=== **MARINE GEOLOGY** ===

Crucial Boundaries in the Development of the Late Cretaceous Biota of Planktonic Foraminifera in the Southern Indian Ocean

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Abstract—The article analyzes the author's own data on the species composition of planktonic foraminifera tests from Upper Cretaceous sediments in the Indian Ocean, as well as from sections of the marginal shelf seas of Australia. Planktonic foraminifera species are grouped and arranged into a climate series. Analysis of the change in the systematic composition of foraminifera made it possible to identify periods of extreme and intermediate climatic conditions in the Late Cretaceous.

INTRODUCTION

The main topic of our research over the past 30 years is reconstruction of the paleoclimatic conditions that existed in the Cretaceous based on planktonic foraminifera (PF). The sequence of this work, based on actualism, is conducted from young and, therefore, better studied time slices to more ancient ones. Usually, when we started studying the next stratigraphic interval, the climatic nature of many types of PF had already been identified in earlier studied younger sections. Therefore, the position of these species in the climate series was undoubted. However, for a number of stratigraphic sections, it proved somewhat difficult to determine the climatic nature of some PFs due to a change in their species and sometimes even generic composition. This article discusses these crucial boundaries in the development of Late Cretaceous PF biota. Climatic fluctuations in the southern Indian Ocean and changes in the systematic composition of PF during the Late Cretaceous have been noted by a number of researchers [21, 26, 29, 30, 36, 39].

MATERIAL AND METHODS

Deep-sea drilling results [32, 34, 37, 38, 40, 43, 45, 51, 52] showed that Late Cretaceous sediments enriched in PF tests were recovered from 12 drilling sites on cruises 26, 27, 28, 119, 120, and 122 in the southern part of the Indian Ocean that washes the west coast of Australia (Fig. 1, Table 1).

The factual material for our research consisted of 680 core samples from these sites. The supervisors of the Deepwater Drilling Project provided samples from US core storage facilities to N.A. Bogdanov, a USSR representative in this project. In addition, V.N. Benyamovskii kindly provided the author with 350 samples selected by Dr. F. Playtord from two sections of Australia's marginal shelf seas (Fig. 1).

In addition, we used species lists of PF with data on the quantitative and semiquantitative species distribution published for the Australian sections [22–24, 41, 42] and for a number of deep-water drilling sites [32, 43, 44].

Table 1. Drilling sites that recovered sediments enriched in PF tests

Cruise no.	Drilling site	References
26	255	[32]
	256	[32]
	258	[32]
27	260	[40]
28	264	[37]
199	738	[34]
120	747	[45, 51]
	748	[45, 51]
	750	[45, 51]
122	762	[43]
	763	[43, 52]
	764	[38]
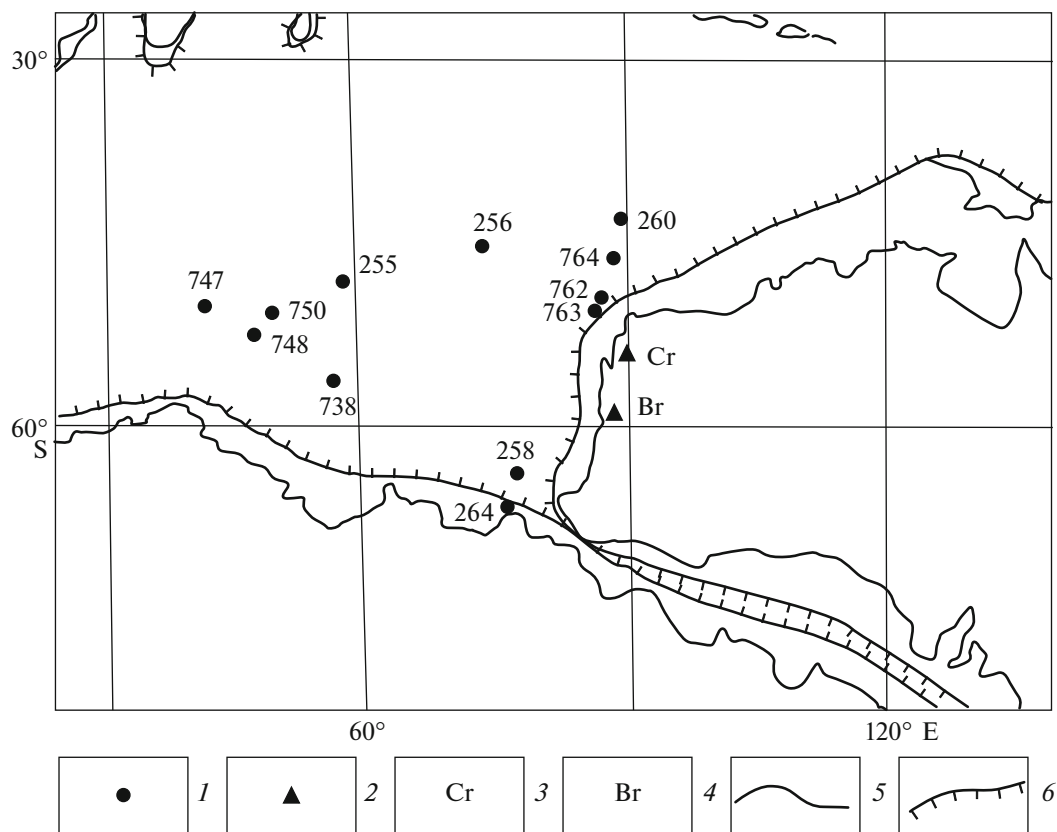
Fig. 1. Location of drilling sites and sections within studied region: (*1*) deep-water drilling sites; (*2*) sections; (*3, 4*) names of sections: (*3*) Carnarvonian, (*4*) Burkean; (*5*) margins of modern continents; (*6*) shelf margins.

Laboratory processing of samples was carried out according to the method developed by Barash [1]. Rock samples were soaked in water; if necessary, they were comminuted and boiled in water. Samples were washed through silk gauze with a mesh size of 50 μm. In the washed powders, the species composition of foraminifera was determined under a binocular microscope and quantitative analysis of PF test complexes was carried out.

Among all the processed material, Early Maastrichtian, Campanian, Santonian, Coniacian, Turonian, and Cenomanian PF species were determined. At the first stage, Early Maastrichtian PFs (*Globotruncana tricarinata* phase) were combined into climate groups [6, 10]. For climate reconstructions, some provisions of methods [2, 21, 31] based on an actualistic approach were applied. However, it was impossible to fully use the above methods when working with Late Cretaceous material. It was necessary to take into account that the natural conditions of the Cretaceous were very different from those in the Cenozoic, so changes and corrections to the mentioned method were needed. According to our methodology [4, 10], all Early Maastrichtian PFs were divided into three climate groups, named in analogy to the modern designations: temperate, subtropical, and tropical. Species

with similar ranges and areas of maximum test abundance are attributed to the same climate group. Further research showed that even within the same climate group, the areas of maximum test abundance for different species shift somewhat with respect to the equator. This made it possible to arrange the species of Early Maastrichtian PF in climate series from the warmest to the most cold-water [10]. Then, for each drilling site and each section, the ratio of PF tests attributed to different climate groups was calculated. Based on the indicators of these ratios, types of PF thanatocenoses were identified. Since thanatocenoses reflect the temperature conditions corresponding to the water masses in which they formed, it is possible to construct climate zoning maps based on their spatial distribution, which was done for the stratigraphic slice of the Early Maastrichtian. The reconstructions have been confirmed by oxygen isotope analysis data [54], for which tests of the following PFs were used: *Globotruncanita stuartiformis* (Dalbiez), *Planoglobulina multicamerata* de Klasz, and *Globigerinelloides volutus* (White). We collected these tests from deep-sea drilling sites of the North Atlantic (95, 98, 390A) and the Falkland Plateau (516F). The obtained estimates for the surface water paleotemperatures in these regions do not exceed 15°C. There, in the Early Maastrich-

tian, the boreal and Australian types of thanatocenosis were widespread.

