Pliocene–Lower Quaternary Planktonic Foraminiferal Biostratigraphy and Paleoceanology, ODP Hole 677A

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Abstract—Planktonic foraminifers from the Pliocene and Lower Quaternary sediments of ODP Hole 677A are thoroughly studied. Many encountered zonal taxa are demonstrated to be the reliable biostratigraphic markers. Planktonic foraminiferal zones PL1b to Pt1 of the Berggren's scale (Berggren *et al.*, 1995) are distinguished in the depth interval of 30–210 m in the hole. Changes in planktonic foraminiferal assemblages from the sediments of Site 677A were under influence of the climate-controlled dynamics of surface water masses in the eastern equatorial Pacific during the period from 4.6 to 0.65 Ma. A sharp decrease in abundance of equatorial-tropical species about 3.4 Ma is correlated with termination of the surface water exchange between the Pacific and Atlantic tropical zones owing to the emergence of the Central American land bridge. Surface water temperatures were reconstructed using the method of Barash (1970). The highest temperatures are estimated for the terminal early Pliocene (26.4°C) and the late Pliocene (26.6°C), and the lowest ones for the initial early Pliocene (18.4°C) and the mid-late Pliocene (19.6°C). Cold events are recorded in sediments 4.6–4.3, 2.8–2.5, and 1.7–1.2 Ma old, while periods of 4.3, 4.18–3.4, 2.5–2.3, and 1.0 Ma correspond to the warm ones. In general, the mid-early Pliocene, mid-late Pliocene, and the initial Pleistocene characterize the cold-water conditions, whereas the terminal early and late Pliocene correspond to warm-water environments.

Key words: planktonic foraminifers, Pliocene–Quaternary sediments, biostratigraphic range, datums, paleoclimatic events, paleotemperatures.

INTRODUCTION

The Late Neogene evolution of the eastern equatorial Pacific was repeatedly investigated by experts in paleoceanology (Saito, 1976; Keigwin, 1982a, b; Prell, 1985; Farrell and Prell, 1991; Ushakova *et al.*, 1995). The climatic impact of the Central American land bridge formation on change of the surface- and deep-water circulation in the region and the World Ocean was demonstrated (Keigwin, 1982b; Haug and Tiedemann, 1998). Variations of the hydrologic regime in the Panama Basin are discussed in this paper using the detailed zonal stratigraphy of planktonic foraminifers from the Pliocene–lower Pleistocene sediments of Site 677A and data of quantitative paleotemperature analysis.

The present-day surface water circulation in the Panama Basin is largely controlled (Fig. 1) by the Peru Current, a branch of the South Equatorial Current, or by the Equatorial Countercurrent (*Tikhii okean*, 1981). The southward California Current and the northward Peru Current transport cold waters to the region. Near the equator, their water mass rises to the surface thus forming the upwelling zone off the American coast. This zone coincides with the Equatorial Divergence Zone. The average annual temperature in the region is 24°C (*Tikhii okean*, 1981), but the seasonal changes of circulation result in temperature fluctuations from 17° to 27°C within the 50-m-thick surface water layer (Levitus, 1982). The dynamic oceanographic regime characteristic of the eastern equatorial Pacific as a whole gives rise to emergence of a latitudinal belt between 4° S to 2° N that is of a high biological productivity and hosts a planktonic foraminiferal assemblage peculiar for the equatorial region: tropical species coexist here with cold-water forms (Thunnel and Reynolds, 1984; Chen and Prell, 1998).

In the Panama Basin, the flourishing of *Neogloboquadrina (N.) dutertrei* and abundance peaks of *N. pachyderma* dex. and *Globorotalia (Gr.) menardii* are registered in February and March during the most intense upwelling associated with a shallow depth of the thermocline and low surface water temperatures (Table 1). Another foraminiferal group of *Globigerinita (Gt.) glutinata, Globigerinoides (Gs.) ruber*, and *Globigerina (G.) bulloides* is maximum abundant in summer, when the thermocline position is deeper and surface water temperatures are high (Thunnel and Reynolds, 1984). Species characteristic of the present-day Panama Basin (see Table 1) prevail in the Pliocene–Quaternary planktonic foraminiferal assemblages and may serve as indicators of hydrologic conditions comparable with the recent ones.
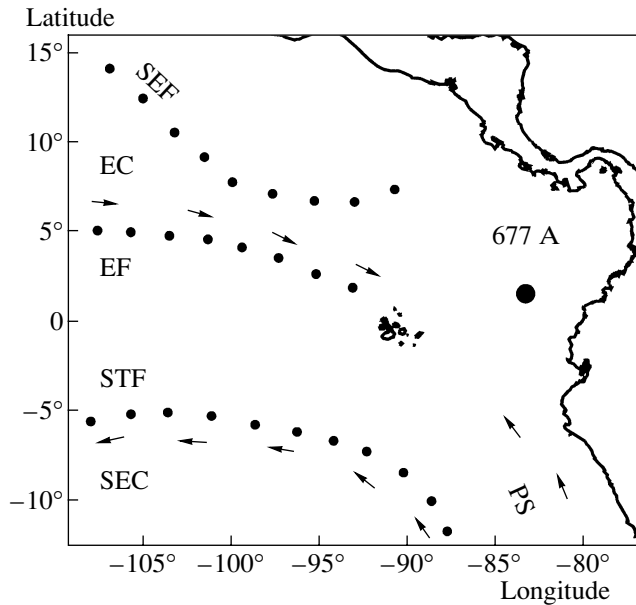
Latitude

Fig. 1. Map of surface-water circulation in the eastern equatorial Pacific (*Tikhii okean*, 1981) and location of Hole 677A: (SEC) South Equatorial Currents; (EC) Equatorial Countercurrent; (PC) Peru Current; (STF) South Tropical Front; (EF) Equatorial Front; (SEF) Subequatorial Front; arrows mark the current direction and points the position of fronts.

MATERIALS AND METHODS

Site 677A (1°12.14′ N, 83°44.22′ W) of the ODP Leg 111 was drilled on the southern flank of the Costa Rica Rift at the bottom depth of 3461 m. The Pliocene–Lower Quaternary sediments recovered by the hole are mainly represented by siliceous and nanno-foraminiferal oozes. Recent deposits are accumulated in the Panama Basin within the depths range from 3200 to 4000 m of the foraminiferal lysocline (Chen and Prell, 1998). I studied 66 samples from the section of Hole 677A, which enable the mean time resolution of 60 thousand years. For quantitative foraminiferal analyses, I used the fraction coarser than 100 μm. About 300 planktonic foraminiferal tests were counted in each sample and percentages of species, except for *Gt. glutinata*, were calculated. *Gt. glutinata* is widespread in the Pliocene–Lower Quaternary sediments of the North Pacific and often constitutes 30–60% of foraminiferal assemblages, that is why one may suspect its cosmopolitan character (Bubenshchikova, 1996). Table 2 presents the results of the foraminiferal analysis. Additionally, ratios of planktonic to benthic foraminifers, the "foraminiferal number" (the number of shells per 1 g of sediment), and the total number of species were calculated. I used the taxonomy and contracted generic names suggested by Kennett and Srinivasan (1983) with some additions (Rögl and Bolli, 1973). The Late Neogene summary zonation (Berggren *et al.*, 1995) was taken as a basis for paleoceanologic reconstruc-

tions. The Neogene–Quaternary boundary is placed in it at the base of the Olduvai Subchron (1.81 Ma).

