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11. Pliocene Paleoclimatology at ODP Site 1115, Solomon Sea (Southwestern Pacific Ocean), Based on Calcareous Nannofossils[1]

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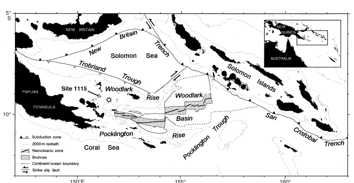
ABSTRACT

The relative abundance of warm-water *Discoaster brouweri* vs. cool-water *Coccolithus pelagicus* provides a useful proxy for interpreting Pliocene surface water temperature trends at Ocean Drilling Program Site 1115 (Solomon Sea). Surface waters were mostly warm during the early Pliocene with a slightly cooler interval centered on 4.5 Ma. A more pronounced cool interval occurred at ~3.2 Ma. The early and mid-Pliocene cool periods may reflect Antarctic glacial growth. A mid-Pliocene warm interval occurred from ~3.1 to 2.8 Ma. Temperature began to decline beginning ~2.7 Ma, marking the onset of Northern Hemisphere glaciation. This long-term decline in surface water temperature is interrupted by a brief warming event at ~2.3 Ma.

INTRODUCTION

The Solomon Sea occupies a small marginal oceanic basin previously uninvestigated by the Deep Sea Drilling Project/Ocean Drilling Program (DSDP/ODP). Holes 1115B and 1115C were drilled in the southwestern part of the Solomon Sea (Fig. F1) during ODP Leg 180 (June–August 1998). Drilling in these holes penetrated a thick Pliocene section, providing an opportunity for paleoclimatic investigation in a previously unstudied part of the world ocean.

F1. Site 1115 location map, p. 10.



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The Pliocene Epoch was a time of global climatic deterioration. The planet was changing from the "Greenhouse Earth" of the early Tertiary to the "Icehouse Earth" of the late Neogene and Quaternary. Climatic change has a direct effect on the temperature of oceanic surface waters. Various proxies have been used to assess the changing temperatures of oceanic waters, and thus climate, with time (e.g., oxygen-isotope ratios, alkenone measurements, temperature-sensitive single species or assemblages of various microfossils, structural changes in microfossil skeletons, etc.). In this study, I have used a technique employing two temperature-diagnostic nannofossil species in an attempt to identify trends in surface water changes in the Solomon Sea during the Pliocene.

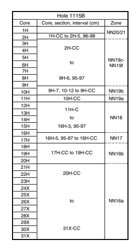
LITHOSTRATIGRAPHY, BIOSTRATIGRAPHY, AND CHRONOSTRATIGRAPHY AT SITE 1115

Holes 1115B and 1115C were drilled in a water depth of 1150 m. Hole 1115B was cored using the advanced piston corer to a depth of 216 meters below seafloor (mbsf), followed by extended core barrel to a depth of 293 mbsf. Hole 1115C was drilled using the rotary core bit from a depth of 283 to hole termination at 802.5 mbsf. The sediments consist mostly of calcareous silty clay and claystone with abundant volcaniclastic ash and sand layers down to ~415 mbsf. Calcareous sandstones and siltstones extend downward from that level to below the base of the Pliocene (inferred to be at 504 mbsf at this site).

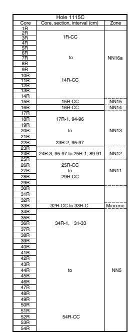
The nannofossil biostratigraphy for the two holes, using the zonation of Martini (1971) with modifications from Rio et al. (1990a), is given in Figures F2 and F3. Several zonal conventions and assignments warrant comment. The Pliocene/Pleistocene boundary is within Subzone NN19a. The top (1.77 Ma) of the Olduvai Chron was determined to be at 90.5 mbsf and the base (1.95 Ma) between 102.5 and 103.5 mbsf in Hole 1115B (**Takahashi et al.,** this volume), which places the Pliocene/Pleistocene boundary (taken to be 1.81 Ma) (Berggren et at., 1995) at 93.5 mbsf by interpolation. The NN16b/NN17 boundary may be somewhat higher than shown on Figure F2. The last occurrence (LO) of *Discoaster surculus* defines this boundary. The LO of *D. surculus* normally occurs closely below the LO of *Discoaster pentaradiatus,* which defines the NN17/NN18 boundary. In this hole, however, the apparent LO of *D. surculus* is 31 m below the LO of *D. pentaradiatus,* even though the last appearance datums (LADs) of the two species are separated by only 0.03 m.y. *D. surculus* is rather rare in these cores, and I believe its stratigraphic range is incomplete here. Paleomagnetic data seem to bear this out. The Gauss/Matuyama boundary (2.58 Ma) is inferred to be at 162.0 mbsf in Hole 1115B (**Takahashi et al.,** this volume). The LAD for *D. surculus* has been shown as 2.55 Ma (Berggren et al., 1995). Thus, the 2.55-Ma LAD between 175.7 and 178.6 mbsf for *D. surculus* and the 2.58-Ma age at 162.0 mbsf for the Gauss/Matuyama boundary are inconsistent.