Subsequently, similar work was done sequentially for four slices of the Campanian [11], three for the Santonian [7], one for the Coniacian [12], four for the Turonian [13, 19, 20], and three for the Cenomanian [14−18]. Maps were compiled on palinspastic principles developed by Sonenshine et al. [5]. The paleocoordinates of the most recent drilling sites were refined by the reconstructions of S.R. Skotiz [49, 50]. We used our own and published estimates of paleotemperatures obtained from oxygen isotope analyses [25, 27, 33, 35, 53, 54]. For each studied stratigraphic interval, a climate series was constructed in which the position of each species does not change from the time of its appearance to its complete disappearance. This is because the sensitivity of a particular species to certain environmental conditions does not change for the entire existence of the species; when optimal conditions are established, the species increases its abundance, and during exacerbated conditions, abundance decreases or the species goes extinct [9]. This greatly simplified our work in cases when the transition from one time slice to another was accompanied by a gradual, consistent change in species composition. Difficulties in constructing the climate series arose when the species composition, and sometimes even the generic composition, changed precipitously at the boundary of a particular time slice.

PF distribution in sections of the studied region. Campanian sediments enriched in PF tests were discovered in the studied region in two sections of Australia's marginal shelf seas and at nine deep-water drilling drilling sites (255, 264, 738, 747, 748, 750, 762, 763, 764) (Fig. 1). Most of the Campanian species continued to exist in the Maastrichtian; therefore, their climatic nature has already been identified. The position of these species in the climate series was not in doubt. Some species from the genus Pseudoguembelina, e.g., *Pseudoguembelina costulata* (Cushman), in Campanian sediments were found from only a few sites; i.e., they were attributed to the category of narrow latitudinal species distribution. It was possible to establish their climatic affiliation only because in the Maastrichtian, they had a widespread species status. The stratigraphic boundary between the Maastrichtian and Campanian stages, according to Robashinsky and Karon's stratigraphic scale [47], passes through sediments of the *Gansserina gansseri* zone, corresponding to a time slice of 71.3 Ma. This boundary is easily traced by the appearance of the species *Abathomphalus intermedius* (Bolli) and *Racemguembelina fructicosa* (Egger) and the extinction of species common to the Campanian: *Roosita fornicata* (Plummer), *Globotruncana bulloides* Vogler, *G. ventricosa* White, *Globotruncanita subspinosa* (Pessagno), and *Globigerinelloides praeriehillensis* Pessagno. The position in the climate series of the last five species was revealed by comparing the areas of their distribution in the Late

Campanian with the ranges of species whose position is already known. For example, the range of the species *Globotruncana ventricosa* coincides with that of *Globotruncana aegyptiaca* Nakkady and *Globotruncana esnehensis* Nakkady in the Late Campanian. Areas of maximum test concentration for these three species are observed at the same drilling sites. The climatic nature of the last two species was established by a study of Early Maastrichtian sediments. This makes it possible to attribute *Globotruncana ventricosa* to the subtropical group and determine its place in the climate series. *Globigerinelloides bollii* Pessagno is attributed to the temperate group because it has a range and area of maximum test concentration similar to *Globigerinelloides impensus* Sliter and *Heterohelix pulchra* (Cushman), the climatic nature of which has already been established.

As a result of the studies, the following composition of climate groups in the Campanian was established (PF species are given in order of decreasing water warmth, in accordance with their position in the climate series):

Tropical group: *Pseudoguembelina costulata* (Cushman), *Roosita plummerae* (Gandolfi), *Globotruncana rosetta* (Carsey), *Rugotruncana subcircumnadifer* Gandolfi, *Roosita patelliformis* (Gandolfi), *Globotruncana ventrticosa* White, *Roosita fornicata* (Plummer), *Globotruncana linneiana* (Orbigny);

Subtropical group: *Globotruncana arca* (Cushman) *Globotruncanita atlantica* (Caron), *Globotruncana orientalis* El Naggar, *Globotruncanita calcarata* Cushman, *Globotruncana bulloides* Vogler, *Globotruncanita stuartiformis* (Dalbiez), *Ruglolobigerina rugosa* (Plummer), *Globotruncanita subspinosa* (Pessagno), *Globotruncana stephensoni* Pessagno, *Globotruncana lapparenti* Brotzen, *Ventilabrella austinana* Cushman, *Globotruncana hilli* Pessagno, *Ventilabrella browni* Martin, *Ventilabrella glabrata* Cushman *Ventilabrella monuelensis* Martin, *Schackoina multispinata* (Cushman and Wickenden), *Globotruncanita elevata* (Brotzen), *Ruglolobigerina pilula* Belford, *Ventilabrella riograndensis* Martin;

Temperate group: *Globigerinelloides multispinatus* (Lalicker), *Globigerinelloides prairiehillensis* Pessagno, *Heterohelix punctulata* (Cushman), *Globigerinelloides bollii* Pessagno, *Heterohelix pulchra* (Brotzen), *Globigerinelloides impensus* Sliter, *Globigerinelloides asperus* (Ehrenberg), *Heterohelix striata* (Ehrenberg), *Heterohelix globulosa* (Ehrenberg), *Hedbergella monmouthensis* (Olsson), *Hedbergella holmdelensis* Olsson, *Globigerinelloides volutus* White.

The PF species composition changed quite gradually during the Campanian. Climatic zoning was reconstructed for each of the four Campanian time slices [11]. Analysis of the compiled maps showed that the studied water area for most of the Campanian section (with the exception of the beginning of the Late Campanian) is characterized by an Australian type of

thanatocenosis. PF complexes are characterized by low species and especially generic diversity (12—13 species). Out of these, no less than nine species belonged to the temperate group. The share of their tests reaches 65%. Along with temperate group, subtropical species are encountered. These are mainly ventilabrellas, ratites, and weakly sculpted globotruncanids. The most important feature of the Australian type of thanatocenosis is the complete absence of tropical group species. North of 50° S (here and below referred to as paleolatitudes), in the sediments recovered at drilling sites 255, 747, 762 and 764, a transitional warm-water Australian subtype of thanatocenosis was widespread. It is also characterized by a low species diversity of PF (13—15 species), but along with moderately warm and subtropical species, tropical group species were present. At the beginning of the Late Campanian, the warm-water Australian subtype of thanatocenoses spread to 60° S This is evidence of a certain short-term warming. At the end of the Late Campanian, abrupt cooling began, which continued in the Maastrichtian. The northern boundary of the Australian zone shifted to 45° S [11]. The Late Campanian cooling was recorded by V.N. Benyamovsky et al. [3] and a number of other researchers [26, 29, 30]. A similar boreal type of thanatocenosis was detected [11] in the North Atlantic (sites 98, 390A, and 392A) and was confirmed by our own isotope analysis data [54].