The annual surface water temperatures were calculated, using the Barash methods of paleotemperature analysis (Barash, 1970; Barash and Blyum, 1975), based on proportions between climatic groups of planktonic foraminifers and the resultant table for the pelagic zone of the World Ocean with the temperature range from 8 to 30°C (Ivanova, 1983).

The general similarity between the modern and Pliocene–Lower Quaternary thanatocoenoses was established previously in the quantitative study of planktonic foraminifers in 576 samples from the North Pacific and simultaneous generalization of the published materials (Bubenshchikova, 1996). For instance, percentage of now-living species in the studied thanatocoenoses of Hole 677A decreases with the age of sediments and corresponds to 94–100% in the Early Pleistocene, 70–100% in the late Pliocene, 52–85% in the terminal and 50–77% in the initial early Pliocene. Paleoecological data obtained earlier for Pliocene species from comparison of their distribution area during a given period (Bubenshchikova and Blyum, 1996) were used to discriminate certain climatic groups of the extinct species, which are ranked (Table 2) as subpolar (SP), temperate (TP), subtropical (ST), tropical (T), and equatorial-tropical (ET). Accordingly, it is possible to use in the Pliocene reconstructions the relation between the particular climatic groups of planktonic foraminifers known in the present-day ocean and the annual surface water temperatures (Barash and Blyum, 1975; Ivanova, 1983).

BIOSTRATIGRAPHY

The recognition of planktonic foraminiferal tropical zonations in the Late Neogene sediments of the eastern equatorial Pacific is usually difficult because of absence of stratigraphically important species. Analyzing the representative factual material from Site 677A, I detected however a number of such forms, the zonal

Table 1. Percentages of planktonic foraminifer species in the sediment traps set in the Panama Basin (Thunnel and Reynolds, 1984)

Species	Range of concentrations (%)	Mean concentrations (%)
N. dutertrei	7.0–59.5	27.23
Gt. glutinata	5.3–43.5	23.53
Gs. ruber	4.6–26.8	14.88
G. bulloides	0.6–19.0	13.32
Gr. menardii	1.1–9.0	4.65
N. pachyderma dex.	0.2–7.4	2.99
Gs. sacculifer	0.8–13.0	2.86
Others	0.0–29.1	10.54

Series		Zone	Age, Ma	Depth, m	Section Core Interval	Depth, m	Datum levels
Pleistocene	Early	Pt1 b	0.65	30	4H 4 (86–89)	30	
		Pt1 a			5H 5 (44–48)	40	
					5H 6 (45–48)		
					5H cc (7–9)		
					6H 1 (55–58)		
					6H 3 (105–108)		
					6H 4 (88–90)		
					7H 1 (53–55)	50	
					7H 3 (96–98)		
					7H 4 (67–70)	60	
					7H cc (8–10)		
					8H 3 (65–68)		
					8H 5 (65–67)	70	
			1.81	75	9H 1 (53–56)		
Pliocene	Late	Pl6			9H 4 (53–55)		
					9H 5 (106–108)	80	
					9H 6 (83–85)		
					9H cc		
			2.30	88	10H 4 (44–46)		
		Pl5			10H 5 (48–52)		
					10H 7 (4–6)	90	
					11H 1 (80–83)		
					11H 4 (66–68)		
					11H 6 (60–63)	100	
					11H cc (7–9)		
					12H 2 (90–93)		
					12H 6 (50–53)	110	
					12H cc (17–19)		
					13H 2 (74–76)		
					13H 4 (88–90)		
					13H 5 (95–97)		
					13H 7 (60–63)	120	
					14H 4 (67–69)		
					14H 6 (67–69)		
			3.09	128	14H cc (8–10)	130	
	Early	Pl4	3.12	136	15H 3 (45–48)		
					15H 5 (48–50)		
		Pl3			15H 6 (58–60)		
			3.58	144	16X 2 (15–18)	140	
					16X 3 (48–50)		
					16X 5 (53–55)		
					16X cc (6–8)		
		Pl2			17X 1 (65–68)	150	
					17X 3 (66–69)		
					17X 4 (70–73)		
					17X 5 (123–126)		
					17X cc		
					18X 1 (63–65)		
					18X 2 (73–75)	160	
					18X 3 (60–63)		
					19X 1 (59–61)		
					19X 2 (65–67)		
					19X 3 (50–53)		
					19X 4 (42–44)		
					19X 5 (63–65)	170	
					20X 1 (63–65)		
			4.18	175	20X 2 (20–23)		
					20X 5 (60–63)	180	
		Pl1 b			20X cc		
					21X 2 (82–85)		
					21X cc	190	
					22X 1 (18–20)		
					22X 3 (30–32)		
					22X 5 (17–19)	200	
					23X 2 (3–5)		
			4.60	210	23X 5 (20–23)	210	

Datum levels (species): N. acostaensis, Gs. obliquus, N. humerosa, Gs. extremus, Gr. truncatulinoides, Gr. limbata, Gs. fistulosus, Ss. paenedehiscens, Gs. fistulosus, D. altispira, Ss. kochi, Ss. seminulina, Gr. margaritae, G. nepenthes, Gr. crassaformis.

Fig. 2. Biostratigraphic subdivision of the Pliocene–Lower Quaternary sediments at the Site 677A according to zonation of Berggren *et al.* (1995); symbols as in Fig. 3.

index species included, (Fig. 2) which were missed by previous researchers (Jenkins and Houghton, 1989. These are *G. nepenthes, Gr. margaritae, Gr. truncatulinoides, Gr. limbata* (the synonym of *Gr. pseudomiocenica* according to the adopted taxonomy), *Sphaeroidinellopsis (Ss.) paenedehiscens, Ss. kochi, Globoquadrina (Gq.) pseudofoliata,* and some others (Table 2). In my opinion, stratigraphic ranges of *G. dec-* *oraperta, Gs. obliquus, Gs. extremus, N. humerosa, N. acostaensis, Ss. seminulina, Gr. crassaformis, Gr. flexuosa, Sa. dehiscens, Gq. venezuelana, Dentoglobigerina (D.) altispira, Pulleniatina (Pu.) primalis, Pu. obliquiloculata,* and *Gs. fistulosus* are somewhat different as well. The data obtained show that the Berggren's zonation (Berggren *et al.*, 1995), contrary to the previously applied ones (Jenkins and Orr, 1972; Keig-

Table 2. Distribution ranges of planktonic foraminifers in the Pliocene–Lower Quaternary sediments, Hole 677A, and climatic groups of taxa

