squinabol); z. *D. antiqua* (Squinabol); ab. *D. euganea* Squinabol. Specimens in figs. a–e, g, i, j, l, n–p, r, s, w are from sample 18A (Turonian); specimens in figs. f, h, k, m, q, t–v, z–ab from sample 136 (Upper Cenomanian/Lower Turonian boundary). Specimens in figs. f, g are taken from Vishnevskaya et al. (2005a,b), Figs. 1, 2; o, v, x are taken from Vishnevskaya (2001, pl. 129).

very good in the soft, carbonate-rich sediments but moderate to poor in the harder rocks. Scanning Electron Microscope images of the foraminifera and radiolarians were taken by TESCAN at the

Paleontological Institute of Russian Academy of Sciences (Moscow) and by SCAN ISI-90 at the Geological Institute of the Russian Academy of Sciences.

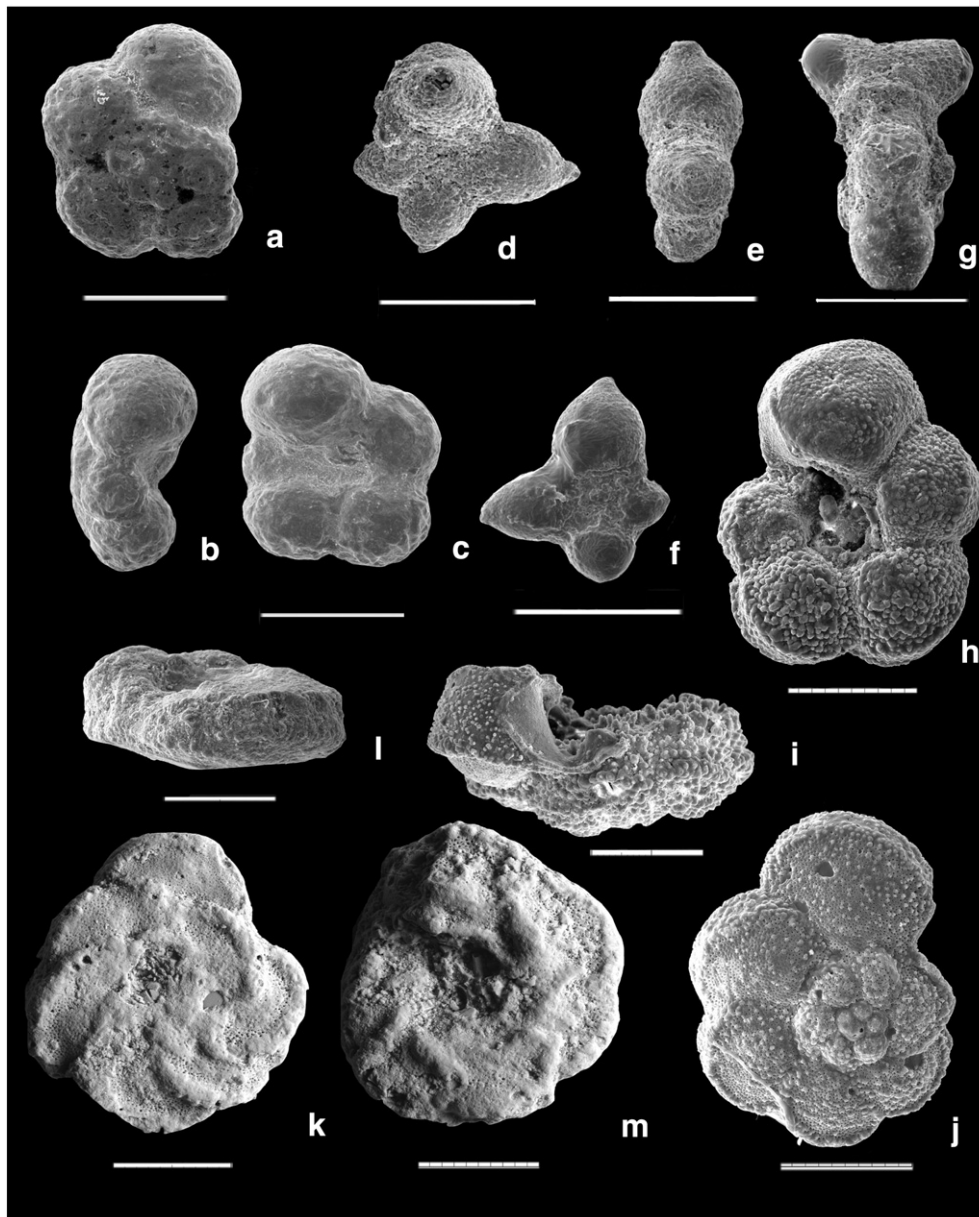


Fig. 10. Planktonic foraminifera from the Cenomanian–Turonian boundary of the Selbukhra section (a–f) and the Turonian of the Uruk section (k–m): a–c. *Whiteinella baltica* (Douglas and Rankin), sample 135, a – spiral side, b – axial side, c – umbilical side; e–f. *Schackoina cenomana* Schako, sample 136, e – axial side, f – umbilical side; g. *Schackoina multispinata* (Cushman and Wickenden), sample 146, axial side; h–j. *Marginotruncana marginata* (Reuss), sample X-13-7, h – spiral side, i – axial side, j – umbilical side; k–m. *Marginotruncana pseudolimneiana* (Pessagno), sample, X-13-7, k – spiral side, l – axial side, m – umbilical side. Scale bars equal 200 μm .

4. Aims and objectives

The aim of this present study is the documentation of the distribution of foraminifera and radiolarians in the Mid–Upper Cretaceous successions of the Crimean Peninsula and the northern and western margins of the Great Caucasus (Figs. 1, 2). Assemblages of planktonic foraminifera and radiolarians have been investigated from the same samples collected from the Cenomanian–Campanian sequence of the Uruk Section and other localities in the northern Caucasus, as well as from the Cenomanian–Turonian of the five sections of Crimea (Fig. 1, 2) within an interval enriched by organic matter up to 7.2–8.0% (Naidin and Kiyashko, 1994a,b; Kopaevich and Kuzmicheva, 2002; Fisher et al., 2005). The Middle Turonian–Coniacian and Santonian–Campanian intervals were studied in three sections of the Crimea (Fig. 1).

The Crimea–Caucasus Basin was situated in the northern part of the Neo-Tethys Ocean, and formed part of the Temperate Realm of the Peri-

Tethys, being transitional between the warm Tethys and higher latitudes where climatic variations (warming/cooling) are assumed to have been better preserved in the fossil record (Petrisso, 2002; Baraboshkin et al., 2003). Planktonic foraminiferal and radiolarian assemblages from the same samples of these sections have been studied in detail as far as variations in composition are concerned, in order to identify fluctuations in diversity and abundance of major morphotypes, which can be used to determine palaeoceanographic changes, water depth, position of the coastlines, water temperature and the structure of the water column, as well as to correlate foraminiferal and radiolarian bioevents (Fig. 3).

The evolution of planktonic foraminifera from the Cenomanian to the Campanian is characterized by an increase in species diversity and morphological complexity (Bandy, 1953, 1961; Bolli, 1959; Borsetti, 1962; Maslakova, 1978; Caron, 1985; Gorbachik, 1986; Krasilov, 1986; Premoli Silva and Sliter, 1995, 1999; Hart, 1999 and many others). Numerous scientists have determined the Upper Cretaceous foraminiferal

zonations for the Crimea and the northern and western Caucasus. The most important contributions are those of Maslakova (1978), Samyshkina (1983), Plotnikova in Astakhova et al. (1984), Tur (1996), Tur et al. (2001), Korchagin, 2001; Kopaeovich (2009), and Korchagin et al. (2012). The Albian–Cenomanian and Cenomanian–Turonian boundaries in these areas have been studied by Vishnevskaya (1991), Alekseev et al. (1997, 2007), Kopaeovich and Kuzmicheva (2002), Vishnevskaya et al. (2006, 2013a,b) and Vishnevskaya and Kopaeovich (2008, 2014).

The Late Cretaceous radiolarian assemblages from the successions of the Crimea have been previously studied by Bragina (1999), Vishnevskaya (2001), Bragina (2004), Bragina and Bragin (2006), Vishnevskaya et al. (2006), Vishnevskaya and Kopaeovich (2007), Vishnevskaya and Kurilov (2007), Bragina (2009a,b, 2011). The Cenomanian–Turonian transition of Selbukhra has been described by Bragina and Bragin (2007). The Turonian–Coniacian of the Bel'bek River has been described by Bragina et al. (2014) and the Turonian–Lower Coniacian of the Biyuk–Karasu by Korchagin et al. (2012), which also includes the Santonian of Mt. Ak-Kaya. The assemblages from the Caucasus have only been recorded in a limited number of papers, including those by Vishnevskaya et al. (1991), Vishnevskaya and Agarkov (1998), Postuma (1971), Vishnevskaya (2001), Bragina et al. (2007) and Vishnevskaya and Kopaeovich (2014).