When studying Santonian sediments (*Dicarinella asymetrica* zone) [28], PFs were found in samples from two sections and from core samples from six drilling sites (255, 258, 260, 762, 763, 764) (Fig. 1). When we processed the factual material in order to reconstruct the climatic zoning of the Santonian, it turned out that the upper stratigraphic boundary of the latter is quite clearly traced [7]. At the threshold of the *Dicariinella asymetrica* and *Globotruncanita elevata* zones, eight Santonian species went extinct and six Campanian species appeared. Moreover, the species composition at the threshold of the *Dicariinella asymetrica* and *Globotruncanita elevata* zones [28] does not only change among warm-water species, so does the composition of the temperate group. Some unusual distribution ranges and areas of maximum test concentration were observed in representatives of the genus Dicariinella and Marginotruncana not found in younger sediments. It was necessary to painstakingly compare their latitudinal distribution maps with maps of all types that crossed the Santonian—Campanian boundary. Studies of the Late Santonian made it possible to construct a climate series (Fig. 2). Although the studied region is located entirely in the Southern Hemisphere, for comparison, the figures (here and below) show the distribution ranges of PF species not only at southern, but also northern paleolatitudes. The considered climate series is very typical of the Late Cretaceous. PF species belonging to the temperate group are found throughout the entire water area of the ocean. Single specimens have been noted even at the lowest lati-

tudes. However, the areas of their maximum test concentrations are found only at high latitudes (Fig. 2). The subtropical group species are quite widespread in all studied sections. With increasing thermophilic nature of the species, the areas of their maximum test concentrations shift closer and closer to the equator and gradually go beyond the considered water area. Tropical species are found only in the northern part of the studied region. They have one area of maximum test concentration at low latitudes. For each drilling site and section of the Upper Santonian, the ratio of PF tests of different climate groups was calculated and, according to the indicator of these ratios, the types of thanatocenoses were identified. It turned out that in Santonian, the warm-water Australian subzone was widespread in most of the studied region. Its southern boundary was delineated in the area of drilling site 258. The northern boundary of the warm-water Australian subzone passed at the paleolatitude of 50° S; the intermediate zone was located to the north.

Sediments in the upper part of the *Dicarinella concavata* zone [28] (drilling sites 258, 762, 763) (Fig. 1), which include the entire Coniacian stage, are extremely enriched in PF tests. At the threshold of the *Dicarinella concavata* and *Dicarinella asymetrica* zones, the systematic PF composition was enriched in six Santonian species. In the studied region, the value of subtropical group species increased. Some representatives of the genera Dicarinella, Marginotruncana, and Whiteinella went extinct in the Early Santonian; therefore, their climatic nature could not be clarified by studying younger stratigraphic sections. The latitudinal distribution maps for these species, were compared in detail with maps of all types whose position in the climate series was not in doubt. Further processing of the factual material showed that down-section, the thick sequence of Coniacian sediments hosted more than 30 widespread PF species [12], represented by a large number of tests with predominantly good preservation. All these species were assigned to a particular climate group. The climate series was complete with pronounced areas of maximum test concentration. It differed somewhat from the above-mentioned Santonian series. The areas of maximum test concentration for the temperate and subtropical species groups are ubiquitously shifted toward the equator by 5°—6°. Moreover, there are very few "problematic" PF species whose climatic nature was not established when studying younger stratigraphic sections at the Coniacian—Santonian boundary [12]. In the southern Indian Ocean, the Australian type of thanatocenosis dominated throughout the studied water area. The boundary of the Australian and intermediate zones in the studied region passed at a latitude of 45° S (drilling site 764). In addition to temperate group species, thermophilic species are found there. According to PF analysis, relative cooling continued throughout the entire Coniacian and Early Santonian. The climatic zones hardly migrated at all during this period. Only in
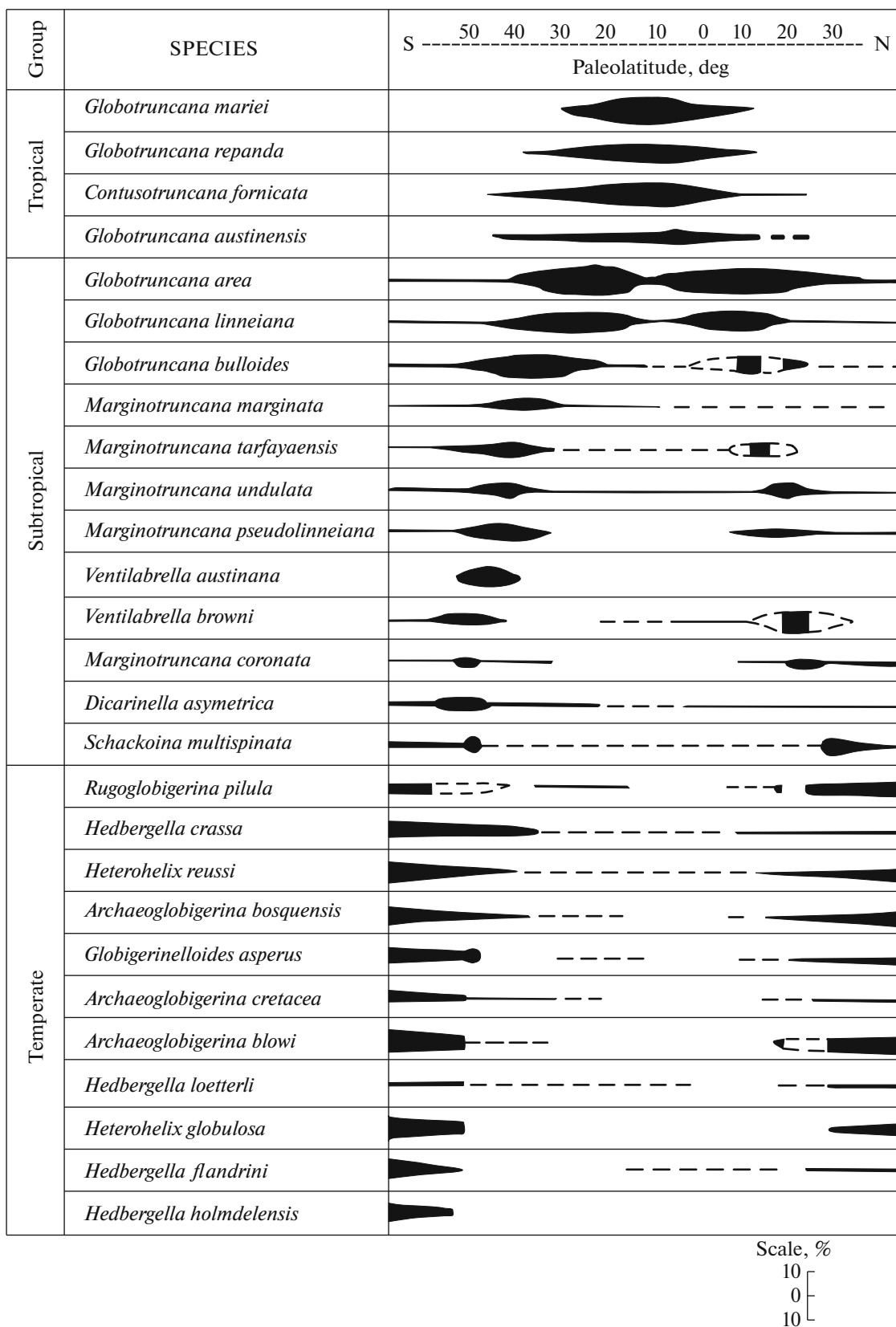
Group	SPECIES	S ——— 50 40 30 20 10 0 10 20 30 ——— N Paleolatitude, deg
Tropical	*Globotruncana mariei*	
	Globotruncana repanda	
	Contusotruncana fornicata	
	Globotruncana austinensis	
Subtropical	*Globotruncana area*	
	Globotruncana linneiana	
	Globotruncana bulloides	
	Marginotruncana marginata	
	Marginotruncana tarfayaensis	
	Marginotruncana undulata	
	Marginotruncana pseudolinneiana	
	Ventilabrella austinana	
	Ventilabrella browni	
	Marginotruncana coronata	
	Dicarinella asymetrica	
	Schackoina multispinata	
Temperate	*Rugoglobigerina pilula*	
	Hedbergella crassa	
	Heterohelix reussi	
	Archaeoglobigerina bosquensis	
	Globigerinelloides asperus	
	Archaeoglobigerina cretacea	
	Archaeoglobigerina blowi	
	Hedbergella loetterli	
	Heterohelix globulosa	
	Hedbergella flandrini	
	Hedbergella holmdelensis	