The Miocene/Pliocene boundary (5.32 Ma) lacks a recognizable biostratigraphic event, being defined by a historic event—the reflooding of the Mediterranean following the Messinian salinity crisis. Reflooding occurred within Zone NN12 (5.00–5.54 Ma), which spans the Miocene/Pliocene boundary. The top of Zone NN12 is marked by the first occurrence (FO) of *Ceratolithus rugosus* (or approximated by the LO of *Ceratolithus acutus*) (Perch-Nielsen, 1985) and the base of the LO of *Discoaster quinqueramus*. The LO of *D. quinqueramus* between 514.3 and

F2. Neogene calcareous nannofossil zonation, Hole 1115B, p. 11.



F3. Neogene calcareous nannofossil zonation, Hole 1115C, p. 12.



516.4 mbsf is an easily recognizable event, but confident recognition of the actual FO of *C. rugosus* and/or LO of *C. acutus* is difficult because of the rarity of ceratoliths in this section (Taylor, Huchon, Klaus, et al., 1999). Relying mostly on the LAD of *D. quinqueramus* at 5.54 Ma and the estimated sedimentation rate for this interval (**Takahashi et al.,** this volume), I estimate the Miocene/Pliocene boundary to be at ~504 mbsf in this hole.

A detailed summary of the sedimentology, lithostratigraphy, biostratigraphy, and other characteristics of the sediments at this site may be found in the Leg 180 *Initial Reports* volume (Taylor, Huchon, Klaus, et al., 1999).

NANNOFOSSIL CLIMATIC PROXIES

Calcareous nannoplankton live in the upper surface waters of the oceans and are thus directly influenced by surface water changes. The discoaster group has long been recognized as a group that prefers warm waters, and several earlier workers have produced paleotemperature studies using the ratio of warm-water discoasters as a group to cool-water *Chiasmolithus* or *Coccolithus* (e.g., Bukry, 1978, 1981; Haq et al., 1977; Siesser 1980, 1984; Raffi and Rio, 1981). In the Neogene, however, several discoasters (*D. variabilis, D. intercalaris, D. tamalis,* and *D. asymmetricus*) are believed to have preferred cool waters (Bukry, 1981; Rio et al., 1990b). A single discoaster species, *Discoaster brouweri,* which has a well-established preference for warm waters (e.g., Bukry, 1978, 1981; Siesser, 1975; Müller, 1985; Wei et al., 1988) was thus selected as the warm-water proxy for this study.

Coccolithus pelagicus is used as the cool-water proxy. *C. pelagicus* lives in cold-temperate (6°–18°C) Northern Hemisphere waters and upwelling regions today (McIntyre et al., 1970; Raffi and Rio, 1981; Giraudeau et al., 1993; Giraudeau and Bailey, 1995; Cachao and Moita, 2000) but has apparently changed its habitat with time. In the Miocene and early Tertiary, *C. pelagicus* was common in tropical environments as well as in cooler waters (Bukry, 1981). Bukry (1981) made a careful analysis of the distribution of this species, concluding that by the Pliocene *C. pelagicus* had evolved an affinity for cool water that made it an effective proxy for determining paleotemperature trends. Raffi and Rio (1981) also concluded that *C. pelagicus* was a good paleotemperature indicator for the Mediterranean during the late Pliocene.

D. brouweri and *C. pelagicus* have additional advantages in that they are both normally significant components of nannofossil assemblages and are also less affected by diagenetic changes than many other species. The changing downhole relative abundance of these two nannofossil species should, therefore, be a good paleotemperature indicator, reflecting gross changes in water temperature with time.