The previous publications have shown that radiolarians constitute the best tool for the determination of the stratigraphical ages of the siliceous strata (with cherts), including the documentation of the rapid changes of these assemblages over time. The radiolarians have been shown to have wide vertical and geographical distributions in the successions of the Crimea–Caucasus region (Vishnevskaya, 2001; Bragina, 2004; Vishnevskaya et al., 2005a,b). Most importantly, radiolarians are also present in the 'black shales', which are associated with the strongly dysaerobic to anoxic events recorded by Mid-Cretaceous OAE 1–2. In southwest Crimea and the northern Caucasus, the Cenomanian–Turonian interval is characterized by a marked drop in taxonomic diversity of the benthic foraminifera (Kopaeovich and Kuzmicheva, 2002) and by the presence of cosmopolitan species among planktonic foraminifera: i.e., the zone of "Grandes Globigerines seules" (Sigal, 1977) or – as it is now known – the *Whiteinella archaeocretacea* Zone (Kopaeovich and Kuzmicheva, 2002; Alekseev et al., 2007; Kopaeovich, 2010).

5. Results

5.1. Foraminiferal assemblages of the Cenomanian

The first appearance of *Thalmaninella globotruncanoides* and the consistent presence of *Thalmaninella gandolfii* at the Albian–Cenomanian boundary are recorded in the Selbukhra section of the Crimea (Gorbachik et al., 2000; Kopaeovich and Khotylev, 2014). The same bio-events are recorded in the Bacsan succession (Figs. 2, 4, 5) and also in the succession at Kheu (locality 6 on Fig. 2) and Podkumok (locality 4 on Fig. 2) (Kopaeovich and Khotylev, 2014). The consistent presence of these two species is indicative of the Lower Cenomanian, *T. globotruncanoides* Zone (Robaszynski and Caron, 1995). This is equivalent to the *Rotalipora brotzeni* Zone of Lehmann (1966). The base of this zone marks the GSSP between the Albian and Cenomanian (Robaszynski et al., 1990; Robaszynski and Caron, 1995; Gale et al., 1996; Kennedy et al., 2004; Caron and Premoli Silva, 2007; Spezzaferri and Caron, 2008; Scott, 2014). In the study area, we have identified a *T. globotruncanoides* Interval Range Zone (IRZ) in the Lower Cenomanian, a *Thalmaninella deecke* or *Thalmaninella reicheli* IRZ in the Lower to Middle Cenomanian and a *Rotalipora cushmani* Total Range Zone (TRZ) in the middle and most of the Upper Cenomanian of the Selbukhra and Balaklava successions (see Borsetti, 1962; Maslakova, 1978; Vishnevskaya and Kopaeovich, 2008; Kopaeovich, 2010; Nikishin et al., 2013; Kopaeovich and Khotylev, 2014). This biozonation is very close to that documented by Robaszynski and

Caron (1995). In the Crimea, at the boundary between the Lower and Middle Cenomanian, a *T. deecke* IRZ has been established, because *T. reicheli* is very rare (Maslakova, 1978). At the same time, in the Caucasus successions, this species occurs consistently (Tur et al., 2001; Kopaeovich, 2009). Assemblages of the *T. globotruncanoides*, *T. deecke* and *R. cushmani* Zones are represented by *Thalmaninella* (5 species), *Rotalipora* (2 species), and also by the presence of *Hedbergella* spp., *Whiteinella* spp., *Praeglobotruncana* spp. and rare *Heterohelix* spp.

The *Whiteinella archaeocretacea* Partial Range Zone (PRZ) established by Bolli (1966), which is the equivalent of the *Praeglobotruncana gigantea* Zone, includes the interval from the last occurrence of *Rotalipora cushmani* to the first occurrence of *Helvetoglobotruncana helvetica* (assemblages "b" and "c" in Fig. 6). Illustrations of Albian–Cenomanian planktonic foraminifera are shown in Figs. 5, 8, (partly) 9, and 10.

5.2. Radiolarian assemblages of the Cenomanian

The Cenomanian assemblages from the Crimea (15 samples from Selbukhra and 3 samples from Belaya) and the Great Caucasus (2 samples from Bacsan and 1 sample from Uruk) include more than 50 species (Vishnevskaya et al., 1991, 2006; Bragina, 1999, 2004, 2014). The marker taxa are *Orbiculiforma maxima* Pessagno, *Petasiforma foremanae* Pessagno, *Pyramispongia glascockensis* Pessagno, *Savaryella navalis* (Squinabol), *Staurosphaeretta wisniowski* (Squinabol), *Xitus spicularius* (Aliev) and *Pseudodictyomitra pseudomacrocephala* (Squinabol), as well as the prevailing cryptocephalic *Cryptamphorella conara* Foreman, *Hiscocapsa asseni* (Tan), *Holocryptocanium barbui* Dumitrica, *Holocryptocanium astiensis* Pessagno, *Holocryptocanium geysersensis* Pessagno, *Holocryptocanium tuberculatum* Dumitrica and *Diacanthocapsa antiqua* (Squinabol) with an hyperspherical abdomen (Figs. 6, 7, 9, 11).

The Cenomanian radiolarian assemblages of the Lesser Caucasus (Geys and Amasia successions, Fig. 2) with typical *P. pseudomacrocephala* (Squinabol) (Fig. 12) include the following characteristic taxa: *Cryptamphorella sphaerica* (White), *H. tuberculatum* Dumitrica, *H. barbui* Dumitrica, *Dictyomitra lilyae* Tan, *Dictyomitra torquata* Foreman, *Pseudodictyomitra tiara* (Holmes), *Petasiforma* cf. *P. glascockensis* Pessagno, *P. ex gr. foremanae* Pessagno, *Thanarla elegantissima* (Cita), *Thanarla veneta* (Squinabol) and *Amphipyndax stocki* (Campbell and Clark) (compare Vishnevskaya et al., 2013a,b; Danelian et al., 2014). A Cenomanian age is defined by the occurrence of *P. tiara* (Holmes), which has a first appearance datum (FAD) in the Cenomanian. This is the equivalent of the *Dactyliosphaera silviae* Zone of O'Dogherty (1994) which is recorded from the Cenomanian sedimentary cover member of the Amasia ophiolite in Armenia (Danelian et al., 2014), and *H. tuberculatum* Dumitrica which has been recorded from Cenomanian deposits in Romania (Dumitrica, 1970), the Franciscan Complex of the Cenomanian in the Great Valley, California (Pessagno, 1976, 1977), and the Cenomanian–Turonian boundary interval in the Polish Carpathians (Bağ, 2000, 2011). It has not been found below the base of the Cenomanian according to current data.

At the end of the Cenomanian, the family Rotaformidae (first known from the Albian) went extinct, with the genus *Obeliscoites* (Nassellaria) known only from a single locality in the Lower Turonian of Poland, according to Bağ (2000, 2011). The genus *Godia* (Spumellaria) also disappears, and the earliest representatives of *Alievium* (*A. antiquum*) gradually die out (Pessagno, 1976; Vishnevskaya, 2001).

Petrological data indicate a change from extensional conditions to general compression that led to the deformation of oceanic basement and its obduction during the Late Cretaceous, which is reflected in the radiolarian record (Zakariadze et al., 1983; Vishnevskaya, 2001).