Scale, %
10
0
10

Fig. 2. Climate groups of PF species in Late Santonian (*Dicarinella asymetrica* zone).

the vicinity of the northern boundary of the Australian zone did regions periodically appear characterized by a transitional warm-water Australian thanatocenosis. Despite the abundance of factual material, it was possible to reconstruct climatic zoning only for the Coniacian−Lower Santonian sequence. For the rest of the Late Cretaceous stratigraphic sections, our reconstructions have much greater detail. During the Coniacian−Early Santonian, the PF species composition changed very gradually. Some literature data [46, 48] divide the Coniacian into Lower and Upper stages. The boundary is delineated by the appearance of the species *Archaeoglobigerina blowi* Pessagno, *Archaeoglobigerina bosquensis* (Pessagno), and *Pseudoguembelina costulata* (Cushman) and extinction of the species *Dicarinella imbricate* (Mornod) and *Whiteinella paradubia* (Sigal). Unfortunately, based on our material, we were unable to observe these changes in the PF species composition. Maybe this can be done in the future, after new material is processed. F.P. Falzoni et al. [29, 30] noted cooling in the area of southeastern Tanzania, which replaced the "greenhouse Turonian temperature maximum."

Turonian sediments enriched in PF tests were recovered in the studied region with the Carnavonian section and deep-water drilling (sites 258, 750, 762, 763) (Fig. 1). We selected for study four stratigraphic slices corresponding to [47] the beginning of the Lower Turonian (upper *Whiteinella archaeocretacea* zone), the end of the Lower Turonian (*Helvetoglobotruncana helvetica* zone), and Middle (*Marginotruncana schneegansi* zone) and Late Turonian (base of the *Dicarinella concavata* zone). The systematic composition of PF during the Turonian changed somewhat. A sequential comparison of the chosen slices makes it possible to trace the development of natural processes in the dynamics [13, 19, 20]. The climate series constructed for the Turonian significantly changes its appearance at the threshold of the *Dicarinella concavata* and *Marginotruncana schneegansi* zones [33] (end of the Middle Turonian) (Fig. 3). The PF composition in the Late Turonian is enriched in the species *Marginotruncana bouldinensis* Pessagno, *M. pseudolinneiana* Pessagno, *M. paraconcavata* Porthaullt, *Dicarinella concavata* (Brotzen), *Dicarinella primitiva* (Dalbiez), and *Hedbergela flandrini* Porthault. In the studied region in the Late Turonian, the area of maximum test abundance for the temperate group was recorded near 55−60° S. Species of the subtropical group (mainly representatives of the genus Marginotruncana) are found in all studied sections; the maximum concentration of their tests is observed near 40−50° S (Fig. 3). The southern boundary of the intermediate zone was delineated in the Late Turonian at the paleolatitude of 55−60° S (sites 258, 750V). The intermediate thanatocenosis was revealed in the sediments of drilling sites 762, 763 and in the section of the Australian shelf basin; the northern boundary of the intermediate zone passed through the vicinity of site 762.

The Middle Turonian climate series differs significantly from all previously described series. Species of the temperate group are encountered in the studied region only as single finds. Areas of their maximum concentration are not observed even at the highest latitudes; the maximum concentration of some subtropical group species is observed south of 60° S. (Fig. 4). Most of the studied region was dominated by the intermediate climate zone. The intermediate type of thanatocenosis was detected even in sediments at drilling site 258. The northern boundary of the intermediate zone passed between sites 763 and 762.

Downsection, at the threshold of the *Helvetoglobotruncana helvetica* and *Marginotruncana schneegansi* zones (beginning of the Middle Turonian) [47], the systematic composition of the PF changes insignificantly. However, compared to the Middle Turonian, areas of maximum test concentration for the subtropical and tropical groups are shifted to the south by 10° in the studied region (Fig. 5). The ratio of the number of PF tests of tropical and subtropical groups at drilling sites 762, 763 and in sections of Australia's marginal seas is characteristic of the Tethyan type of thanatocenosis. The southern boundary of the Tethyan zone at the beginning of the Early Turonian passed at the paleolatitude of 50° S. Early Turonian warming in the studied region is confirmed by the data of several researchers [26, 30, 36].

In Cenomanian sediments, PF tests in the studied region are found in samples from cores of sites 256, 258, 260, 750, 762, 763 and in the Carnarvonian section (Fig. 1). To study Cenomanian sediments, three slices were selected corresponding to [47] the Lower (*Rotalipora globotruncanoides* zone), Middle (*Rotalipora reicheli* zone), and Upper Cenomanian (*Rotalipora cushmani* zone).