Sample	Species	Gq. venezuelana ST	G. nepenthes T	Gr. margaritae ET	Ss. kochi ET	Ss. seminulina ET	Ss. paenedehiscens ET	D. altispira ET	Gr. puncticulata ST	Gr. exilis ET	Gr. multicamerata ET	Gr. pertenuis ET	Gr. limbata ET	Gs. extremus T	Gs. obliquus T	Ge. praecalida ST	G. decoraperta T	Gr.flexuosa T	N. acostaensis ST	N. humerosa ST	Pu. primalis ET	B. praedigitata ET	Gq. pseudofoliata ET	Gr. menardii ET	Gr. scitula ST	Gr. pumilio T	Gs. ruber T	Gs. conglobatus T	Gs. quadrilobatus ET
4H 4																								17.9	0.5		9	0.5	1.5
5H 5																								34	0.6		5		1.6
5H 6																						0.2		6.6	0.8		9.2	+	1.8
5H cc																								23.2	0.8		10.5	+	0.8
6H 1																								17	0.3		20.2	1.6	5
6H 3																	0.3							3.5			11.1		4.5
6H 4																						0.5		12.8			16.6	0.8	3
7H 1															+						0.3	0.3		16.3	1.1	2	22.9	1.1	3.1
7H 3															0.3							0.6		8.3	0.3		36.1	0.3	3
7H 4																						0.4		+	0.4		15.4		1.6
7H cc															+							1.5		12.3	1		26.6	+	0.8
8H 3															0.9				0.9	3.5	0.9			13		6	20.7		2.7
8H 5																			3.9	2.2				19.5		4.4	19.4	0.5	0.5
9H 1	Pt1a																		0.4	0.7	4	0.4		43	0.7	8	19.5		8
9H 4															+		0.4	0.4	0.4	2.4	0.4	0.4		+	3.2		38	0.4	4.2
9H 5																				0.7				23.2	1.5	4.3	32	0.7	3.7
9H 6													0.3					+	1.2	2.5	0.3			9.8		4	24.7	0.3	5.3
9H cc																			1.3	1.7				14.4	1.4	3	24.4		4
10H 4	PL6														0.5		0.5		2.8	2.4	4.3	0.5	0.5		0.5	2.8	38.4	1	5.5
10H 5									0.2	+			1.5						0.8	7.3	2.7			16.9	1.9	3.8	21.8	1.1	1.1
10H 7													0.4	0.8						3.5			0.4	14.6	2.8		29.8	0.4	2.8
11H 1													0.8				0.4		2	3.6	1.6		+	16.2	0.4	+	29.7		3.3
11H 4													8	+			+	0.8	3.7	10.4	3			28.3	0.8	1	15.2	+	+
11H 6													5.4		0.4				0.4	1.5				7.3	0.4		6.5	0.4	14
11H cc													0.6	0.6	0.3	0.4			2	2				9.2	0.6	0.6	9.3	0.8	5.3
12H 2							0.7							2.7	0.7					6.8	10.3				15.7			28.8		4.2
12H 6														+	0.6	2.2				1.9	0.6				2	0.9		13		9.5
12H cc														5.1	0.9	1.3				7.4	2.9	0.6	0.3		11.6			31.1		7.3
13H 2									0.2					3.8		0.8		1		5.2	4	0.8		+	8.4	1.5		19.4	0.2	8.2
13H 4														0.5	0.5	1.2		1.4		10.4	5.2	0.5			5.5	0.3		17.6	+	6.6
13H 5														2.4	3	5.1	0.3	5.4		8	7.5	1.6			4.6	0.6		13.6	+	4.3
13H 7														0.3	0.7	1.7		4.4		5	4.1	1.9		0.5	+	0.9		16.3	0.3	14.6
14H 4							0.3							0.5	2.4	11.2		0.3	+	5.3	3.5	4			+	0.8		32.8		8.2
14H 6	PL5							3.6						1.6		0.8	0.5	0.8	3.2	6	6.9	2			1.6	0.5		6		6.2
14H cc								0.7						1.1	1.1	3.8		2	+	6.2	2.8	2			9.8	0.7		9.2		7.8
15H 3							0.3	0.6						3.5	2.2	6.5	1			3.8	10.1	2.8	0.3	0.3	12.8	0.3		9.1		8
15H 5	PL4				+	0.6	0.6							0.7	9			0.3	3.5	2.3	3.2	+		4.6	1.3		3.5	1	13
15H 6					0.8	+		1.3						1	3		1	0.6	3.8	4.6	1			5.7	0.5		9.4	+	12.1
16X 2						1.5		1							8.4			0.5	2	1	4.3	+	0.5	7.7	1			0.5	
16X 3							13	0.5					2	0.7	3	0.2	1.7	+	3	1.2	13.5	0.7	0.5	9.6	1		15	0.5	4.2
16X 5	PL3	0.6						1.2						0.6	10.8	0.6	3.6		4.8	1.2	17.5	3		18.6	0.6		5.5	+	9.1
16X cc						2.2		7.7					1.6		3.2				2.2	3.2	3.8		0.6	13.2			11	0.6	24.8

Gs. sacculifer ET	G. bulloides TP	G. falconensis ST	G. quinqueloba TP	Gt. uvula TP	N. pachyd. sin. SP	N. pachyd. dex. TP	N. pseudopima TP	O. suturalis T	O. universa T	C. nitida ET	Gd. hexagona ET	Ge. aequilateralis ET	St. tokelauae ST	T. humilis ST	Sa. dehiscens ET	Gr. tumida T	Gr. ungulata ET	N. dutertrei blowi T	N. dutertrei T	Gr. crassaformis ST	G. rubescens T	Pu. obliq. dex. ET	Pu. obliq. sin. ET	Gr. inflata ST	Gs. fistulosus ET	Gr. tosaensis ST	Gr. truncat. dex. ST	Ge. calida ST	Gt. glutinata
	0.5	1			1		19.4				1				1	3.5	1	31.8	6	1.5	2.9		+						9
+	1	3.3	1	0.2		0.7	9.1		0.5			0.5	+		0.5	17.3		14.7	5		2	2.4						0.6	21
1.5	4.8	0.5	3.4	0.4	0.2	23.7	8.7	0.4	0.4	+		0.5				1.5	+	21	7.6		4.6	2						0.2	26
+	3	0.8	0.4	0.4		13.1	4.1					+				2.3	1.1	18.4	13.9	+	3.7	0.8	2.3					0.4	24
0.3	2.2	0.6	0.6			12.5	7.1	0.3	0.6		0.3	0.3			+	2	0.3	18.3	7		1.9	1.6							27
0.6	2.5	0.6	1			38	4.2		0.6		0.3	0.6			0.9	0.6		14.7	8.3		3	4.4					0.3	+	26
+	3.5		2.5			19.6	6.4		0.8		1.2	0.5			0.5	4.3		18.3	3.5		2.6	0.5	0.8	0.8				0.5	36
0.3	2	1.4	1.8			18.8	2		0.9		0.9	0.3			0.3	2.3	1.4	6.8	6.5		4	0.3	2.3	+				0.6	44
	3		0.6			16.4	4.2		0.9							4.5	0.3	12.8	4.8		1.8	1.8							19.5
	3.6	0.4	1.2		0.4	25.8	11.4	0.4	3.5			+						29.6	4.7		1.2	+							12
	2.7	0.8	1.5		0.8	18.8	6.4		+						0.4	3.5		15.3	1		3.8					0.8	2	+	21
	1.7					10.4			0.9						0.9	0.9	0.9	20	14	+	2.6							+	27
	3.9					1	4.9								0.5	0.5	1.6	27.4	9.3		0.5								23
	0.5					1	0.7								1.8	5.1		3.6	1		0.7	0.5						0.4	12
0.8	0.4	1.2	0.4			3.2	9		0.4		0.4				0.4	10.6		9	11	0.4	2.2							0.4	29
	3.6	1.4				0.7		0.7	0.7			0.7			1.4	0.7		20.4	2.2		1.4								26
0.6	4.6	1.5		0.3	0.3	2.1	5	0.3	2.8			0.6	+		0.6	8	1.2	10.5	9.3		3					0.3		0.6	32
0.3	1.6	1				2.7	8.1	0.3	1.7		0.7	0.7			0.3	5		19.4	5.7		1.3	0.3						0.7	25
0.5	2.3	0.5				0.5	5.6		0.5		0.5				1	3.8		15.6	4.7		3.8	0.5						0.5	20
	5.4	0.8	0.4	0.4		3	3.4	0.8	0.4		1.5				0.4	6.3	0.8	9.2	1.5	0.4	5.4	0.4	0.4						28
0.4	6.3				0.4		5.5	0.4	0.4		0.4	0.4			0.4	1.2	+	13.8	5.1	2.8	0.4	1.5				+			36
	2					0.8	1.7		0.4		0.4	0.4			0.4	4.4	+	15.4	10.5	4	1.2					0.4			9
	0.8	0.8				2.1	2.7				0.8	0.3			0.8	1		13.1	3.2	0.5	2.7								15
	8.8					3.5	5.8	0.4	0.4		0.4	0.4		1.1	+	1.2		21	19.2		1.5								22.5
	13.2	0.3			8.7	11	2.7	1.1	3.7		0.6				0.5	0.3		16.8	6.5	0.3	1.4	0.6				0.6	+		34
	2.7				0.7		7.5							+		0.7		12.2	0.7	+	5.6								8
	0.5				19.4	10.6	3.6	0.6	2.2		0.3			0.3	+	1.8		23	6.4	+	0.6								13
	4.2					1.6	5.1				0.3				0.9	1.3		15.7	0.6		1.8								18
+	2.7	0.2			10.3	1.7	5		0.8	+	0.4	0.2			0.2	0.8		18.4	3.1		2.7								17
	3.5					2.6	5.2		0.9		0.2	0.2			0.2			28	5.8	0.2	3.5								20
	0.9	1				3.7	11.1	0.3	1.6	+	+	0.6		0.6	0.3	0.6		15.6	4.3		3						+		31
	4.6		0.2			2.9	12.1	0.3	0.5		1	0.3			1.7		0.3	13.8			11.6					+	+		19
0.8	2.7					2.6	3.7	0.5	2.1		0.5	0.5			0.5	6.1		6.7			4								7
0.5	2.4	0.8	0.5			2.4	9.5		0.8		+				0.5	30	1.2	7.7	0.8		3.2								15
0.3	4.8	1	0.7		1.4	3	19.6		0.3		0.3	0.3			0.6	0.3		16.8	1.4		2								18
0.8	4.9	1.4				8.4	7.6		1		3.2	1	+			+		6.7				0.3	3.1						11
	9	1.3				6.7	16.4		+		0.6	0.3			1	1.6		12.2	0.3	0.3	6.7								21
0.3	3	0.5		0.3	0.5	7.2	17.6	+	0.3		0.8	+			1.3	2.6	+	17.2	0.6	0.3	2.7								17
1	4.9					3.8	13.1	0.5	+		1.5				0.5	28.4		11.4	0.5		6								45
0.9	2.9	0.8				1.7	9.6		+		1	1.5		0.2	+	1		5.7	0.7	1.5	2.2								39
0.6	2.4	0.6				0.6	5.5		0.6						0.6	4.8		6.6											15
	3.2						6.5				1.2	0.6	+		2.2	8.8		2.2	0.6	0.6									10