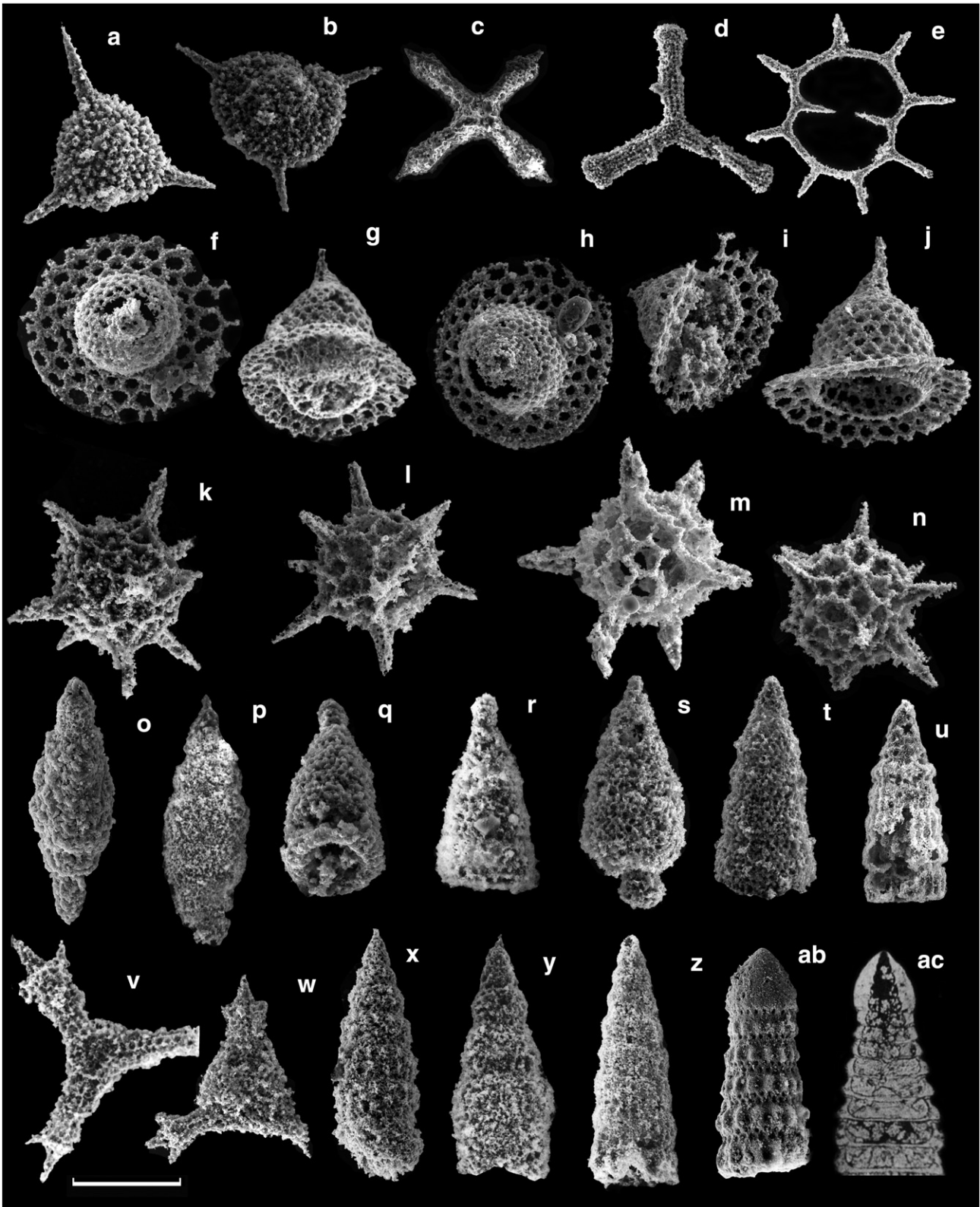


Fig. 12. Zonal and marker species among radiolarians from Upper Cretaceous sequences of the Caucasus: a. *Alievium superbum* (Squinabol), sample X-13-7, Uruk, Turonian; b. *Pseudoaulophacus praeflorescens* Pessagno, sample X-13-77, Uruk, Coniacian; c. *Crucella irwini* Pessagno, sample X-13-7, Uruk, Turonian (taken from Vishnevskaya, 2001); d. *Pessagnobrachia fabianii* (Squinabol), sample X-13-7, Uruk, Turonian; e. *Spongosaturminus hueyi* Pessagno, sample 1058-2B, Agura, Santonian; f–j. *Neosciadiocapsa diabloensis* Pessagno, f, h–j, sample X-13-7, Uruk, Santonian, g – sample 1058-2B, Agura, Santonian (taken from Vishnevskaya, 2001); k–n. *Quinquecapsularia panacea* (O'Dogherty), k, l – sample X-13-115, Uruk, Santonian; m, n – sample 1058-2B, Agura, Santonian; o. *Prunobrachium articulatum* (Lipman), sample X-17-58, Uruk, Lower Campanian; p. *Prunobrachium articulatum* (Lipman), sample 1055, Hosta, Campanian; q–t. *Amphipyndax* ex gr. *stocki* (Campbell and Clark), q, t – sample X-13-115, Uruk, Santonian, s – sample X-17-81, Uruk, Cenomanian; u. *Dictyomitra torquata* Foreman, sample X-17-58, Uruk, Lower Campanian; v, w. *Paronaella* cf. *venadoensis* Pessagno, v – sample 1058-2B, Agura, Santonian; w – X-13-7, Uruk, Turonian (taken from Vishnevskaya and Agarkov, 1998); x. *Xitus spineus* Pessagno, sample X-17-81, Uruk, Cenomanian; y. *Xitus? spineus* Pessagno, sample 1058-2B, Agura, Santonian; z. *Dictyomitra andersoni* (Campbell and Clark), sample X-17-58, Uruk, Lower Campanian; ab, ac. *Pseudodictyomitra pseudomacrocephala* (Squinabol), ab – Lesser Caucasus, Amasia, Cenomanian (adopted from Danelian et al., 2014), ac – Lesser Caucasus, Giysu, sample 127, Cenomanian. Scale bars are 100 μ m.

vacaensis Pessagno. The Coniacian age is confirmed by the presence of the inoceramid *Volviceramus involutus* (Sowerby) (Stratigraphy, 1986). Assemblage V is equivalent to the *C. concavata* ARZ (samples X-13-115 and X-17-1), and represents the Upper Coniacian–Lower Santonian interval (Fig. 3). Furthermore, this interval contains *Archaeoglobigerina* spp. and *Globigerinelloides asper* (Ehrenberg), the latter being a marker for the Lower Santonian on the eastern European Platform (Kopaevich, 2010). Radiolarian assemblage V, with *Pseudoaulophacus floresensis* Pessagno, *Archaeospongoprimum nishiyamae* Nakaseko and Nishimura and *Euchitonia santonica* Lipman has been referred to the *Archaeospongoprimum nishiyamae* and *Euchitonia santonica* Bed (Vishnevskaya and Agarkov, 1998). It can be attributed to the *Alievium gallowayi* Zone of Pessagno (1976) of the Santonian due to the presence of index species. The high taxonomic diversity of Quinquecapsulariidae and Neosciadiocapsidae is characteristic of this interval. The age is confirmed by the inoceramid *Cladoceramus undulaticus* Roemer (Stratigraphy, 1986). It is the primary criterion for the definition of the GSSP for the base of the Santonian stage (Lamolda et al., 2014). As a result of the acme of *Neosciadiocapsa diabloensis* Pessagno, this interval can be compared with the Santonian of the Ak-Kaya section in the Crimea (Korchagin et al., 2012) and the Voronezh Region of Russian Platform (Popova-Goll et al., 2005). Assemblage VI, with the *Globotruncanita elevata* PRZ and *Globotruncana arca* characterizes the uppermost Santonian–Lower Campanian (Fig. 3). It can be correlated with the Kudrino succession of the Crimea (Fig. 14). Previously, radiolarian assemblage VI was recognized in the Uruk and Agura sections as the *D. torquata* Bed (Vishnevskaya and Agarkov, 1998). It is now known as the *D. torquata*–*Amphipyndax tylotus* Bed (Figs. 3, 11). The first appearance of *Prunobrachium articulatum* Lipman and *Amphipyndax tylotus* Foreman in sample X-17-58 allows us to equate this interval with the *Amphipyndax pseudoconulus* Zone of the Tropical Realm (Sanfilippo and Riedel, 1985), as well as the Campanian *P. articulatum* Zone of the Russian Platform (Vishnevskaya, 2010). The radiolarian assemblage of Hosta (locality 3 on Fig. 2) also contains *P. articulatum* (Fig. 12), occurring just above of the interval with *Alievium gallowayi* (White): see Vishnevskaya (2001, pl. 99).

6. Discussion

The Late Cretaceous palaeoceanography and palaeogeography of the Crimea–Caucasus area has never been documented in detail. Informative stage-by-stage maps for the north-eastern Peri-Tethys area are contained in two palaeogeographical atlases (Vinogradov, 1961, 1968), which provide the only data available for the entire region. Other maps, for several areas within this region, may be found in a range of papers, while Dercourt et al. (2000) published maps for selected intervals (i.e., Late Cenomanian and Early Campanian) for the whole of the Peri-Tethys area. The most recent paper, which summarizes our knowledge of the palaeogeographical development of the northeast Peri-Tethys during the entire Cretaceous is that by Baraboshkin et al. (2003). However, in that paper, the main focus is on the East European Platform and the Crimean–Caucasian region only receives passing mention.