The upper boundary of the Cenomanian is very well illustrated by micropaleontological data and is very clearly traced throughout the water area [14, 18]. Twenty widespread PF species in the Cenomanian are completely extinct, and 18 Turonian species replace them. The group of single-keel rotaliporids completely disappeared. This group dominated throughout the Cenomanian. Its extinction is associated with the widespread Ocean Anoxic Event (OAE 2) in oceanic and even in some epicontinental basins [8, 39] that occurred at the Cenomanian−Turonian boundary. It is due to this event that the importance of the species *Dicarinella hagni* (Scheibnerova) and *D. imbricate* (Mornod) increased in PF associations, and various species of the genus Marginotruncana appeared and began to vigorously develop and dominate (Figs. 5, 6). The appearance of forms with elongated chambers in sections is also related to OAE 2. They appear where only the upper water layer becomes habitable; the elongated chambers and thin-walled tests increase buoyancy [8]. It is no accident that the elevated content of such taxa in PF associations is confined to the
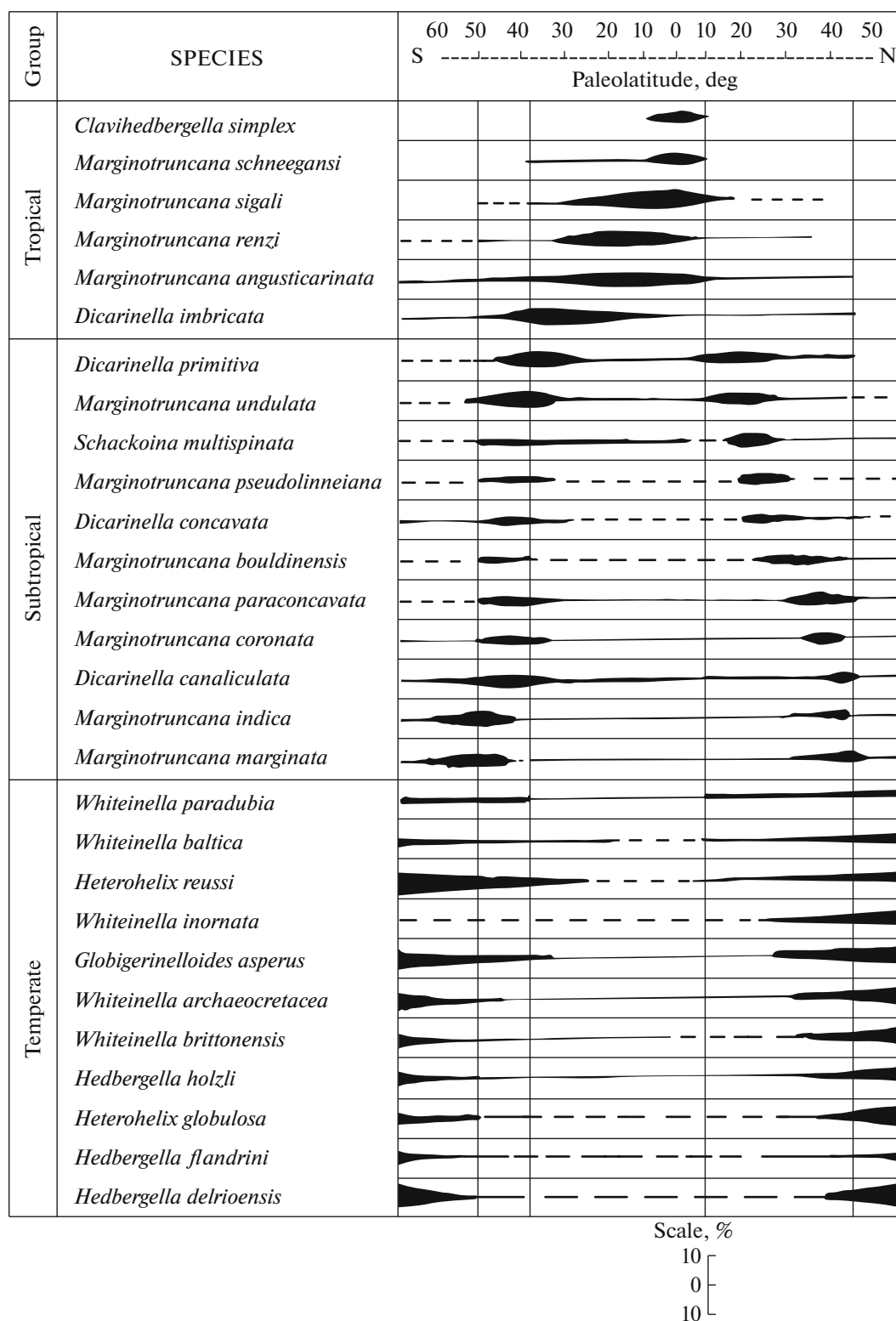
Group	SPECIES	Paleolatitude, deg

(Paleolatitude scale: S 60 50 40 30 20 10 0 10 20 30 40 50 N)

Tropical
- *Clavihedbergella simplex*
- *Marginotruncana schneegansi*
- *Marginotruncana sigali*
- *Marginotruncana renzi*
- *Marginotruncana angusticarinata*
- *Dicarinella imbricata*

Subtropical
- *Dicarinella primitiva*
- *Marginotruncana undulata*
- *Schackoina multispinata*
- *Marginotruncana pseudolinneiana*
- *Dicarinella concavata*
- *Marginotruncana bouldinensis*
- *Marginotruncana paraconcavata*
- *Marginotruncana coronata*
- *Dicarinella canaliculata*
- *Marginotruncana indica*
- *Marginotruncana marginata*

Temperate
- *Whiteinella paradubia*
- *Whiteinella baltica*
- *Heterohelix reussi*
- *Whiteinella inornata*
- *Globigerinelloides asperus*
- *Whiteinella archaeocretacea*
- *Whiteinella brittonensis*
- *Hedbergella holzli*
- *Heterohelix globulosa*
- *Hedbergella flandrini*
- *Hedbergella delrioensis*

Scale, %
10
0
10

Fig. 3. Climate groupings of PF species in Late Turonian (*Dicarinella concavata* zone).