Table 2. (Contd.)

Sample	Species	Gq. venezuelana ST	G. nepenthes T	Gr. margaritae ET	Ss. kochi ET	Ss. seminulina ET	Ss. paenedehiscens ET	D. altispira ET	Gr. puncticulata ST	Gr. exilis ET	Gr. multicamerata ET	Gr. pertenuis ET	Gr. limbata ET	Gs. extremus T	Gs. obliquus T	Ge. praecalida ST	G. decoraperta T	Gr. flexuosa T	N. acostaensis ST	N. humerosa ST	Pu. primalis ET	B. praedigitata ET	Gq. pseudofoliata ET	Gr. menardii ET	Gr. scitula ST	Gr. pumilio T	Gs. ruber T	Gs. conglobatus T	Gs. quadrilobatus ET
17X 1							0.9	2.5					5.2		7.2		0.9	0.6	2.2	2	8.1			20.3	0.6		10.6	0.3	6
17X 3			0.3			0.3					1.6		1.1		1.9				10	5.7	0.6	0.3		36.6	0.8		10.5	0.8	4.3
17X 4					0.4	+		0.4	+			0.7	1	1.4	7.7				7.7	6.6	0.7	1.4		25	0.3		9.5	2.4	6.3
17X 5					0.5	+					1.4		1.7	0.3	6.3		0.9		1.9	0.7	15.7	+	0.3	14.7	0.9		3.9		22.8
17X cc							0.8	1.1			3.8			0.4	6				0.8	0.8	8.3	0.4	0.4	34	0.8		3		14.4
18X 1							+	2.5					+	0.6	9		0.3	0.3	3.7	1.4	18			5.9	2		0.6		9.3
18X 2							1.2	0.5			10.5		1.7		13		0.5		1.5	0.9	12.5			11.5			1.5	0.3	13.2
18X 3							0.5	2.8			1		2.3		12.2		0.5		1.4	1.4	7.5	0.5	1	23.9	0.5		2.3		11.7
19X 1							1.9	0.9			5.6		3.3				0.9	+	1.4	0.5			+	11.2	1.9		0.5	0.5	14
19X 2							+	+			21.3		+	0.6	2.8	+	0.5	+	3.4	3.4	2.2	1.7	+	9.5	1.8		+	+	10.3
19X 3							+	1			3.4			0.5	10.3		0.5	2	2	0.5	1.5	1		5.9	0.5				24.7
19X 4					+	1.3	1.6	1.6					2.2		6		0.9	0.3	1.6	1.3	4.1			17.4	0.6		0.3	+	6.7
19X 5							0.4	1.6			3.2		2	+	4	0.8	2	0.4	4		2.8		+	10.8	0.4		13.7	0.4	11.2
20X 1	PL2						0.8	0.8			9.8	0.4	9	0.4	6.2		1.9	0.4	2.5	1.4	9.5			16	1				10
20X 2			+	1			0.6	1.2			8.4		11.1	0.6	12.2		3.7	1.2	2.2	3.7	1.2			16	0.3		0.3	0.6	8
20X 5		0.8	0.3				0.3	0.9			7.5		1.6	1	17		5	+	8.8	3.9	4.3			9.8	0.3				6.8
20X cc			+	0.4			1.6	4			9.1		13	+	6.3		0.8	0.4	3.2		7.9			12.7	1.2				10.5
21X 2						+	1.6	1.2			9.2		5	0.7	7.9		1.8	0.2	4.2	2.8	1.8		0.2	6.7	0.2			1.8	13.4
21X cc	PL1b					+	0.4	1.2			15.5		2.8	2.4	12.7		0.8		0.8	2.7	2.4		0.8	14.7	0.2			0.4	11.5
22X 1		0.3		2			0.5	0.8					2.6	0.6	7.7		1.5	0.3	1.5	1.3	2.3			1.3	1			0.3	10.9
22X 3		+	0.5		0.6	1.3	3.7				7.1		4.2	1.8	4.5		+	1.3	1.8	2.1			0.3	3.2	1.3		0.3	0.3	10.5
22X 5		+	0.8				0.4	1			4.2		4.8	0.4	7.5		0.4	0.6	4.2	1.3	1.3		0.2	11.9	1.4				7
23X 2		+		0.2	0.6	2.5	3.8						3.3	1	7.3		1.4		1.5	0.4	0.5		0.6	2	0.6			0.2	4
23X 5		+	2.9	1.4	2.2	5.8	6.8						4	1	11		2.5	0.9	7.2	0.8	0.8			2.5	0.6			0.4	3.6

Note: (SP) subpolar, (TP) temperate, (ST) subtropical, (T) tropical, and (ET) equatorial–tropical groups of species; symbol "+" denotes presence of species; (*O. bilobata* is present in Sample 14H4).

win, 1982a; Saito, 1985; Jenkins and Houghton, 1989, and others), can be used with a slight modification (Fig. 2) to subdivide the sediments of Hole 677A.