The depth distributions of Cretaceous planktonic foraminifera may have been similar to that of modern analogs with some globular morphotypes present in near-surface waters and with some flattened, keeled, biconvex and plano-convex forms representing increasingly deeper habitats (Hart and Bailey, 1979; Hart, 1980; Caron and Homewood, 1983; Leckie, 1987, 1989; Premoli Silva and Sliter, 1999). Three groups have been proposed for low-latitude, Mid-Cretaceous planktonic foraminiferal assemblages (Leckie, 1987). The first is the “Epicontinental Water Fauna” (EWF, <100 µm) characterized by species of *Heterohelix* and *Guembilitria* with relatively high percentages of small specimens of *Hedbergella* and *Globigerinelloides*. The second group, “Shallow Water Fauna” (SWF, <120 µm) comprises mainly *Hedbergella*,

Globigerinelloides, *Ticinella* and small species of *Praeglobotruncana* with ornamented tests in the Early Cretaceous assemblages. Species of *Whiteinella*, *Archaeoglobigerina*, *Praeglobotruncana* and *Dicarinella* were also components of the SWF assemblage during the Late Cretaceous (Hart and Bailey, 1979; Leckie, 1987, 1989; Gorbachik and Kopaevich, 1992). The typical species of *Dicarinella* include *D. algeriana* (Caron), *D. imbricata* (Mornod) and *D. hagni* (Scheibnerova). These species have a biconvex test and two closely-spaced, poorly developed keels. Some species of *Rugoglobigerina* may also be included in this group. The third group, the “Deep Water Fauna” (DWF, >100 µm) are assumed to have been the deepest-dwelling forms among Mid-Cretaceous and Late Cretaceous taxa. This includes species of the genera *Rotalipora*, *Thalmaninella*, *Marginotruncana* s. lato, *Concavatotruncana* (including *C. primitiva* (Dalbiez), *C. concavata* (Brotzen) and *C. asymetrica* (Sigal)), *Globotruncana* s. lato, *Globotruncanita* and *Contusotruncana*. Simple morphotypes, with short life cycles, were possibly the inhabitants of shallower water depths, identified as epicontinental water foraminifera (EWF). Intermediate morphotypes were the inhabitants of the shallow waters of the open sea (SWF), while complex morphotypes, with long life cycles, are characteristic of deep water (DWF) (Leckie, 1987, 1989). Detailed analyses of variations of planktonic foraminiferal assemblages may yield data on depth fluctuations (Hart and Bailey, 1979; Hart, 1980) and relative temperatures (colder–warmer). The ratio of planktonic and benthic foraminifera (P/B) can also serve as an additional indication of relative depth and position to the shoreline, if used with caution (Kopaevich, 1996).

Caron and Homewood (1983) developed the biological concept of *r*-strategists and *k*-strategists (MacArthur and Wilson, 1967) to Cretaceous planktonic foraminifera. It can assume that Cretaceous extinct planktonic foraminifera lived in the water column like their modern counterpart and were controlled by similar environmental factors (water temperature, water-mass structure, amount of nutrients, stability/instability of oceanographic conditions). Planktonic Foraminifera, inhabiting the “mixed” layer today, characteristically decrease in number from the tropics toward the high latitudes and, in general, are absent in polar waters. The decrease in species richness from tropics to high latitudes is reflected in the planktonic foraminiferal assemblages which progressively lose the less tolerant species (*k*-selected strategists), characterized by complex morphologies, and become dominated by the most tolerant, cosmopolitan and opportunistic taxa, characterized by small-sized, simple morphologies (*r*-selected strategists). *R*-strategists included small hedbergellids, biserial heterohelids, while *k*-selected strategists contained single keeled *Sigalitrunca*, *Globotruncanita*, and double-keeled *Marginotruncana*, *Globotruncana*, *Contusotruncana*. This concept has subsequently been extended by Petrizzo (2000, 2002). She offered to allocate intermediate morphotypes (*k/r* strategists) such as *Concavatotruncana*, *Helvetoglobotruncana* and (*r/k* strategists) *Praeglobotruncana*, *Whiteinella*, *Archaeoglobigerina* and *Rugoglobigerina*. *R*-strategists taxa belonged to the EWF group. They had an high reproductive potential and preferred nutrient-rich waters (eutrophic conditions). *K*-selected (*k*-strategists) foraminifera were abundant at low latitudes, preferred deep-water habitats and were unable to adapt quickly to changing environmental conditions (including oligotrophic conditions). They had a lower reproduction potential, but were highly competitive (Spezzaferri and Caron, 2008). These taxa belonged to the DWF group. Probably, transitional taxa (*k/r* and *r/k* strategists) can be included in SWF group.

An increasing diversity of planktonic foraminifera is recorded during the Late Albian–Cenomanian, especially in the rotaliporids with a wide range of morphological features (Leckie, 1987, 1989; Gorbachik and Kopaevich, 2002, 2011; Vishnevskaya and Kopaevich, 2008).

In the Cenomanian interval the *k/r* strategists (*Thalmaninella*, *Rotalipora*), and *r/k* morphotypes (*Whiteinella* and *Praeglobotruncana*) are predominant (Gorbachik and Kopaevich, 2011, Fig. 6). The *r*-strategist group, with *Hedbergella* as the predominant genus, shows rare cyclic fluctuations. The distribution of foraminiferal taxa is shown in

Figs. 7, 8 and 10. In the study area, a deep-water basin (<500 m deep) existed during the Cenomanian (Alekshev, 1989; Nikishin et al., 2008), based on a P/B ratio of 50–75% and a predominance of DWF/SWF taxa (Fig. 7). The deepest-water conditions were found in the western part of the Great Caucasus Basin, which is characterized by the presence of turbidites and deep-water periodites (Fig. 2, localities 1–6; see Badulina et al., 2009); radiolarians dominate the planktonic assemblages in this area.

The foraminiferal assemblages across the Cenomanian–Turonian boundary are characterized by the extinction of *Rotalipora* prior to the end of the Cenomanian (Leckie, 1987, 1989; Jarvis et al., 1988; Tur, 1996; Keller et al., 2001; Tur et al., 2001; Kopaeovich and Kuzmicheva, 2002; Coccioni and Luciani, 2002; Keller and Pardo, 2004; Alekshev et al., 2007; Figs. 6, 7). The *W. archaeocretacea* Zone contains (Figs. 6–8) only species of *Hedbergella*, *Heterohelix*, *Schackoia* (r-strategists) and *Whiteinella* (r/k intermediate strategists). This interval coincides with the OAE 2 event and the presence of “black shale” facies in the Belaya, Aksudere and Selbukhra successions (see Figs. 6, 7). The clear prevalence of non-keeled, small forms and the presence of *schackoia*ids, species with perforate, elongated tubulospine-bearing chambers, may represent the best tool for survival by allowing a more efficient uptake of oxygen and nutrients (Coccioni and Luciani, 2002; Coccioni et al., 2006). The *Heterohelix* peak is recorded in the Selbukhra and Aksudere successions (Fig. 7). This peak appears to be a reliable biological indicator that is coincident with the expansion of the $\delta^{13}\text{C}$ peak and the proposed expansion of the oxygen minimum zone (Keller and Pardo, 2004).

Fluctuations in biological productivity may have been associated with periods of upwelling (Badulina et al., 2009; Levitan et al., 2010, p. 549). This contributed to the so-called “Radiolaria bloom” (Kopaeovich and Kuzmicheva, 2002), associated with the anoxia recorded at the Cenomanian–Turonian boundary, has been described from the Crimea and Caucasus region.

Diverse radiolarian assemblages (>70 species) have been recorded in the chert-rich sediments above the bituminous shale horizon which marks the presence of OAE-2 close to the Cenomanian–Turonian boundary in the upper flysch-type deposits of the Ananuri Formation of Lazarevskoe area in the western Caucasus (Bragina et al., 2007). The radiolarian assemblage from the bituminous marls and clays (e.g., Aksudere, Selbukhra and Belaya successions in Crimea, and the Uruk succession in the Caucasus; see Vishnevskaya et al., 2006) of the uppermost Cenomanian is very characteristic. There is an increase of ‘spongy’ forms among the Spumellaria and the cryptocephalic and cryptothoracic Nassellaria (i.e., the appearance of *Diacanthocapsa anti-gua* (Squinabol), *Diacanthocapsa ovoidea* Dumitrica, *Diacanthocapsa euganea* Squinabol, *Diacanthocapsa brevitroax* Dumitrica among the Diacanthocapsidae), a reduction of morphological variability, a smoothing of external sculpture, and forms with irregular, abnormal or abhorrent patterns of porosity (Figs. 7, 9). Bjorklund and Swanberg (1987) explained reticulated pores (abnormal porosity) by the presence of neritic conditions or cold water in contrast to the round pores seen in normal oceanic conditions. Therefore, ‘spongy’ and abnormal porosity can be explained with rise of sea level or anoxic influence. At the same time, due to good preservation potential in organic-rich and phosphate-rich layers, some nassellarian forms demonstrate perfectly preserved basal tubes (Fig. 9), which are never seen in organic-poor sediments.