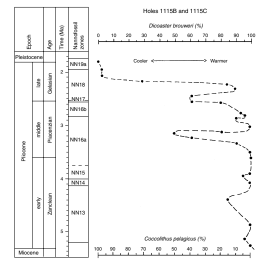
METHODS

In this study, I counted 100 specimens of *D. brouweri* and *C. pelagicus* along random traverses across smear slides made from Holes 1115B and 1115C samples. I included all varieties of “*D. brouweri*” in the count of *D. brouweri* s.l. (i.e., *D. brouweri* ssp. *recurvus* Cati and Borsetti, *D. brouweri* var. *rutellus* Gartner; *D. brouweri* ssp. *bipartitus* Haq and Berggren; *D. brouweri* ssp. b*rouweri* Theodoridus; and *D. brouweri* ssp. *streptus*

Theodoridus). Species counts for each sample examined are shown in the "Appendix," p. 9. Results are expressed as the percentage of each species in the total count of 100 *D. brouweri* and *C. pelagicus* specimens (Fig. F4). Using two species that vary inversely in relative abundance rather than using the absolute abundance of only one species avoids potential error caused by variations in the density of specimens sedimented on a slide. Siesser and de Kaenel (1999) used a similar method of investigation for the Pliocene in the western Mediterranean, and Wei et al. (1988) used a ratio of these two species on the Galicia Margin.

Samples investigated are plotted against the timescale (Fig. F4) by using selected nannofossil, foraminifer, magnetochron and $^{40}Ar/^{39}Ar$ datums identified in Holes 1115B and 1115C as tie points (Lackschewitz et al., in press; Resig et al., in press; Takahashi et al., this volume) (Table T1) and interpolating the position of samples between datums (see "Appendix," p. 9) (Fig. F4). I attempted to select samples with an ~0.1-m.y. separation (see "Appendix," p. 9), although this was not always possible, owing to sample availability and differing degrees of preservation among samples.

F4. Changes in Pliocene surface water temperature, p. 13.



T1. Datum events, p. 14.

RESULTS

Figure F4 shows the number of *D. brouweri* and *C. pelagicus* specimens counted plotted against the Pliocene timescale and biozones. The underlying assumption in the following discussion is that fluctuations in the abundance of *D. brouweri* relative to *C. pelagicus* are primarily caused by changing surface water temperatures. A larger number of *D. brouweri* indicates relatively warmer waters and vice versa.

Surface water temperatures were warm during most of the early Pliocene at Site 1115 (Fig. F4). A minor cool interval occurred at ~4.5 Ma. Temperatures began to decline markedly only in the early mid-Pliocene. A pronounced incursion of cool water occurred at this site between ~3.3 and 3.1 Ma. Warm surface water returned during late Zones NN116a and NN16b. Temperatures began to fall again in late Zone NN16b (at ~2.7 Ma), a trend that continued into early Zone NN18 (until at least 2.5 Ma). The overall decline in temperature, which began at 2.7 Ma, was interrupted briefly by an influx of warmer water at ~2.3 Ma. Surface waters continued to cool after that time, with *D. brouweri,* the warm-water proxy used here, becoming extinct at the end of Zone NN18 (1.95 Ma).

DISCUSSION

Site 1115 is in a low-latitude (9°11.4′S), warm-water environment (average surface water temperature = 25°–28°C today [Garrison, 1996]), with no reports of upwelling. Thus, it is not surprising to find that warm-water conditions dominated here throughout the Pliocene, because the site has moved northward less than about 1.5° of latitude since the beginning of the Pliocene (Goodliffe, 1998). The temperature trends on Figure F4 show only two divergences from the generally warm-water conditions that prevailed throughout the Pliocene, until the final sharp decline which began ~2.7 Ma and continued into the Pleistocene.