Levels of evolutionary and ecologic changes in planktonic foraminiferal assemblages are successfully used for the biostratigraphic subdivision of deep-sea sediments. At the same time, diachronism of datum levels marking events of species appearance or extinction in different climatic zones and separate realms has been established in specialized works. It is conceivable that in the regions with a dynamic oceanographic regime, e.g., in the Panama Basin, the first and last occurrence levels of species in the section may discordant with datums of their evolutionary appearance and extinction. The comparison of the sedimentation rate curves (Fig. 3), which have been plotted with due account for the appearance and extinction of nannoplankton (Houghton, 1989), radiolarian (Alexandrovich, 1989), and planktonic foraminifer species, suggests that most of the recorded events are isochronous, traceable in various regions of the Pacific (Berggren *et al.*, 1995). Most of the planktonic foraminiferal datums (Fig. 3) are reliable biostratigraphic markers for the subdivision of the Pliocene–Lower Quaternary sediments of the Panama Basin. In the case of a steady sedimentation, the earliest findings of stratigraphic markers *Sa. dehiscens* (about 4.35 Ma) and *Gs. fistulosus* (2.9 Ma) and the last occurrence of *Gr. limbata* (2.0 Ma) are recorded at Site 677A later, as compared to the corresponding datums reported by Berggren *et al.*, (1995), while the disappearance of *Gs. fistulosus* (1.9 Ma) took place here earlier (Fig. 3)

In the section of Hole 677A, I distinguished planktonic foraminiferal zones Pl1b to Pt1 (Fig. 2 and Table 2). The studied interval is above the Miocene-Pliocene boundary and incompletely represents the lower

Gs. sacculifer ET	*G. bulloides TP*	*G. falconensis ST*	*G. quinqueloba TP*	*Gt. uvula TP*	*N. pachyd. sin. SP*	*N. pachyd. dex.TP*	*N. pseudopima TP*	*O. suturalis T*	*O. universa T*	*C. nitida ET*	*Gd. hexagona ET*	*Ge. aequilateralis ET*	*St. tokelauae ST*	*T. humilis ST*	*Sa. dehiscens ET*	*Gr. tumida T*	*Gr. ungulata ET*	*N. duertrei blowi T*	*N. duertrei T*	*Gr. crassaformis ST*	*G. rubescens T*	*Pu. obliq. dex. ET*	*Pu. obliq. sin. ET*	*Gr. inflata ST*	*Gs. fistulosus ET*	*Gr. tosaensis ST*	*Gr. truncat. dex. ST*	*Ge. calida ST*	*Gt. glutinata*
0.3	2.5	1.3				2.5	8.7				1.2	0.6			0.3	3.7		8.4			3.1								19
	6.7					1.4	8.1		0.3		0.5				0.6	2.7		3.8	1.1										9
0.7	5.6					1.7	12.2		0.3		0.4	+			0.4	1.7		3.5			2								28
0.6	1.9	0.3	0.2			2.9	5.3	0.3	0.4		0.7	0.7	+					10.6	1.2		2.9								23
0.8	6.8					0.4	5.2				0.4				2	2.2		6.4	0.8	+	+								47
	7.9					9	13	0.6			2.5	0.6	+			0.6		9.2	2		1								19
0.5	0.2					1	14.7	0.5	0.3		0.3							7.7	0.5	5	0.5								25
1.4	0.5					0.9	3.2	0.5			1.4	1			0.5	8.9		6.1	0.5	4.7	0.9								21
0.5	2.3					4.7	23.8				1					4.2		17.3	2.3		1.3								53
0.6	3.9	1.1				3.4	4.5	+	+		1.7	1.7		0.5		11.2		12.9	+	+	1								4
0.5	2		0.4			2	10.8		+		0.5	1			+	0.5		25.1	3.4										42
0.3	8.9	0.3				4.1	10.6	0.3	0.3		1.6	0.9				10.1		13	0.6		3.1								31
1	1.2	4				6.4	17.3				0.4	0.4	+			1.6		8.8			1.2								12
0.7	1				2.8	1.4	8.5	0.4	0.7		1.4	0.8	+			3.2		9											48
0.6	3.1	1.8			5.3	1.5	7.7	0.6	0.3		0.9	+				2.5		3.4											24
0.6	0.7	0.6			2.4	2.6	9.5		0.3		1.6	0.5	+			0.8		12.1											46
0.4	3.2	0.4			4.3	9.1	2.7	+	1.2		+	+	+		1.2	1.6		4.8											29
2.2	0.7	0.5			16.6	6.5	2.8		0.2		0.5		+		0.7	3		6.2	1.4										31
0.4	0.8					3.6	11.2		+		1.2	0.8			+	+		12.7											45
	1.3				24	0.7	13.6		0.3		1.3	0.5				8		10.8	2.6		2								32.5
	1				15.7	2.7	9		0.3		0.3	1				13.2		8.3	1.6	0.3	2.1								18.5
	0.8				5.6	3.5	18		0.2		4.4		+			9.8		8.3	0.6	0.4	1								39
0.2	2	0.6			32	8	8.6				1					6.9		5.4			5.4								32
0.4	2		1	1	12	8	1	0.4			1.8	0.8				10		5	0.4		1.8								43

Pliocene sediments. Foraminifers characterizing sediments of the early Pliocene Zone Pl1b are *Gr. margaritae, D. altispira, Ss. paenedehiscens, Ss. kochi*, and *Ss. seminulina*, which are inherited from the Miocene. Latest specimens of *Gq. venezuelana* and *G. nepenthes* and the earliest ones of *Gr. crassaformis* and *Sphaeroidinella (Sa.) dehiscens* are also recorded in this zone. The overlying early Pliocene zones Pl2, Pl3, and Pl4 are defined in accord with datum levels of *Gr. margaritae, Ss. seminulina*, and *D. altispira.* In addition, sediments of zones Pl2 and Pl3 yield few specimens of *Gr. pertenuis* and *Gr. multicamerata*, whereas *Ss. kochi* disappears near the base of the Zone Pl3.

Composition of planktonic foraminiferal assemblage of the late Pliocene Zone Pl5 is substantially different. *Ss. paenedehiscens, Ge. praecalida, Gq. pseudofoliata*, and *Gr. limbata* disappeared successively within it and *Gs. fistulosus, Gr. pumilio, Pu. obliquiloculata, Ge. calida,* and *Gr. ungulata* appeared there. Few specimens of the Pliocene forms *Gr. exilis, Gr. multicamerata, Gr. conomiozea, Gr. puncticulata,* and of modern *Gr. inflata* are also present in this assemblage. In the late Pliocene Zone Pl6, *Gs. extremus, N. acostaensis, N. humerosa, Gr. flexuosa*, and *G. decoraperta* become extinct. The planktonic foraminiferal assemblage of the Zone Pt1a is most similar to the present one. The top of the zone is marked by extinction of *Gs. obliquus, Gr. fistulosus*, and *Pu. primalis; Gr. pumilio* disappears in its middle part. Few specimens of *Gr. tosaensis* and *Gr. truncatulinoides* occur within the zone.