Species of the Order Nassellaria are always a more progressive group of radiolarians (Vishnevskaya, 2009). A very important morphological nassellarian element is the first segment. This comprises an initial chamber with spicula, called the cephalis. It contains the initial multi-beam spicula, which supported the nucleosopodial apparatus in Recent radiolarians. At times of palaeoceanographical reorganization or crises, it is this part of the skeleton that underwent the most essential changes (Vishnevskaya, 2009).

The emergence of pseudocephalic (“the false head”) forms in the chalk facies took place at the end of the Albian, when numerous morphotypes of *Pseudodictyomitra* with hyperbolically-sized first 3–5 segments appeared. These include *Dictyomitra disparlita* Aliev,

Dictyomitra malleola Aliev, *Dictyomitra nardaranensis* Aliev, *Dictyomitra sagitafera* Aliev and *P. pseudomacrocephala* (Squinabol). It is possible that the sudden emergence of all these pseudocephalic forms, was linked to the final phase of the OAE 2 event (Vishnevskaya et al., 2006). Most of the radiolarian pseudocephalic types listed above went extinct in the Cenomanian. The last form of *P. pseudomacrocephala* (Squinabol), a cosmopolitan species, has great stratigraphical and palaeoceanographical value (Basov and Vishnevskaya, 1991). Detailed research on the structure of the initial segments of *P. pseudomacrocephala* (Squinabol) has shown that in the Albian–Early Cenomanian the so-called pseudocephalic forms have a form which comes closer to a sphere, whereas the end-Cenomanian pseudocephalic forms are sub-conical with the maximum increase of additional fabric not on the first, but on the second and third segments. The Early Turonian *P. pseudomacrocephala* (Squinabol) are strictly conical in form.

Thus, the Cenomanian–Turonian boundary is closely related to the OAE-2 event, which can be traced worldwide (Koutsoukos et al., 1990; Fisher et al., 2005; Forster et al., 2007), and which is characterized by the occurrence of primitive cosmopolitan taxa and abundance of cryptocephalic and pseudocephalic forms. It is often characterized by the presence of not more than 5–6 species of planktonic foraminifera, with – in some cases – their complete absence. Radiolaria also show comparable changes over the same interval.

The Turonian interval is characterized by an abrupt reduction in the number of species of the more r-selected and r/k intermediates (*Whiteinella*, *Praeglobotruncana* and *Hedbergella*). Simultaneously, there was a progressive evolution of the marginotruncanids (k-strategists); see Kopaeovich (1996). This continued until the end of the Coniacian, which is characterized by a variety of concavotrun-canids (Fig. 11). The rapid diversification and increase in the number of keeled specimens of *Marginotruncana* can be interpreted as related to a temperature rise possibly associated with a gradual increase in stratification of surface and near-surface waters (Fig. 11). Consequently, ecological niches became more numerous and could be occupied by specialized taxa. The fluctuating increase in the abundance of *Whiteinella* and *Archaeoglobigerina* indicates that water masses may have been periodically unstable, and that near-surface waters could be more mesotrophic. The P/B ratio in the Turonian–Coniacian sediments varies between 45 and 70%, with DWF and SWF taxa predominating (Kopaeovich, 1996, Fig. 4; Fig. 11).

The Turonian–Coniacian assemblages of planktonic foraminifera in the Uruk succession of the Caucasus are comparable to those with *M. pseudolinneiana* (uppermost Middle Turonian) and *M. coronata* (upper Turonian) in the Biuk-Karasu succession of Crimea (Bragina et al., 2014), as well as the Coniacian of Ak-Kaya (Korchagin et al., 2012).

Following the Coniacian peak of k-strategists there is a progressive decrease in the number of species of *Marginotruncana* and *Concavotrun-canida*: SWF and DWF taxa in the Uruk succession decrease to 12–15%. During the Santonian and Early Campanian, when *Marginotruncana*, *Globotruncana* and some intermediate forms coexisted, there was an interval of significant change. The most important was the disappearance of all marginotruncanids, except for *M. marginata*. The first species of *Globotruncana*, *Globotruncana bulloides* (Vogler) and *G. linneiana* (d’Orbigny), were initially quite rare. At the same time, r/k intermediate taxa, such as *Whiteinella* and *Archaeoglobigerina*, are always present in all samples. The r-strategists, *Heterohelix* and *Globigerinelloides*, are also consistently present. The P/B ratio continues at median levels, as before, but the DWF and SWF groups are sharply reduced (<20–30%) and the proportion of EWF taxa increases (Figs. 11, 13, Uruk section).

The extinction of the marginotruncanids and the disappearance of most of the specialized taxa, coincides with an increase in diversity of the opportunistic r-strategists (there are representatives of *Archaeoglobigerina*, *Whiteinella*, *Heterohelix*, *G. asper* (Ehrenberg); see Fig. 14). This turnover provides evidence of more unstable eutrophic conditions and suggests a temporal disruption of the water masses.

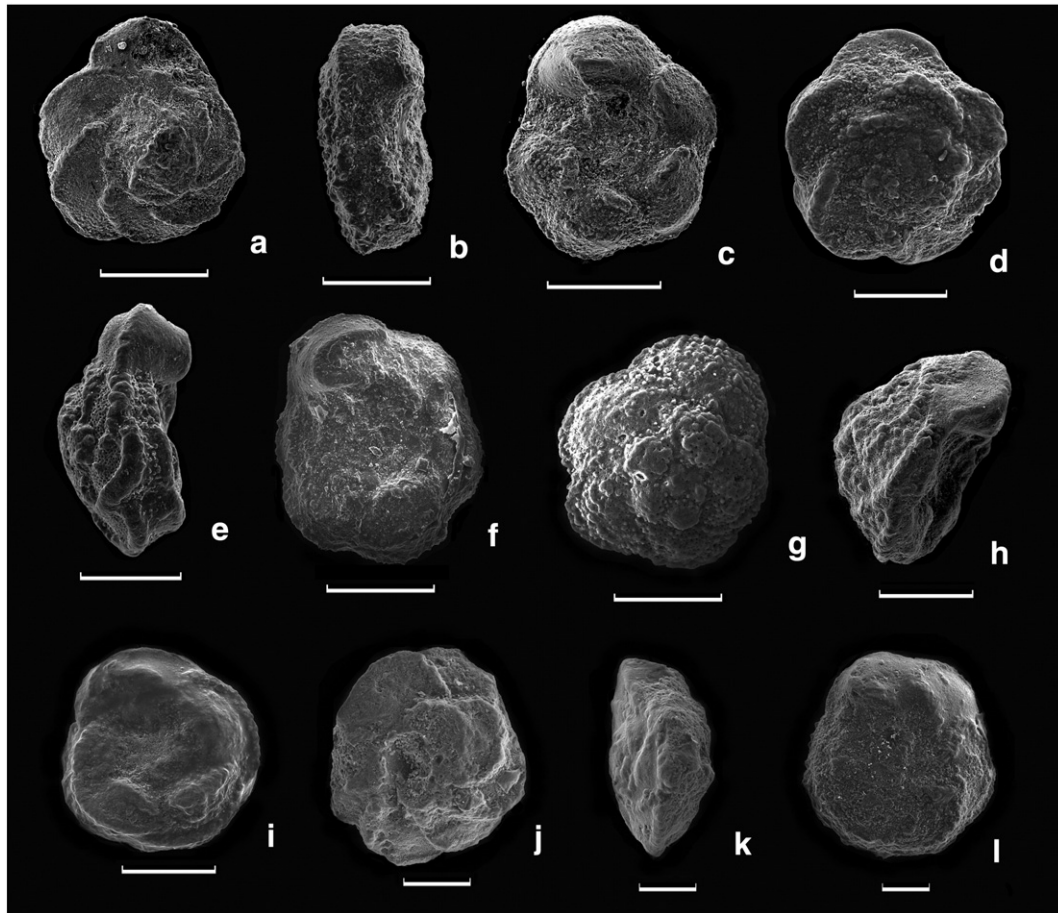


Fig. 13. Santonian–Campanian planktonic foraminifera from the Uruk section; a–c *Globotruncana bulloides* Vogler, sample X-17-1, a – spiral side, b – axial side, c – umbilical-side; d–f *Globotruncana arca* (Cushman); sample X-17-58, d – spiral side, e – axial side, f – umbilical-side; g–i – *Contusotruncana formicata* (Plummer); sample X-17-1, g – spiral side, h – axial side, i – umbilical side; j–l – *Globotruncanita elevata* (Brotzen), sample X-17-58, j – spiral side, k – axial side, l – umbilical side. Scale bar equals 200 μm .