levels of anoxic events in the Aptian (Selli event) and at the Cenomanian–Turonian boundary (Bonarelli event). A study of the remaining Late Cretaceous slices showed no such global change in the PF species composition. Along with the anoxic conditions in the southern Indian Ocean, the composition of the PF thanatocenoses makes it possible to establish that the beginning of the Turonian was marked by significant
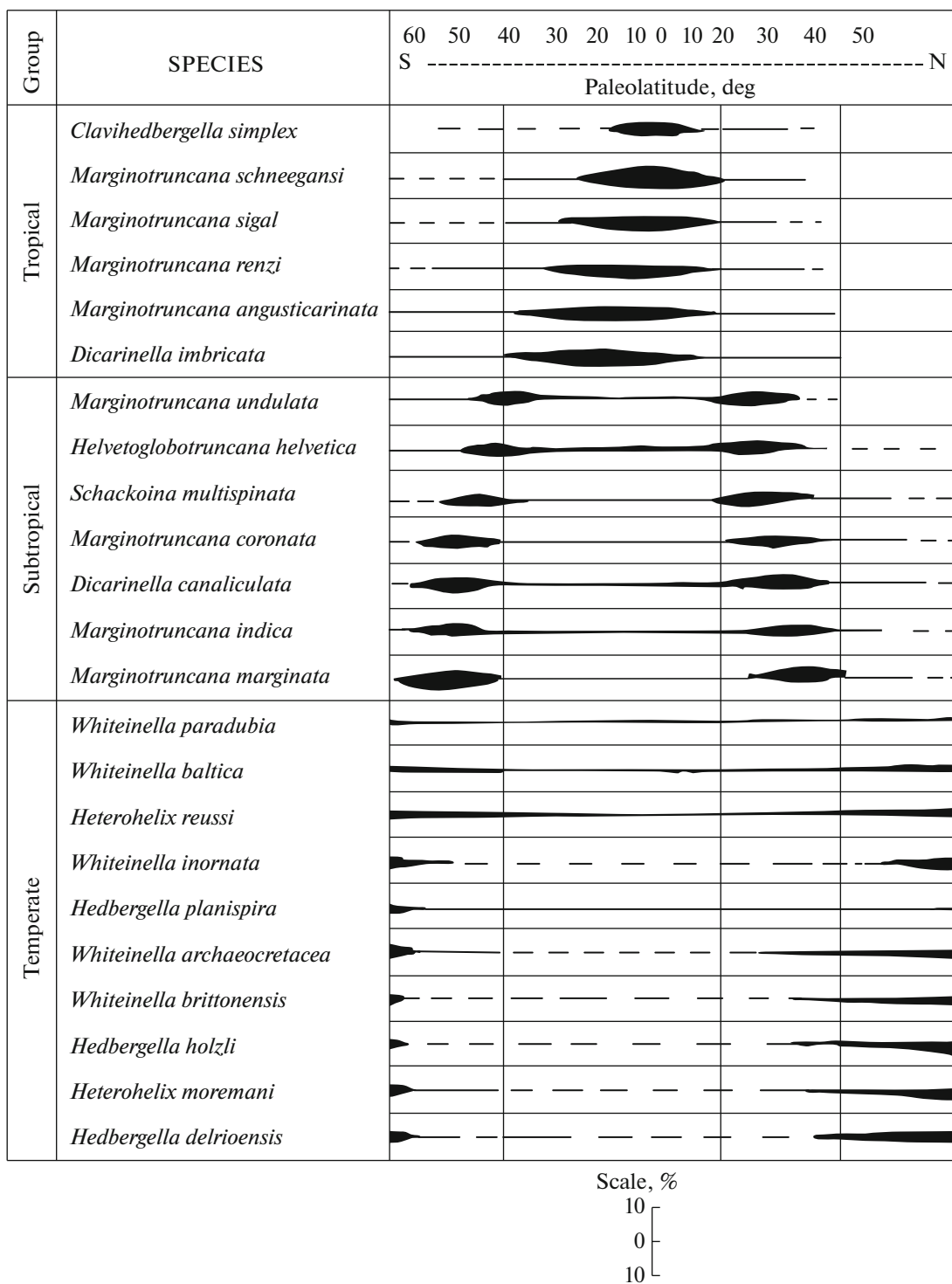
Fig. 4 Climate groupings of PF species in Middle Turonian (*Marginotruncana schneegansi* zone).

warming. The systematic composition of the PF at the upper boundary of the Cenomanian changed dramatically. Different Marginotruncana species that accounted for 80% of the total number of tests of the subtropical group species in the Turonian were completely absent in the Cenomanian. The same can be said about Dicarinella, which were very widespread in the tropical group in the Turonian. However, in the Cenomanian, various representatives of rotaliporas dominated, which were not found in younger sediments and, therefore, their climatic nature was not established. For each widespread species of the genus Rota-
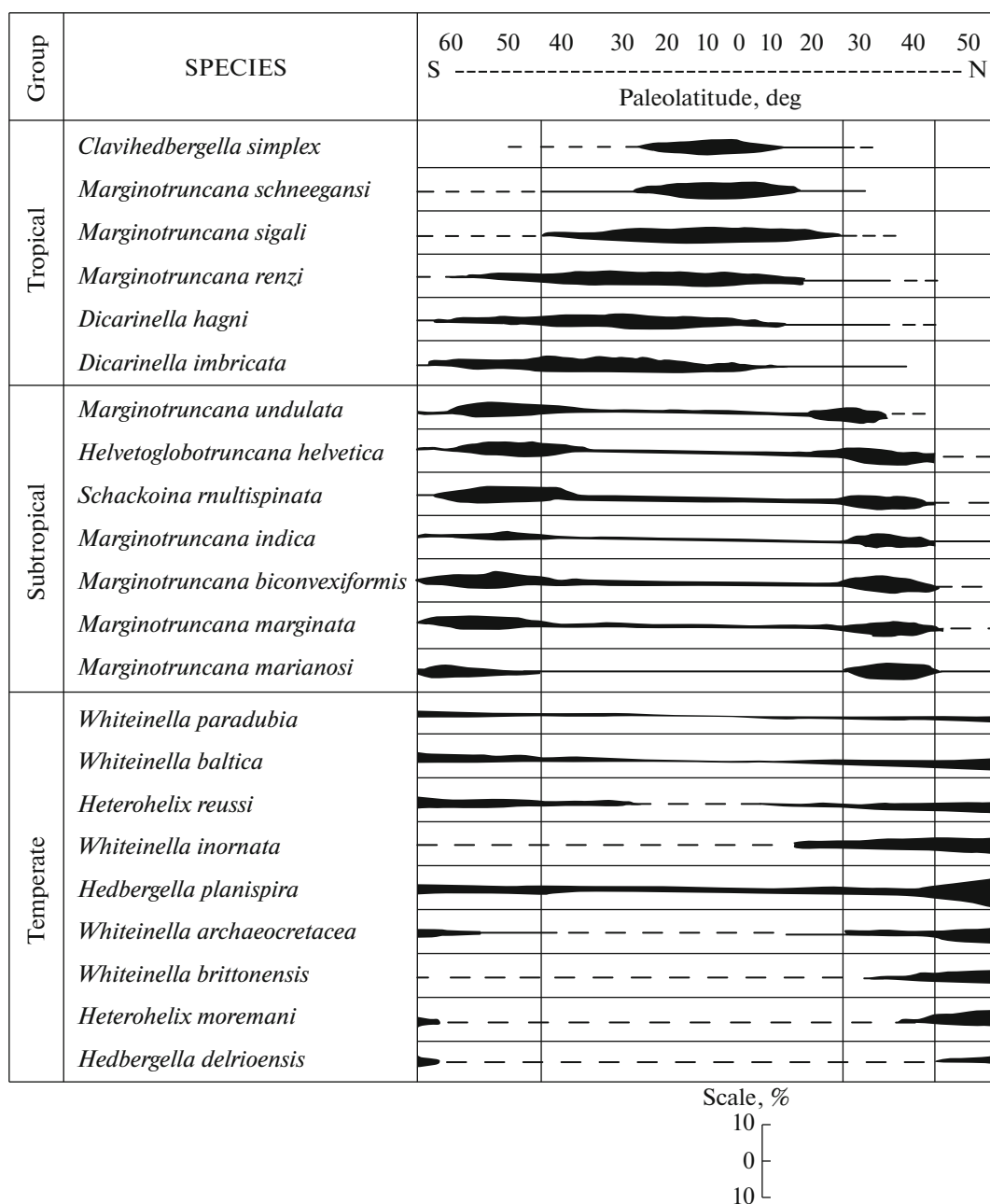
Group	SPECIES	Paleolatitude, deg