Thus, the stratigraphic distribution of 60 planktonic foraminiferal species and morphological varieties has been established, and 34 among them are the modern forms (Table 2). Twenty five species became extinct and nine forms appeared during the studied time span. As for the species of foraminiferal climatic groups mentioned above (Table 2), their general diversity decreased owing to the disappearance of tropical and
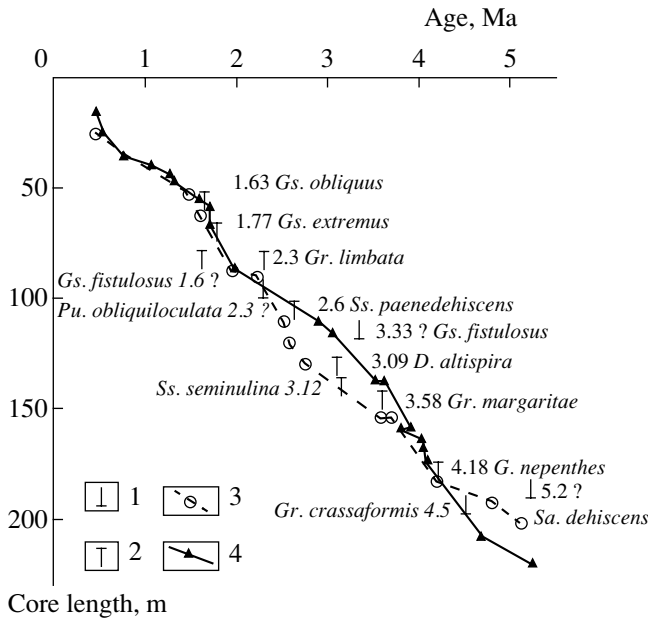
Fig. 3. Secular variations of sedimentation rate at the Site 677A: (1) first and (2) last occurrence levels of planktonic foraminifers (this work), ages in Ma after Berggren *et al.* (1995); (3) nannofossils (Houghton, 1989); (4) radiolarians (Alexandrovich, 1989).

equatorial-tropical forms, whereas the subtropical taxa were predominantly developing. The species diversity as a whole decreased from 48 forms in the early Pliocene to 34 in the Early Pleistocene.

According to the curve of accumulation rate based on nine planktonic foraminiferal datum levels, the early–late Pliocene (3.08 Ma) and Pliocene–Quaternary (1.81 Ma) boundaries are defined at the depth levels of 128 and about 75 m below the sea floor (Fig. 3). Sedimentation rate calculated from the planktonic foraminiferal data, decreased from 54 m/m.y. in the early Pliocene to 44 m/m.y. in the late Pliocene, and down to 41 m/m.y. in the Early Pleistocene.

PALEOCEANOLOGIC RECONSTRUCTIONS

High sedimentation rate and lithologic features of the section indicate that the Pliocene–Quaternary sediments recovered by Hole 677A accumulated under conditions of a high biological productivity characteristic of the present-day Panama Basin. To reconstruct the conditions of accumulation of planktonic foraminiferal assemblages and variations of the carbonate compensation depth (CCD) in Hole 677A, I used the following
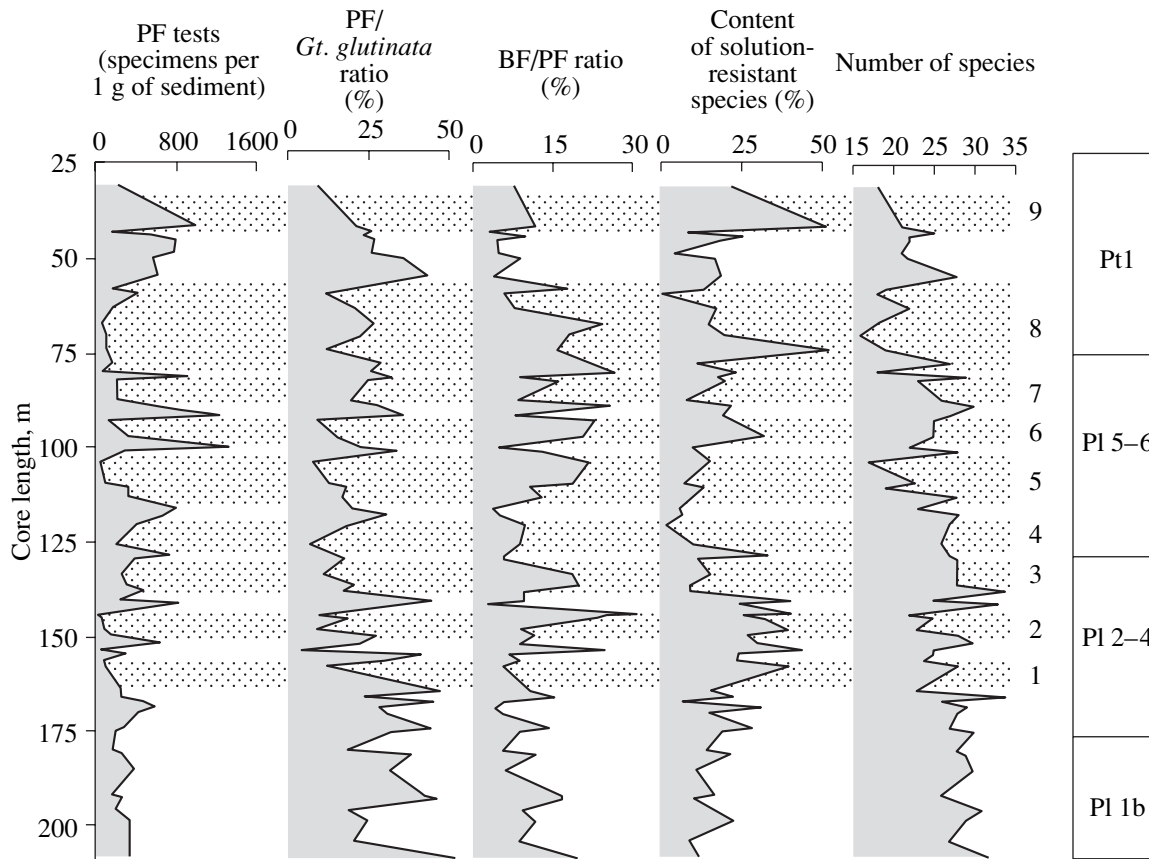
Fig. 4. Pliocene–Lower Quaternary horizons (1–9) of Hole 677A, Panama Basin, accumulated in periods of the CCD rise; abbreviations PF and BF denote planktonic and benthic foraminiferal tests; solution-resistant species are *Gr. tumida, Gr. menardii,* and *Pu. primalis.*
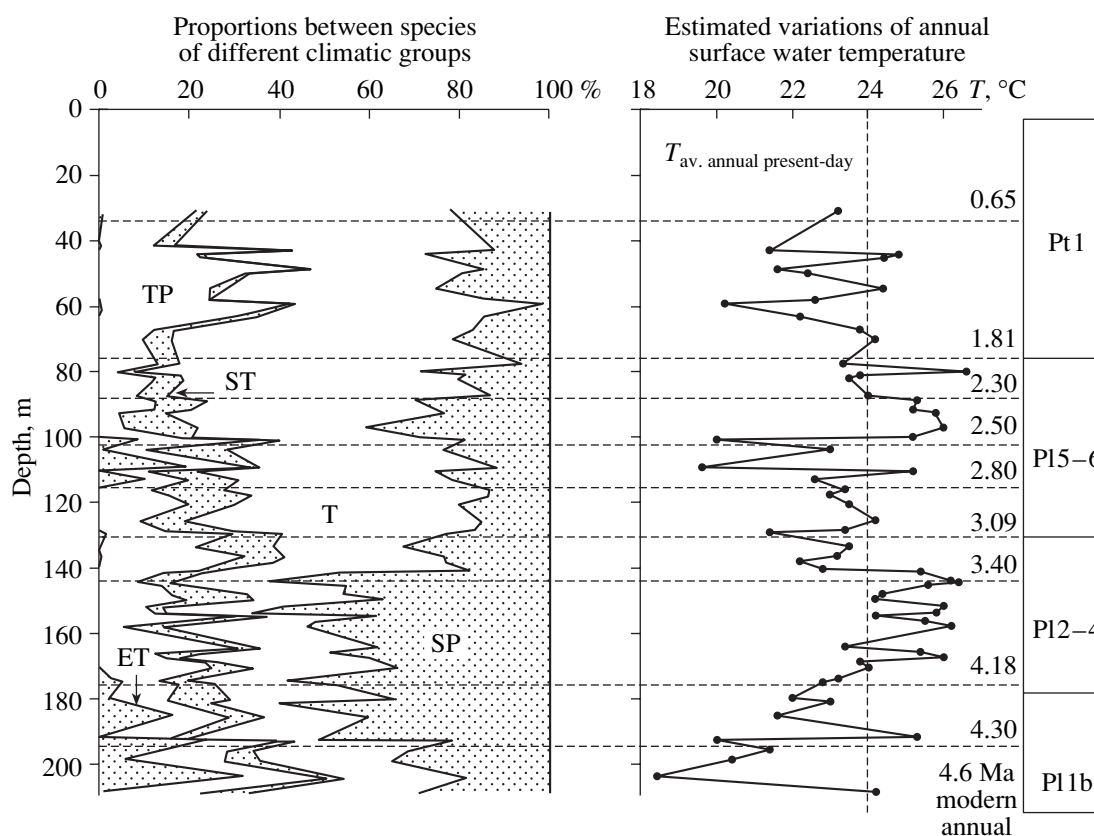
Fig. 5. Secular variations of surface water temperature and proportions between planktonic foraminiferal species of different climatic groups in Pliocene–Lower Quaternary thanatocoenoses at the Site 677A: (SP) subpolar, (TP) temperate, (ST) subtropical, (T) tropical, and (ET) equatorial-tropical species.