The crisis for the k-strategists could have been related to an episode of climatic cooling (Petrizzo, 2002; Vishnevskaya and Kopaevich, 2008; Gorbachik and Kopaevich, 2011). Isotope data presented by Jenkyns et al. (1994) suggest that, in the chalk seas of northwest Europe, the temperature fell below 20 °C. Huber et al. (2002) also indicated that the Early Campanian marked the boundary between ‘hot greenhouse’ and ‘cool greenhouse’ regimes.

The *A. superbum* Zone equates with the upper part of the foraminiferal zone of *W. archaeocretacea* (Fig. 3), and yields *A. superbum* (Squinabol), *Cavaspongia antelopensis* Pessagno, *Xitus spineus* Pessagno, *P. pseudomacrocephala* (Squinabol), *Stichomitra communis* Squinabol and others (Figs. 7, 9). This provides a comparison with the section at Biyuk-Karasu in the central part of the Crimean Mountains, where the zonation, which includes *A. superbum*–*Phaseliforma turovi* (Middle Turonian), *Dactylo-discus longispinus*–*Patulibracchium* (?) *quadroastrum* (Upper Turonian), and *Orbiculiforma quadrata*–*Patellula* sp. *B* Beds (Turonian–Coniacian boundary deposits), have been subdivided by Bragina et al. (2014). The recognition of the *A. superbum*–*Phaseliforma* sp. *A* Zone (Middle Turonian, Mt. Chuku section, southwest Crimean Mountains, and Middle Turonian, Mt. Ak, central Crimean Mountains according to Bragina, 2014) confirms the wide distribution of *A. superbum* in Crimea. It is evident that the interval with *A. superbum* can be traced in the Uruk succession of the northern Caucasus (Fig. 11).

The Coniacian *Alievium praegallowayi* Zone of the Caucasus (Uruk, Agora, Hosta, Tuapse localities) includes the marker species *Alievium praegallowayi* Pessagno, *Orbiculiforma quadrata* Pessagno, *Pseudoaulophacus praeflorescens* Pessagno and *Pseudoaulophacus florescens* Pessagno. This allows correlation with the *Alievium*

praegallowayi–*Crucella plana* Bed (Upper Coniacian–Lower Santonian) of the Mt. Ak-Kaya section in the central Crimean Mountains (Korchagin et al., 2012).

The Santonian assemblage of the Great Caucasus (Uruk succession, as well as the Agura, Hosta and Tuapse successions) belonging to the *Alievium gallowayi* Zone (proposed by Pessagno, 1976), includes a variety of discoidal taxa such as *Euchitonia santonica* Lipman, *Crucella membraniferum* (Lipman), *Pseudoaulophacus florescens* Pessagno, prunoidal *Archaeospongoprunum nishiyamae* Nakaseko and Nishimura (Vishnevskaya and Agarkov, 1998), as well as coarsely porous Actinommidae and parachute-type of the cyrtids *Lithostrobos rostovzevi* Lipman, *Neosciadiocapsa agarkovi* Vishnevskaya, and *Neosciadiocapsa diabloensis* Pessagno (Fig. 12; sample X-13-115). It should also be noted that the sub-tropical Californian species of the Family Pseudoaulophacidae and others continue in the Santonian of the Tuapse and Sochi areas in the Great Caucasus (Vishnevskaya, 2001) while, since the latest Santonian, mid-latitude species predominate in the Uruk section of the northern Caucasus (Fig. 12). The Late Santonian faunal turnover (marginotruncanids replaced by globotruncanids) and invasion of the Boreal family Prunobrachiidae (see *P. articulatum* in the Uruk section; Fig. 11) confirms the cooling event of the Early Campanian.

The Campanian interval is characterized by a high percentage of k-strategist taxa including *Globotruncana*, *Globotruncanita*, *Contusotruncana* (see Kudrino, locality 1 on Figs. 1; 13, 14) and some multiseriate heterohelicids, such as *Pseudotextularia* and *Racemiguembelina*. However, the periodic occurrence of juvenile globotruncanids suggests that water masses were unstable and characterized by an alternation of a mesotrophic/eutrophic regime with

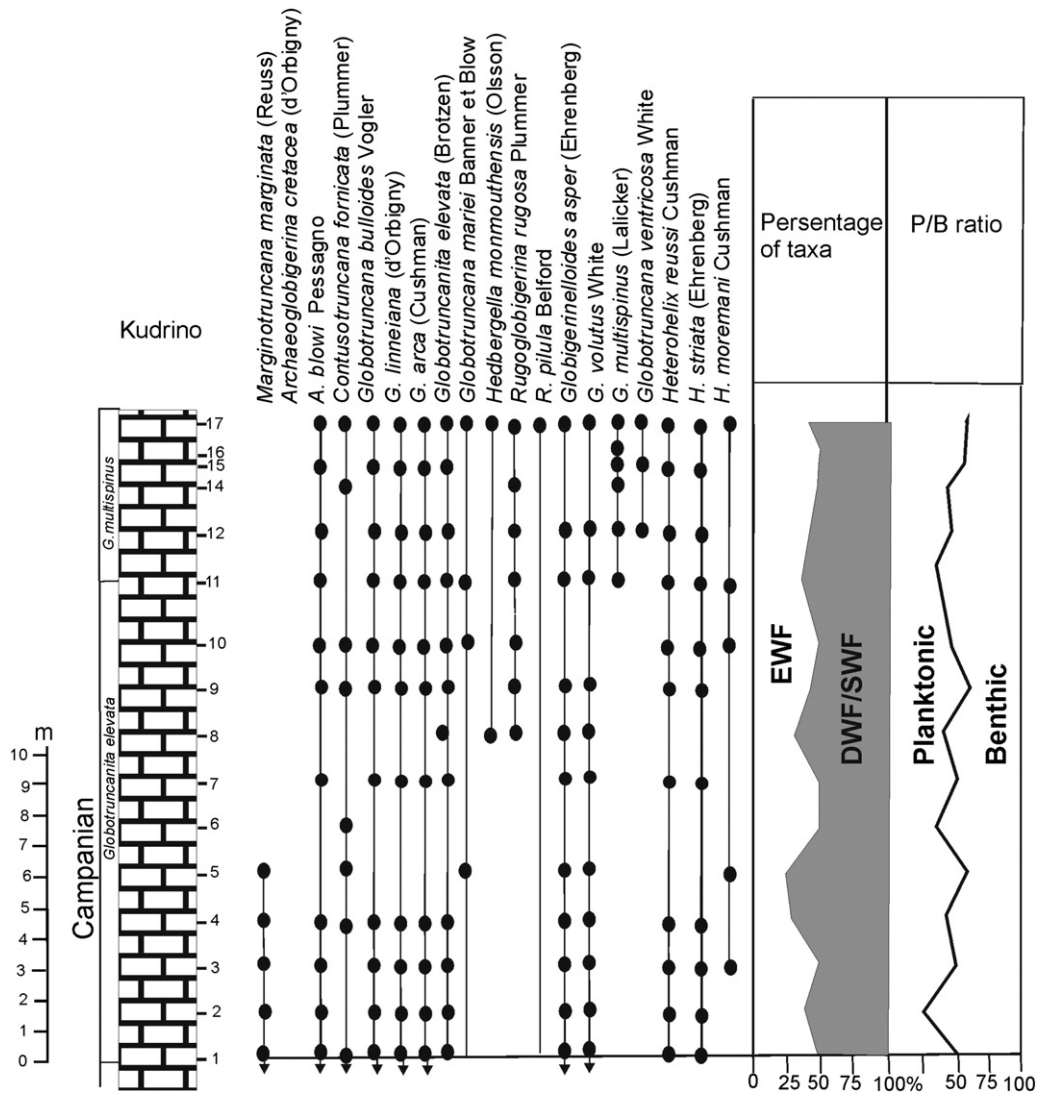


Fig. 14. The distribution of planktonic foraminifera from the Lower–Middle Campanian of the Kudrino section in Crimea (for legend see Fig. 6).

oligotrophic episodes. The genus *Globigerinelloides* is also present throughout the Campanian interval, recording significant fluctuations in abundance and with its maximum diversification in the Mid-Campanian (Peryt, 1983; Kopaevich, 2010). *Globigerinelloides multispinus*, with common bilobation in the final chambers, has been recorded from the uppermost Santonian–Maastrichtian (Peryt, 1983; Petrizzo, 2000; Venturati, 2006; Kopaevich, 2009). This morphotype may be related to the presence of OAE-3 (Locklair et al., 2011; Wagerich, 2012) near the Santonian–Campanian boundary or, more probably, with global climatic change during the Campanian–Maastrichtian (Venturati, 2006; Hart, 2007). The P/B ratio varies between 50 and 70%, but in some intervals it can be reduced to 25–30%. DWF taxa are abundant in samples with high P/B ratios while EWF and SWF taxa are common in other intervals.