It is instructive to compare the temperature trends at this site, based on nannofossil proxies, to those of other areas. The geographically closest study is that of Jansen et al. (1993), who investigated Pliocene climatic trends by oxygen-isotope analysis at a site on the Ontong Java Plateau. Their timescale uses slightly different ages for some datum tie points, but recalculation of their ages using my datum points shows an average difference of <3% between their timescale and the scale I have used here. Jansen et al. (1993) interpreted their results as reflecting expansion of Antarctic glacial ice between 4.6 and 4.3 Ma, which corresponds rather well with the minor cool peak centered on 4.5 Ma shown in Figure **F4.** Similarly, pronounced cool-water events centered on 3.2 Ma occur in both the Solomon Sea (Fig. **F4**) and on the Ontong Java Plateau (Jansen et al., 1993). This brief cool interval has also been reported in other studies (based on diverse analytical techniques), ranging in (recalculated) ages between 3.5 and 3.0 Ma (e.g., Keigwin, 1987 [3.1 Ma]; Raymo et al., 1987 [3.4–3.2 Ma]; Rio et al., 1990b [3.1 Ma] [ages in brackets are the originally published ages]). Siesser and de Kaenel (1999) showed the same general cooling trend between 4.5 and 4.2 Ma in the Mediterranean for the early Pliocene but did not show a definite mid-Pliocene cool interval at 3.2 Ma.

Surface waters warmed appreciably in the Solomon Sea after the 3.2-Ma cool peak with a substantial warm peak from ~3.1 to 2.8 Ma. This may correspond to the "mid-Pliocene warm interval" described in several recent papers (e.g., Crowley, 1996; Dowsett et al., 1996; Siesser and de Kaenel, 1999). Crowley (1996), Dowsett et al. (1996), Raymo et al. (1996) and others have stated that the mid-Pliocene was the last time when global average temperatures were greater than temperatures of today. The time of this last warm period is estimated by Raymo et al. (1996) to be around 3.0 Ma. Siesser and de Kaenel (1999) found this to be a recognizable warm peak at several sites in the western Mediterranean; the age of the warm peak there ranges from ~3.0 to 2.6 Ma.

After this warm interval at Site 1115 in the Solomon Sea, temperatures began to decline in Zone NN16b (starting at ~2.7 Ma). I believe this signals the beginning of the well-documented cooling related to the onset of Northern Hemisphere glaciation. King (1996) has summarized the evidence for the timing of the onset of glaciation at between 2.8 and 2.5 Ma. The decline beginning here at 2.7 Ma fits this time frame well. Wei et al. (1988) found that cooling began after ~2.5 Ma on the Galicia Margin, and Siesser and de Kaenel (1999) recorded the beginning of cooling around 2.5–2.6 Ma in the Mediterranean. Jansen et al. (1993) found temperatures progressively declining on the Ontong Java Plateau after 2.85 Ma, with a short but dramatic cool peak occurring just before 2.5 Ma superimposed on the longer-term cooling trend.

An unexpected event occurred in the middle of Zone NN18 (at ~2.3 Ma) in the Solomon Sea, when the overall cooling trend was interrupted by a brief warming event (Fig. **F4**). This has not been reported elsewhere. However, inspection of the expanded oxygen-isotope plot of Jansen et al. (1993, p. 357) also shows a slightly warmer interval at ~2.25 Ma, interrupting the overall cooling trend on the Ontong Java Plateau.

SUMMARY

D. brouweri and *C. pelagicus* abundance values show that warm-water conditions prevailed at Site 1115 in the Solomon Sea during most of the early and middle Pliocene. Incursions of cooler surface water at times centered on 4.5 and 3.2 Ma interrupted the long-term warm-water conditions at this site. The “mid-Pliocene warm interval” occurred from 3.1 to 2.8 Ma, followed by a marked decline in surface water temperatures beginning ~2.7 Ma. Cooling continued to the end of the Pliocene, with a brief influx of warmer water appearing at ~2.3 Ma.

ACKNOWLEDGMENTS

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APPENDIX

Number of *Discoaster brouweri* and *Coccolithus pelagicus*, Holes 1115B and 1115C