Paleolatitude scale: 60 50 40 30 20 10 0 10 20 30 40 50 S --- N

Tropical
- *Clavihedbergella simplex*
- *Marginotruncana schneegansi*
- *Marginotruncana sigali*
- *Marginotruncana renzi*
- *Dicarinella hagni*
- *Dicarinella imbricata*

Subtropical
- *Marginotruncana undulata*
- *Helvetoglobotruncana helvetica*
- *Schackoina rnultispinata*
- *Marginotruncana indica*
- *Marginotruncana biconvexiformis*
- *Marginotruncana marginata*
- *Marginotruncana marianosi*

Temperate
- *Whiteinella paradubia*
- *Whiteinella baltica*
- *Heterohelix reussi*
- *Whiteinella inornata*
- *Hedbergella planispira*
- *Whiteinella archaeocretacea*
- *Whiteinella brittonensis*
- *Heterohelix moremani*
- *Hedbergella delrioensis*

Scale, %
10
0
10

Fig. 5. Climate groupings of PF species at end of Early Turonian (*Helvetoglobotruncana helvetica* zone).

lipora, a map of its distribution range was compiled. Based on the actualistic method, we compared the ranges of species that went extinct at the end of the Cenomanian with the ranges of species whose climatic nature had already been determined for younger sections. As a result, the composition of the climate groups for the Late Cenomanian was established. The constructed climate series (Fig. 6) is very different from the Turonian series. The PF species composition changes dramatically. In addition, in the Cenomanian series, the species of the temperate group have distinct areas of maximum test concentration in the studied

region. Species of the subtropical group are very widespread throughout the entire ocean both in the Cenomanian and the Turonian. However, in the Cenomanian, the areas of their maximum concentration shifted to low latitudes. In the studied region, an abundance of subtropical tests was noted in the Upper Cenomanian only in sections of drilling sites 256, 260, and 762. The southern part of the studied water area was occupied by the Australian zone in the Late Cenomanian. Its northern boundary is around 50−55° S. Downsection throughout the Middle and Lower Cenomanian, the systematic composition of PF
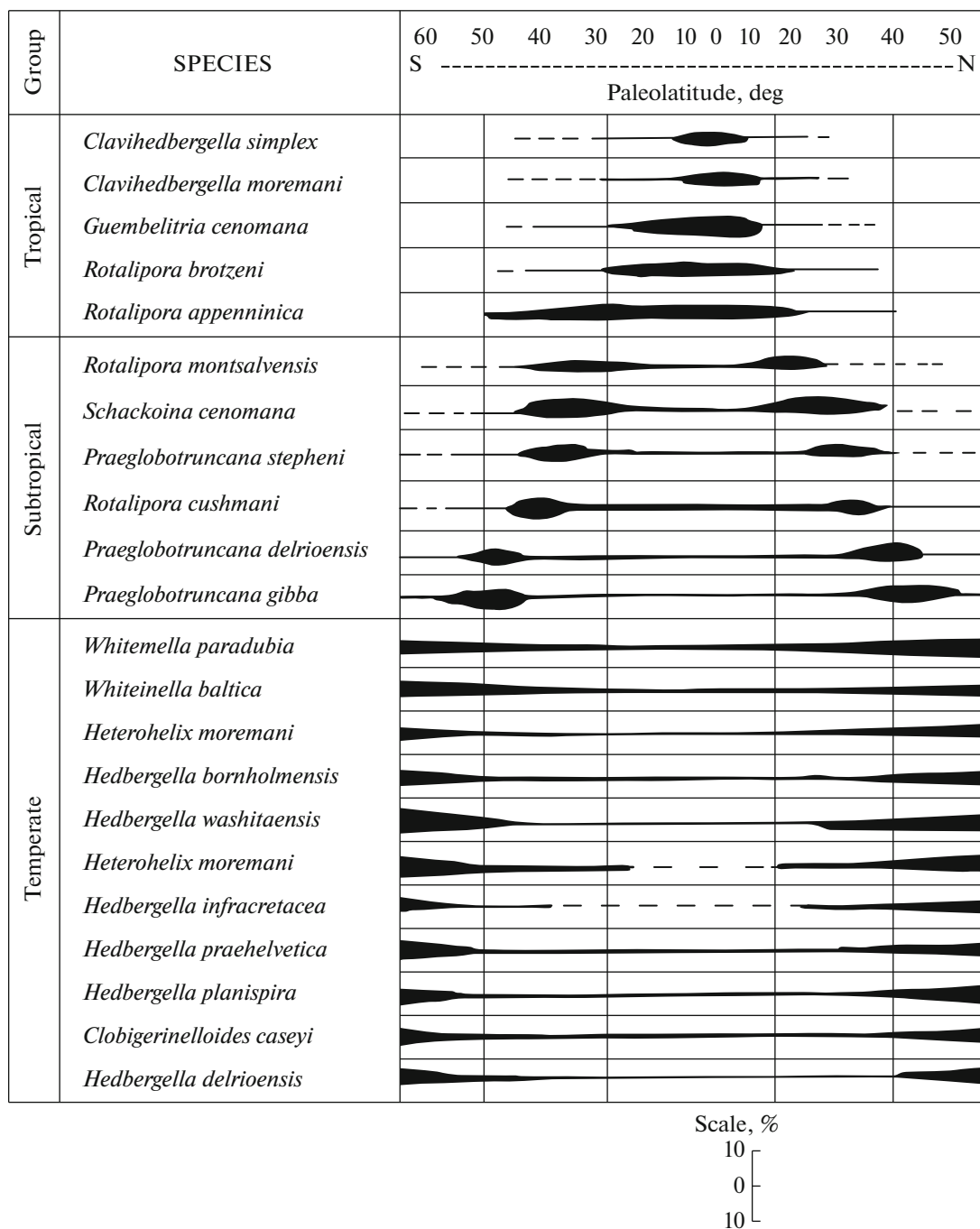
Group	SPECIES	60 50 40 30 20 10 0 10 20 30 40 50 S --N Paleolatitude, deg
Tropical	Clavihedbergella simplex	
	Clavihedbergella moremani	
	Guembelitria cenomana	
	Rotalipora brotzeni	
	Rotalipora appenninica	
Subtropical	Rotalipora montsalvensis	
	Schackoina cenomana	
	Praeglobotruncana stepheni	
	Rotalipora cushmani	
	Praeglobotruncana delrioensis	
	Praeglobotruncana gibba	
Temperate	Whitemella paradubia	
	Whiteinella baltica	
	Heterohelix moremani	
	Hedbergella bornholmensis	
	Hedbergella washitaensis	
	Heterohelix moremani	
	Hedbergella infracretacea	
	Hedbergella praehelvetica	
	Hedbergella planispira	
	Clobigerinelloides caseyi	
	Hedbergella delrioensis	