parameters: the foraminiferal number; ratio of benthic to planktonic foraminifers calculated as (BF/BF+PF) × 100%; percentages of *Gt. glutinata* in the foraminiferal assemblages; number of foraminiferal species; and overall concentrations of forms most resistant to dissolution, such as *Gr. tumida, Gr. menardii*, and *Pu. primalis* (Fig. 4).

The use of *Gt. glutinata* concentrations among other analyzed parameters is dictated by its peculiar distribution in the Pliocene–Lower Quaternary deposits of the North Pacific. Earlier (Bubenshchikova, 1996), I showed a cosmopolitan character of this species whose concentrations may be as high as 30–60% of the foraminifer assemblage as a whole, though its predominance in subtropical and tropical realms and its relation to highly productive oceanic zones was also noted. It was also recognized that considerable variations of that species content from 0.5 to 60% resulted not only from ecologic reasons, but also from dissolution.

Despite a complicated character of curves shown in Fig. 4, the following regularities can be marked. In the early Pliocene, i.e., from 4.6 to 3.8 Ma (210–155-m interval in the section), conditions of sedimentation (productivity of planktonic foraminifers, the CCD level, and characteristics of water mass) were relatively stable. The preservation of planktonic foraminifers was

comparatively good, as it is evident from the high concentrations of *Gt. glutinata*, relatively low content of solution-resistant species, and low benthic-to-planktonic form ratios (Fig. 4). In the subsequent period from 3.8 to 0.65 Ma (155–30 m below sea floor), there were recorded nine extended intervals of the decreased abundance and species diversity of planktonic foraminifers, within which concentrations of *Gt. glutinata* are reduced, while the content of solution-resistant species and benthic-to-planktonic form ratios grow. These data indicate a decline of planktonic foraminiferal productivity and/or the CCD rise and more intense dissolution of foraminiferal tests in the intervals 1 to 9 (Fig. 4). However, the content of solution-resistant species is below 25%, suggesting a relatively well preservation of foraminiferal assemblages at that time except for those in samples 5H5 and 9H1, which were excluded from the paleotemperature analysis. The deep-sea drilling records indicate the betterment and deterioration of carbonate preservation in the Atlantic and Pacific oceans, respectively, beginning from 4.6 Ma that was associated with the gradual closure of the Panama Strait and with changes in the bottom- and surface-water circulation (Haug and Tiedemann, 1998). The results obtained for Hole 677A well agree with this conclusion.

Let us consider now the data on species climatic groups of foraminifers and inferable temperatures of surface water (Fig. 5). The Lower Pliocene sediments (4.6–3.09 Ma) yield contrasting thanatocoenoses characterized by the predominance of foraminifers of non-contiguous SP-M and ET climatic groups (Fig. 5, *I*). The content of T and ST species is significantly lower than in the low-latitude assemblages of the open ocean (Ivanova, 1983). Assemblages with predominance of species of non-contiguous climatic groups, i.e., the contrasting thanatocoenoses, are characteristic of the frontal zones and upwelling areas (Os'kina and Blyum, 1984). Thus, a more significant seasonal contrast of surface water temperatures than in the present Panama Basin was characteristic of the early Pliocene. The surface-water circulation was more intense in general than nowadays. The temperature minimums evidently reflect the influence of the Equatorial Divergence, Peru Current, and the associated upwelling. The temperature maximums were likely related to periods of a weakened water uplift and strengthened equatorial countercurrent, and also to open connections between the Atlantic and Pacific tropical regions at that time.

Variations in abundance of members of the *N. dutertrei* lineage (*N. pachyderma* sin.–*N. pachyderma* dex.–*N. pseudopima*–*N. dutertrei blowi*), which are the upwelling indicators in the Panama Basin (Tables 1 and 2), enable the following conclusions on the circulation intensity. From 4.6 to 4.3 Ma, the upwelling of cold water was most intense in the period from 4.3 to 4.18 Ma and gradually weakened afterward; its influence was minimal during the time span of 4.18–3.4 Ma and increased again from 3.4 to 3.09 Ma though not up to the level characteristic of the mid-early Pliocene.

The oxygen isotope investigations showed positive excursions of $\delta^{18}O$ in planktonic foraminiferal tests from the equatorial Pacific in the periods of 4.2–4.0 Ma (Whitman and Berger, 1992), 4.45–4.325 Ma (Prentice *et al.*, 1993), 4.6–4.3 Ma (Jansen *et al.*, 1993), and 4.0 Ma (Shackleton *et al.*, 1995), which support our conclusion that these were periods of a relatively cold climate (Fig. 5). Micropaleontological and isotope data for the equatorial Pacific indicate a relatively warm period from 5.0 to 3.3–3.0 Ma (Keigwin, 1982a,b; Prell, 1985; Whitman and Berger, 1992; Prentice *et al.*, 1993; Jansen *et al.*, 1993).