Core, section, interval (cm)	Interpolated age (Ma)	Preservation	*D. brouweri* (number/100 specimens)	*C. pelagicus* (number/100 specimens)
180-1115B-				
10H-CC	1.80	VG	0	100
11H-CC	1.94	VG	2	98
12H-CC	2.06	VG	2	98
13H-CC	2.18	VG	28	72
14H-3, 95–97	2.23	VG	83	17
14H-CC	2.31	VG	89	11
15H-CC	2.45	G	62	38
16H-CC	2.54	VG	62	38
17H-CC	2.57	VG	80	20
18H-CC	2.77	VG	93	7
19H-CC	2.80	VG	96	4
20H-CC	2.84	VG	90	10
21H-CC	3.01	VG	98	2
22H-CC	3.12	VG	81	19
23H-CC	3.15	VG	49	51
25X-CC	3.21	VG	62	8
29X-CC	3.31	G	91	9
180-1115C-				
7R-CC	3.49	VG	98	2
11R-CC	3.59	VG	100	0
15R-CC	3.89	M-G	98	2
17R-1, 94–96	3.92	M-G	95	5
18R-1, 59–61	4.05	G	98	2
19R-CC	4.38	M	85	15
21R-CC	4.85	M	100	0
23R-2, 95–97	5.12	M	96	4
24R-3, 95–97	5.28	M	100	0

Notes: VG = very good, G = good, M = moderate.

Figure F1. Location map showing Site 1115 in the Solomon Sea. Map modified from Goodliffe et al. (1997).