The Campanian assemblages of the Uruk, Hosta and Tuapse successions of the Great Caucasus are predominantly cyrtoidal (Fig. 11). The predominant species are *P. articulatum* (Lipman), *D. andersoni* (Campbell and Clark), *D. torquata* Foreman, *Theocapsomma ancus* Foreman, *A. stocki* (Campbell and Clark) and *Stichomitra livermorensis* (Campbell and Clark).

Radiolarian assemblages of the Campanian are more cold-water in character, in comparison with the Santonian. This has been demonstrated previously for the Pacific region of the Russian Far East (Vishnevskaya and Basov, 2007). Warm-water genera, such as *Alievium*, *Microsciadiocapsa*, and *Neosciadiocapsa*, are well represented in the

Santonian radiolarian assemblages, but absent from the Lower Campanian interval of the Uruk succession.

The invasion of cold waters and, perhaps, reduced salinity (Naidin et al., 2007) in the Early Campanian is in good agreement with the models of Hay et al. (1999) and Hay (2008) and the palaeogeographical reconstructions for the Santonian (85 Ma) proposed by Blakey (2012) and Pugh et al. (2014). These show possible oceanic gateways (Fig. 15) with respect to the study locations and potential migration routes for radiolarians through a narrow North Russian connection from the polar region to the Atlantic Ocean. It confirms the cooling episode, which began in the Campanian when the polar region became a primary source of the surface- and bottom-water formation that is indicated by the appearance of the boreal radiolarid *Prunobrachium* in the surface-water of the Caucasus region and cold-water bivalve *Oxytoma* (*Pteria*) *tenicostata* in the bottom-water up to the North Caucasus (Baraboshkin et al., 2003).

6.1. Changes of sea level

During the Mid–Late Cretaceous calcareous oceanic plankton invaded the epicontinental seas, and it is argued here that this was in response to sea level rise (Hay et al., 1999; Hay, 2008). This potential relationship is clearly recorded in the material from the Crimean/Caucasian material. An erosional contact is present between the Albian and

Cenomanian and beds rich in glauconite, and containing quartz gravel, have been described from the base of the Cenomanian in Crimea. The succession displays a transgressive character with sandy/silty marls grading upwards into pure carbonate sediments (marls and limestones). This transgressive episode occurred after a fall in sea level and the formation of incised valleys at the beginning of the Late Albian (Nikishin et al., 2008; Kopaevich, 2009). This erosional boundary and a change to carbonate-rich sediments is also observed in the successions of the North Caucasus (Baraboshkin et al., 2003; Alekseev et al., 2007).

The Mid-Cenomanian non-sequence, first described by Hart and Tarling (1974) after its discovery in the site investigations for the construction of the Channel Tunnel, has been traced throughout the United Kingdom, North Atlantic and northern France (Hart, 2004). In the studied areas, this Mid-Cenomanian non-sequence (Fig. 15) is one of the most important features of the succession and marks a major hiatus in many localities (see Alekseev, 1989; Baraboshkin et al., 2003; Nikishin et al., 2008; Wiese, 2009). Fluctuations in relative sea level formed three full sequences within Cenomanian, while a fourth sequence corresponds to the Late Cenomanian and Early Turonian interval (Gale et al., 1999).

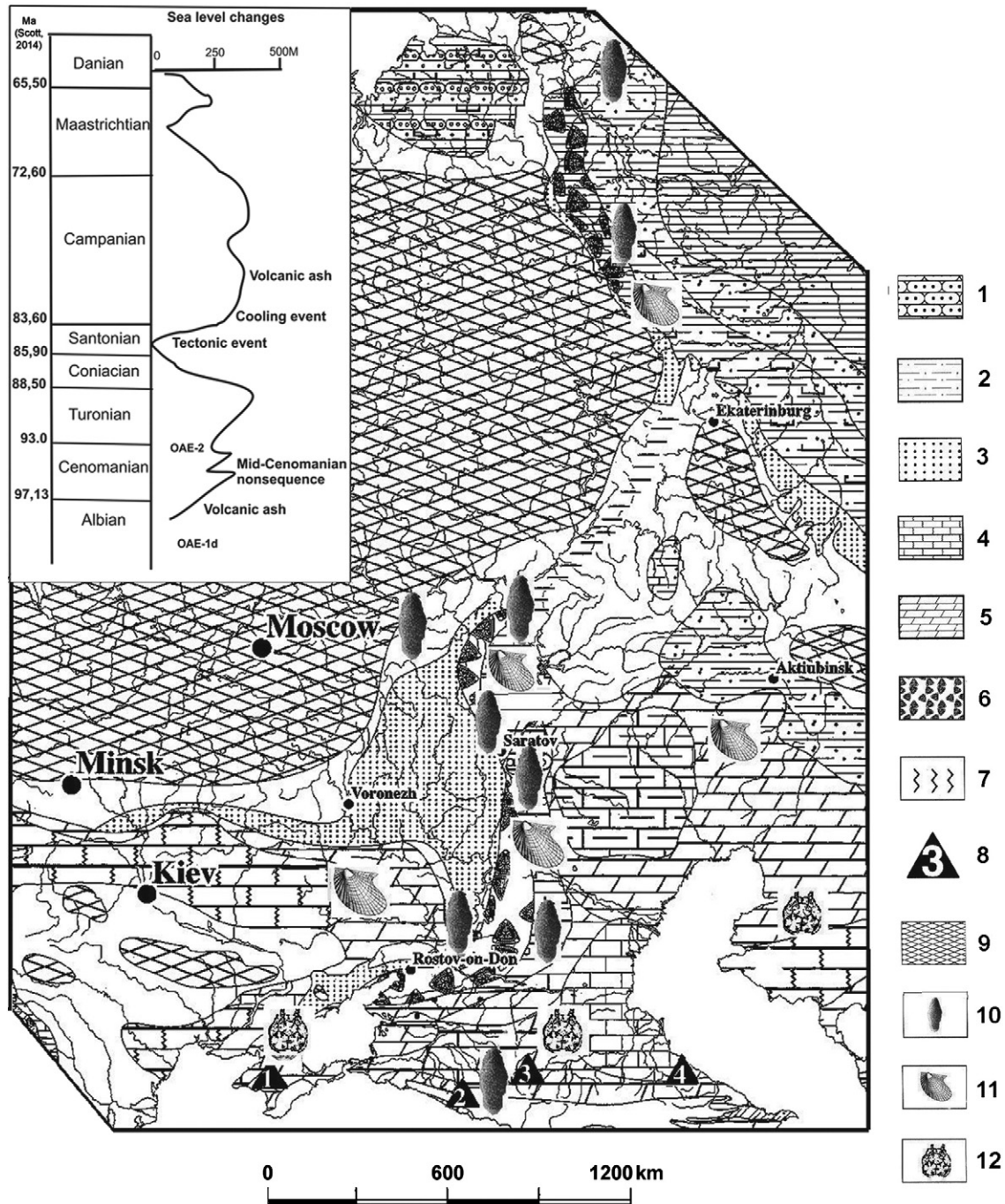


Fig. 15. Sea level changes, palaeotectonic events, Early Campanian palaeogeography of the northeast Peri-Tethys and distribution of the *Prunobrachium articulatum* (modified after Baraboshkin et al., 2003) 1 – sandstones; 2 – silts, siltstones; 3 – sands, soft sandstones; 4 – chalk; 5 – marls; 6 diatomites; 7 – bioturbations; 8 – position of the reference sections: 1 – Crimea, 2 – western Caucasus, 3 – northern Caucasus; 4 – eastern Caucasus; 9 – area of denudation and erosion; 10 – *Prunobrachium articulatum* (Lipman); 11 – *Oxytoma tenuicostata* (Roemer) – Boreal bivalves; 12 – *Marsupites testudinarius* Schlotheim – mediterranean crinoids.

A very short-lived drop in sea level is observed before the accumulation of the black shales at the Cenomanian–Turonian boundary. The latest Cenomanian in Crimea is characterized by a transgressive pulse that was complicated by a very short regressive episode at the base of the “black shales” (Figs. 6, 7, 15). This may be coeval with the sub-plenus erosion surface, because its stratigraphic position equates with events recorded in N. W. Germany and England (Jarvis et al., 1988; Alekseev et al., 1997; Gale et al., 1999). There is currently no reliable information about the existence of this unconformity in the successions of the North Caucasus. The small erosional surface at the base of bituminous layers in the Aimaki succession of the East Caucasus in Aimaki section may be coeval (Gavrilov et al., 2013).

The sea level changes between the Late Turonian and Early Campanian can be quite marked. The absence of parts of the Coniacian–Santonian successions can be explained by tectonic events (Nikishin et al., 2008), as well as eustatic changes of sea level (Hancock and Walaszczyk, 2004). However, the duration and the reasons for this sea level change may be different in the Crimea and the Caucasus.