Scale, %
10
0
10

Fig. 6. Climate groupings of PF species in Late Cenomanian (*Rotalipora cushmani* zone).

changed gradually. At high latitudes in the Southern Hemisphere in the Late Cenomanian, the systematic composition of temperate group species somewhat expanded. Many members of the genus Hedbergella became widespread only in the Late Cenomanian. There were no serious problems in constructing the Middle Cenomanian climate series. The overwhelming majority of PF species continued to exist in the Late Cenomanian and, therefore, their climatic nature

had already been identified. In addition to the increase in the total abundance of PF species in the Late Cenomanian, comparison of the obtained series showed that during the considered time period, the areas of maximum concentration of PF tests gradually shifted toward the South Pole. Species with an obscure climatic nature were quite rare. Species of the temperate group during the Early and Middle Cenomanian were very widespread in the southern part of the studied

region. The abundance of subtropical group species increased in the sections of sites 260, 762 and in sections of Australia's shelf seas. However, the areas of maximum test concentration of the subtropical group in the Middle and Early Cenomanian were located to the north of the studied water area. In the Middle Cenomanian, the boundary of the Australian and warm-water Australian zones passed through drilling site 762 and the Carnarvonian section at the paleolatitude of 55° S. In the Early Cenomanian, it shifted 5° north. The warm-water Australian type of thanatocenosis is widespread in the Early Santonian only in sediments recovered from drilling site 260. The rest of the studied water area, including sections of Australia's shelf seas, is dominated by the Australian type of thanatocenosis, which is quite characteristic of the Late Cretaceous.

EVOLUTION OF THE CLIMATE IN THE SOUTHERN INDIAN OCEAN IN THE LATE CRETACEOUS

A study of Late Cretaceous sediments widespread in the southern Indian Ocean and marginal shelf seas of Australia showed that certain stages of the Late Cretaceous were characterized by extreme climatic states of the ocean environment, which alternated with intermediate, quiescent intervals.

The Cenomanian was a time favorable for the existence of PF. Their systematic composition changed quite gradually. Insignificant migration of climatic zones towards the South Pole indicates a faint warming trend in the Middle Cenomanian. The Australian zone occupied a significant part of the studied water area in the Cenomanian, during which its northern boundary migrated from 50° to 55° S To the north, a transitional warm-water Australian thanatocenosis developed. Only at the very end of the Cenomanian did the boundary of the Australian zone migrate to the more warm-water intermediate zone.

The boundary of the Cenomanian and Turonian was marked by OAE 2, which caused significant changes in the structure of PF complexes. In addition, the beginning of the Turonian was marked by rapid warming. Warming created a favorable environment for the appearance and resettlement of a new PF group: marginotrucanids. At the beginning of the Early Turonian, an intermediate climate zone dominated most of the studied region. This is very uncharacteristic of such high latitudes. North of 50° S, a Tethyan zone was already established. Significant climatic fluctuations were not observed at the end of the Early and Middle Turonian. The systematic composition of PF changed gradually. Towards the end of the Early Turonian, warming intensified somewhat. The southern boundary of the Tethyan zone shifted by 5° south, and in the Middle Turonian, it was again traced at a paleolatitude of 50° S.

At the end of the Middle Turonian, the environmental parameters probably changed somewhat, reflected in the structure of PF complexes. In the Late Turonian, the studied region was still quite warm, which is atypical of high latitudes, but compared with the Middle Turonian, it had become somewhat cooler. The intermediate climate zone narrowed and occupied the water area of 60 to 50° S. Further south, the warm-water Australian thanatocenosis developed.

At the Turonian–Coniacian boundary, no sharp change in the systematic composition of PF was observed. However, the cooling that began in the Late Turonian continued. At the beginning of the Coniacian, the climatic zones in the southern Indian Ocean shifted toward the equator. The boundary of the Australian and intermediate zones passed at the paleolatitude of 45° S. Throughout the entire Coniacian–Early Santonian, the pattern did not change significantly. It was a calm intercrisis period favorable for PF biota.

At the threshold of the Early and Late Santonian, some climatic fluctuations again occurred, which led to a change in the systematic composition of PF at the species and even generic level. As a result, cooling throughout the entire Coniacian–Early Santonian was replaced by warming in the southern part of the studied region. The Australian zone did not extend north of 60° S. From 60 to 50° S throughout the entire Late Santonian, the transitional warm-water Australian type of thanatocenosis dominated.

The lower boundary of the Campanian is marked by a certain crisis situation. Eight Santonian species went extinct and six Campanian species appeared. Along with representatives of the subtropical and tropical climate groups sensitive to environmental changes, PFs belonging to the temperate group died out. The change in climate regime led to another migration of climatic zones. The warm-water Australian thanatocenosis subtype, enriched in thermophilic PF species in the Campanian, was widespread only north of 50° S. The rest of the studied water area was dominated by the Australian climatic zone. Only at the beginning of the Late Campanian did its southern boundary shift 10° south, indicating short-term warming. At the end of the Late Campanian, precipitous cooling began, which continued in the Maastrichtian. The northern boundary of the Australian zone shifted to 45° S.

CONCLUSIONS

Based on analysis of the factual material and study of the literature data, it can be said that the climate in the southern Indian Ocean was mild and uniform. During the Late Cretaceous, sharp changes in natural conditions were rarely observed. The characteristics of water mass types remained constant over long time intervals, along with the PF thanatocenoses identified in the corresponding sediments.

However, quiescent time intervals were interrupted by extreme climatic conditions in the oceanic environment.

Spikes of extreme states were caused by changes in the environmental conditions, which entailed changes in the characteristics of water mass types in the ocean, which in turn changed the systematic composition of PF. That is, a change in climatic regimes entailed biotic crises.

(1) The most global environmental changes in the Late Cretaceous occurred at the Cenomanian–Turonian boundary, which can be considered the turning point in the development of PF biota. The end of the Cenomanian is characterized as an interval with a reduced oxygen content in the water column. OAE 2 significantly changed the characterization of water masses, which affected the morphology of PF tests [8]. There was a mass extinction of PF at the genus level. In the warm, homogeneous water masses of the Early Turonian, new PF genera appeared and began to evolve rapidly. In the southern Indian Ocean, conditions characteristic of the intermediate and even Tethyan climatic zones appeared. This is completely atypical of such high latitudes.

(2) Less significant climatic fluctuations were observed at the end of the Middle Turonian, as well as at the upper boundaries of the Middle and Late Santonian and the end of the Late Campanian. Biota PF "responded" to them with changes in systematic composition. The boundaries of climatic zones migrated.

(3) The intermediate intervals of the Late Cretaceous include the Middle Cenomanian, Coniacian, and the beginning of the Santonian and Campanian. During these periods, no sharp changes in environmental conditions were observed. The characteristics of water mass types remained constant. The systematic composition of PF biocenoses formed in these water masses also remained constant; the composition of PF thanatocenoses identified in the corresponding sediments did not change. During quiescent intermediate intervals in the studied region, the Australian climatic zone and the warm-water Australian subzone dominated.

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