A considerable abundance of ET species (*Gs. quadrilobatus, D. altispira, Gr. menardii*, and *Gr. limbata*) in the early Pliocene (Fig. 5 and Table 2) shows that the surface water temperatures during the weakened upwelling in the Panama Basin were higher than nowadays and reached the maximum values at 4.18–3.4 Ma. A sharp decrease in concentrations of these species and lower contrast of thanatocoenoses in general at about 3.4 Ma (Fig. 5) indicate changes in hydrologic conditions, evidently owing to the uplift of the Central American threshold and to the terminated communication between surface water masses of the

Pacific and Atlantic tropical areas. According to our data (Fig. 5), this event and related changes in planktonic foraminiferal assemblages happened rapidly. However, biogeographic evidences from other groups of microfauna suggest that the event lasted longer, from 3.8 to 3.0 Ma (Jenkins and Orr, 1972; Saito, 1976; Keigwin, 1982b; and others). The uplift of the Central American Isthmus created outlines of the Atlantic and Pacific basins similar to the recent ones and gave rise to circulation and properties of the bottom-water resembling those of the Quaternary (Haug and Tiedemann, 1998). According to our data, this event is recorded in carbonate sediments at Site 677 at the level of 3.8 Ma (Fig. 4).

The late Pliocene sediments (3.09–1.81 Ma) are more rich in foraminifers of T and ST groups and depleted in taxa of ET and M groups, i.e., their thanatocoenoses are less contrasting (Fig. 5). *Gs. ruber* and *N. dutertrei blowi* dominate among T species, *N. acostaensis* and *N. humerosa*, among ST forms, and *N. pseudopima* among M taxa (Table 2). In the period of 2.8–2.5 Ma, the contrast between thanatocoenoses sharply increased and they became close in composition to those of the mid-early Pliocene (4.6–4.3 Ma), despite the lower abundance of foraminifers from SP and ET groups. In the terminal late Pliocene (2.5–1.81) Ma, thanatocoenoses were most similar in composition to the low-latitude tropical assemblages of the open ocean (Ivanova, 1983). They were dominated by *Gr. menardii, Gs. ruber, N. dutertrei blowi*, and *N. dutertrei* characteristic of the present-day Panama Basin.

According to general structure of planktonic foraminiferal assemblage, their species composition, and variations in abundance of species of the *N. dutertrei* lineage, the seasonal contrast of surface water temperatures during the late Pliocene was likely lower than in the early Pliocene. In the period of 3.09 to 2.8 Ma, the upwelling was less intense than in the terminal early Pliocene and strengthened again in the period of 2.8 to 2.5 Ma. It was similar to the recent tropical upwelling in the Panama Basin during the time span of 2.5−1.8 Ma.

Nowadays there is a lot of data implying that the major glaciation epoch began in the Northern Hemisphere 2.8–2.4 Ma ago (e.g., Keigwin, 1982b; Prell, 1985). Oxygen isotope records in planktonic and benthic foraminiferal tests indicate that, according to different estimates, the glaciation peaks occurred 2.4 Ma (Keigwin, 1982b), 2.54 Ma (Jansen *et al.*, 1993), and 2.8–2.85 Ma ago (Whitman and Berger, 1992). The mid-late Pliocene thanatocoenoses close in composition to those of the early Pliocene, formed 2.8 to 2.5 Ma ago according to results of this study (Fig. 5), i.e., most likely during the strengthened circulation of surface water, when its temperature decreased in response to glaciation in the Northern Hemisphere. The comparison of temperature values estimated for the

Early and mid-late Pliocene (Fig. 5) also suggests that glaciation in the northern polar region produced a lesser impact on hydrologic conditions in the Panama Basin than climatic changes in the Southern Hemisphere, which were responsible for the cold event of the early Pliocene.

In sediments recovered by Hole 677A, the Pliocene–Pleistocene boundary marks the beginning of a relatively cold event recorded at about 1.7 Ma, and comparatively cold-water conditions in the region were characteristic of the subsequent period. The species composition of corresponding thanatocoenoses is similar to that of the modern foraminiferal assemblages (Tables 1, 2), though representatives of the M group, among which *N. pachyderma* dex. and *N. pseudopima* dominated, were more abundant in this time than now. These thanatocoenoses most likely reflect changes in the surface-water circulation, which controlled development of microfauna in colder conditions than those of the present-day Panama Basin; the environments were likely close to those of the terminal Early and initial late Pliocene.

Thus, this study shows that the changes in planktonic foraminiferal assemblages from Hole 677A were under strong influence of the climate-controlled dynamics of surface water masses in the eastern equatorial Pacific during the period of 4.6 to 0.65 Ma.

The paleotemperature plot for Hole 677A (Fig. 5) demonstrates the mean secular variations against the background of substantial fluctuations of surface water temperatures during the formation period of studied thanatocoenoses of planktonic foraminifers. The maximum temperatures are estimated for the terminal early (26.4°C) and late Pliocene (26.6°C), and the minimal ones for the initial early Pliocene (18.4°C), mid-late Pliocene (19.6°C), and for the beginning of the Early Pleistocene (20.2°C). The general amplitude of temperature fluctuations is 8°C. The resolution ability of the paleotemperature plot is insufficient for correlation of estimated thermal peaks with the Pliocene oxygen isotope stages (Shackleton *et al.*, 1995), about a hundred of which has been distinguished within the last 3 Ma at Hole 677A (Shackleton and Hall, 1989). It should be noted that the global paleoreconstructions for the mid-Pliocene (or Pliocene optimum) did not reveal a significant rise of surface water temperatures in low latitudes of the World Ocean above their present-day level (Dowsett *et al.*, 1996).

The comparison between paleotemperature (Fig. 5) and sedimentation rate (Fig. 3) plots resulted in recognition of several thermal events. Cold events are recorded within the time intervals of 4.6–4.3, 2.8–2.5, and 1.7–1.2 Ma, and warm events correspond to periods of 4.3, 4.18–3.4, 2.5–2.3, and 1 Ma. The mid-early Pliocene, mid-late Pliocene, and the initial Pleistocene characterize in general the cold-water conditions, while the terminal early and late Pliocene, warm-water ones.

CONCLUSIONS

The general biostratigraphic zonation after Berggren *et al.* (1995) is used for the first time to subdivide sedimentary sequence of Hole 677A, and planktonic foraminiferal zones PL1b to Pt1 are distinguished in this sequence within the subbottom depth interval of 30–210 m. The early-late Pliocene (3.09 Ma) and Pliocene-Quaternary (1.81 Ma) boundaries are situated in the studied section at the levels of about 128 and 75 m below bottom, respectively.

Many planktonic foraminiferal datums are found to be the reliable biostratigraphic markers in the Panama Basin sediments. The following events are established to be diachronous in comparison with those dated by Berggren *et al.* (1995): the appearance of *Sa. dehiscens* at 4.35 Ma and *Gs. fistulosus* at 2.9 Ma, and the last occurrence of *Gr. limbata* at 2.0 Ma and *Gs. fistulosus* at 1.9 Ma.

The distinguished intervals of the decreased planktonic productivity and/or changes of the Pacific bottom waters beginning from 3.8 Ma are marked by decline in abundance of planktonic foraminifers and by lower diversity of their species and lesser concentration of *Gt. glutinata*. In contrast, abundance of solution-resistant species and benthic-to-planktonic species ratios increase within these intervals.

Changes in composition of planktonic foraminiferal assemblages from sediments at Site 677 reflect impacts of the climate-controlled dynamics of surface water masses in the eastern equatorial Pacific during the period of 4.6–0.65 Ma.

A sharp decrease in abundance of equatorial-tropical species about 3.4 Ma ago indicates a transformation of hydrologic regime. This event is correlated with the termination of the surface water exchange between the Pacific and Atlantic tropical zones owing to the emergence of the Central American threshold.

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