7. Conclusions

Assemblages of planktonic foraminifera and radiolarians have been investigated from the same samples collected from the Cenomanian–Campanian successions of the Caucasus (Uruk and other localities) for the first time. A correlation of foraminiferal and radiolarian events in the Crimea and the northern Caucasus is also documented.

7.1. Foraminiferal data

Based on the evolution and life strategies of planktonic foraminifera (Caron and Homewood, 1983; Caron, 1985; Petrizzo, 2000, 2002; Spezzaferri and Spiegler, 2005) it is suggested that there are a number of significant steps in the development of Late Cretaceous planktonic assemblages in the studied area. Each of these steps corresponds to a specific palaeoceanographic situation and associated sea level changes.

- (1) The Cenomanian was a time of diversification of the rotaliporids. In the Cenomanian successions of the study area, there are at least 4–5 species of the genera *Thalmaninella* and *Rotalipora*, which belonged to the group of k-strategists. The group r-strategist species were also abundant at this time, including *Praeglobotruncana*, *Hedbergella*, *Globigerinelloides* and *Guembilitria* (Maslakova, 1978; Tur et al., 2001; Kopaevich, 2010; Gorbachik and Kopaevich, 2011). The Cenomanian interval in the study area is characterized by high P/B ratios and by the predominance of DWF and SWF taxa, and both k and k/r strategists (see Fig. 5). This is suggestive of outer neritic to upper bathyal conditions. It was a polytaxic stage in the development of planktonic foraminifera as described by Leckie (1987) and Leckie et al. (2002).
- (2) These general evolutionary trends were interrupted in the Late Cretaceous by a significant event at the Cenomanian/Turonian boundary: the extinction of the rotaliporids and associated changes in the plankton community. The Cenomanian–Turonian boundary interval is associated with the OAE 2 event, which had a significant impact on the r-strategists and the r/k strategists, with only the EWF and SWF assemblages being present. In the study area, fluctuations in biological productivity are thought to have been associated with the periodic, small scale, upwelling (Badulina et al., 2009; Levitan et al., 2010). This contributed to the “Radiolaria bloom”.
- (3) A new polytaxic stage, having begun in the earliest Turonian, continued into the Santonian. The increased diversification of planktonic foraminifera continued in the Turonian–Santonian interval with the first occurrence (FO) of single- and double-keeled marginotruncanids and concavatotruncanids. Their

diversification appears to have been driven by a long-term transgressive event. The evolution of new k-strategists and their maximum diversification may reflect more stable, oligotrophic conditions (Spezzaferri and Spiegler, 2005). The planktonic foraminifera that characterized the Early Turonian and most of the Santonian in the study area represent assemblages compatible with Tethyan conditions (Tur et al., 2001; Kopaevich, 2010; Korchagin et al., 2012; Bragina et al., 2014). Typical Tethyan umbilico-convex concavatotruncanids and single-keeled marginotruncanids are well-represented in our assemblages. A gradual deepening into an open, basinal, facies is documented by the highest diversity of planktonic foraminifera in the Late Turonian–Early Coniacian. Outer neritic–upper bathyal depths and relatively high temperatures probably existed in the study area up to the Late Santonian, indicated by the presence of marginotruncanids and concavatotruncanids with ornamented, relatively massive tests and well-developed keels. This interpretation is supported by the presence of *Alievium* with regular porosity and the dominance of the Pseudoaulophacidae among Radiolaria.

- (4) A progressive decrease in diversity and extinction of the highly specialized marginotruncanids and concavatotruncanids in the latest Santonian and the replacement of marginotruncanids by globotruncanids, appear to be related to a cooling episode (Huber et al., 1995, 2002; Petrizzo, 2002; Spezzaferri and Spiegler, 2005; Hay, 2008). The progressive decrease of the marginotruncanids and their eventual disappearance is possibly indicative of more unstable conditions. There was a dramatic change in the palaeogeographical situation in northern and eastern parts of the Eastern European Platform, where a siliceous-rich style of sedimentation was initiated (Olfer'ev et al., 2000; Baraboshkin et al., 2003; Vishnevskaya and Kopaevich, 2008). The formation of this ‘wedge’ of siliceous-rich sediments, in which most of the siliceous material is composed of diatom and radiolarian skeletons, continued into the Middle Campanian. Boreal waters may have penetrated through the Palaeo-Urals, as far south as the northern Caucasus and Crimea (Fig. 15). These changes are confirmed by the appearance of the globotruncanids (Figs. 13, 14). It appears to have been a regional event related to a background of global cooling.
- (5) A new episode of planktonic foraminiferal evolution occurred during the Campanian. It was a time of maximum diversification of planktonic foraminifera, with the appearance of highly variable morphological features. A moderately deep basin, with alternating oligotrophic and mesotrophic conditions, appears to have existed during the entire Campanian.

7.2. Radiolarian data

- (1) In the radiolarian assemblages associated with major boundaries (i.e., Albian/Cenomanian, Cenomanian/Turonian, Santonian/Campanian: see Vishnevskaya et al., 2005a,b, 2006; Vishnevskaya and Kopaevich, 2008) the presence of numerous representatives of spherical nassellarians with the cephalothorax almost completely pressed into the abdominal cavity (e.g., cryptocephalic radiolarians of the family Williriedellidae), is noted. The appearance of the Williriedellidae can be interpreted as a sign of adaptation to quickly changing conditions and sea level changes (Vishnevskaya, 1997, 2009; Vishnevskaya and Kopaevich, 2008).
- (2) The final extinction of the pseudocephalic *Pseudodictyomitra* followed an abrupt Mid-Turonian sea level rise. The Early Turonian *P. pseudomacrocephala* (Squinabol) are strictly conical, pseudocephalic and differ in the maximum number of chambers

(Fig. 9) that seem to be associated with a relatively deep water marine environment at a time of sea-level highstand (Fig. 15) and a time of “hot greenhouse” conditions from the Late Cenomanian to the Santonian, when “parachute” radiolarians (*Neosciadiocapsa*, among the Nassellaria and *Quinquecapsularia* among the Entactinaria) dominated. The Cenomanian–Turonian was an interval dominated by multichambered tests, after which they became extinct quite rapidly.

- (3) The Urukhs succession in the northern Caucasus is the key for Boreal/Tethyan correlation of Lower Cretaceous strata, which yield ammonite assemblages. These allow direct comparison of the Tethyan Berriasian and the Sub-Boreal Ryazanian (Vishnevskaya and Agarkov, 1998). On the basis of nannoplankton assemblages, the Urukhs succession is also intermediate between the typically Sub-Boreal (England, Scotland, the East European Platform) and Tethyan (southern France, Spain) sequences (Kolpenskaya et al., 2000). Investigations of Late Cretaceous microfaunas have confirmed the importance of the Urukhs succession for correlation of the Sub-Boreal sequences of the Eastern European Platform with Boreal western Siberia and the Tethyan Mediterranean. The invasion of cold-water masses from the Russian Platform (Baraboshkin et al., 2003; Naidin et al., 2007) to the northern Caucasus is confirmed by the records of *O. (Pteria) tenuicostata* (Roemer) in the Peri-Caspian area (Fig. 15), as well as genus *Prunobrachium* in the Urukhs and Hosta successions (Figs. 12, 15). The latest Cretaceous family Prunobrachidae occurs mostly in temperate and high palaeolatitudes. This family is both interesting and important for the study of the palaeogeographical and ecostratigraphical distribution of radiolarians in the Cretaceous. The mass abundance of Prunobrachidae is indicative of cold-water settings, which were characteristic of the Russian Platform, Siberia, the Russian Far East, the southern Palaeo-Pacific (Tasman Sea) and New Zealand. Analysis of prunobrachid palaeogeography during the Late Santonian–Campanian shows a bipolar distribution at temperate and high palaeolatitudes. The distribution areas are almost symmetrical relative to the equator: 35°–62° N in the northern hemisphere of the Palaeo-Pacific, 48°–62° N in the northern hemisphere in eastern Europe and 44°–52° S in the southern hemisphere (Vishnevskaya and Kopaevich, 2008). New records of boreal *Prunobrachium* in the Upper Campanian of the Urukhs and Hosta successions of the Caucasus are at latitude 44° N (Fig. 15) and indicate that the polar region was a primary source of surface-water formation during Early Campanian times.

Three episodes of significant sea level fall can be identified in the Cenomanian–Campanian of Crimea–Caucasus area: between the Albian and Cenomanian, at the base of the OAE2 “black shale” layers, and in the latest Middle and Early Late Turonian (see Tewari et al., 1998).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at <http://dx.doi.org/10.1016/j.palaeo.2015.09.024>. These data include Google map of the most important areas described in this article.

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