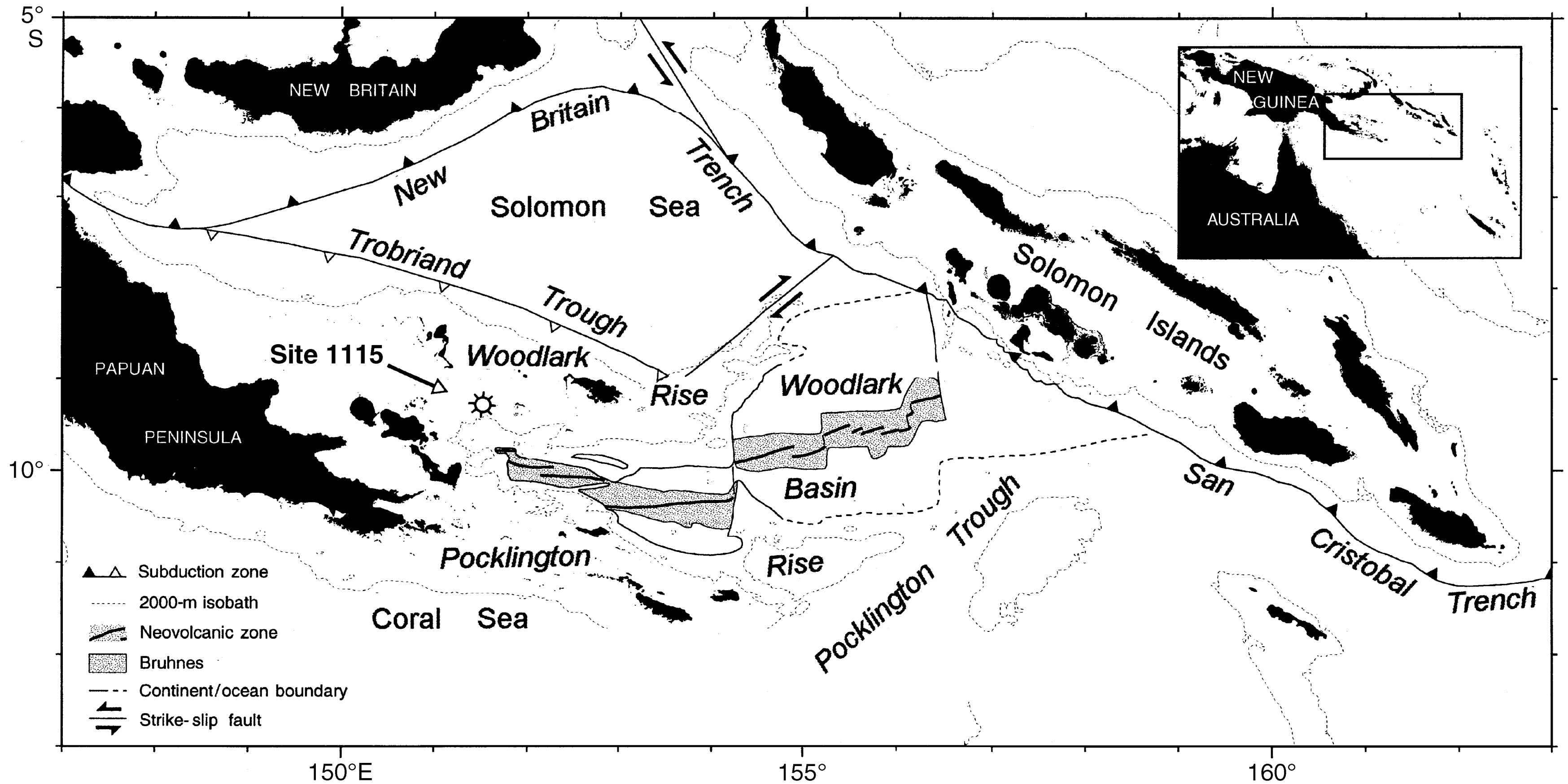

Figure F2. Neogene calcareous nannofossil zonation of Hole 1115B. Zonation is that of Martini (1971) with modifications from Rio et al. (1990a).

<table>
<tr><th colspan="3">Hole 1115B</th></tr>
<tr><th>Core</th><th>Core, section, interval (cm)</th><th>Zone</th></tr>
<tr><td>1H</td><td></td><td rowspan="2">NN20/21</td></tr>
<tr><td>2H</td><td>1H-CC to 2H-5, 96-98</td></tr>
<tr><td>3H</td><td rowspan="7">2H-CC to 9H-6, 95-97</td><td rowspan="7">NN19c-NN19f</td></tr>
<tr><td>4H</td></tr>
<tr><td>5H</td></tr>
<tr><td>6H</td></tr>
<tr><td>7H</td></tr>
<tr><td>8H</td></tr>
<tr><td>9H</td></tr>
<tr><td>10H</td><td>9H-7, 10-12 to 9H-CC</td><td>NN19b</td></tr>
<tr><td>11H</td><td>10H-CC</td><td>NN19a</td></tr>
<tr><td>12H</td><td rowspan="5">11H-C to 16H-3, 95-97</td><td rowspan="5">NN18</td></tr>
<tr><td>13H</td></tr>
<tr><td>14H</td></tr>
<tr><td>15H</td></tr>
<tr><td>16H</td></tr>
<tr><td>17H</td><td>16H-5, 95-97 to 16H-CC</td><td>NN17</td></tr>
<tr><td>18H</td><td rowspan="3">17H-CC to 19H-CC</td><td rowspan="3">NN16b</td></tr>
<tr><td>19H</td></tr>
<tr><td>20H</td></tr>
<tr><td>21H</td><td rowspan="11">20H-CC to 31X-CC</td><td rowspan="11">NN16a</td></tr>
<tr><td>22H</td></tr>
<tr><td>23H</td></tr>
<tr><td>24X</td></tr>
<tr><td>25X</td></tr>
<tr><td>26X</td></tr>
<tr><td>27X</td></tr>
<tr><td>28X</td></tr>
<tr><td>29X</td></tr>
<tr><td>30X</td></tr>
<tr><td>31X</td></tr>
</table>

Figure F3. Neogene calcareous nannofossil zonation of Hole 1115C. Zonation is that of Martini (1971) with modifications from Rio et al. (1990a).

Hole 1115C		
Core	Core, section, interval (cm)	Zone
1R		
2R		
3R	1R-CC	
4R		
5R		
6R		
7R	to	NN16a
8R		
9R		
10R		
11R	14R-CC	
12R		
13R		
14R		
15R	15R-CC	NN15
16R	16R-CC	NN14
17R		
18R	17R-1, 94-96	
19R		
20R	to	NN13
21R		
22R	23R-2, 95-97	
23R		
24R	24R-3, 95-97 to 25R-1, 89-91	NN12
25R		
26R	25R-CC	
27R	to	NN11
28R	29R-CC	
29R		
30R		
31R		
32R		
33R	32R-CC to 33R-C	Miocene
34R		
35R		
36R	34R-1, 31-33	
37R		
38R		
39R		
40R		
41R		
42R		
43R		
44R	to	NN5
45R		
46R		
47R		
48R		
49R		
50R		
51R		
52R	54R-CC	
53R		
54R		

Figure F4. Changes in Pliocene surface water temperature at Site 1115, based on the relative abundance of *Discoaster brouweri* vs. *Coccolithus pelagicus*. See the **"Appendix,"** p. 9, for sample numbers. Curve inflections to the right indicate warmer water and vice versa. The timescale is from Berggren et al. (1995).

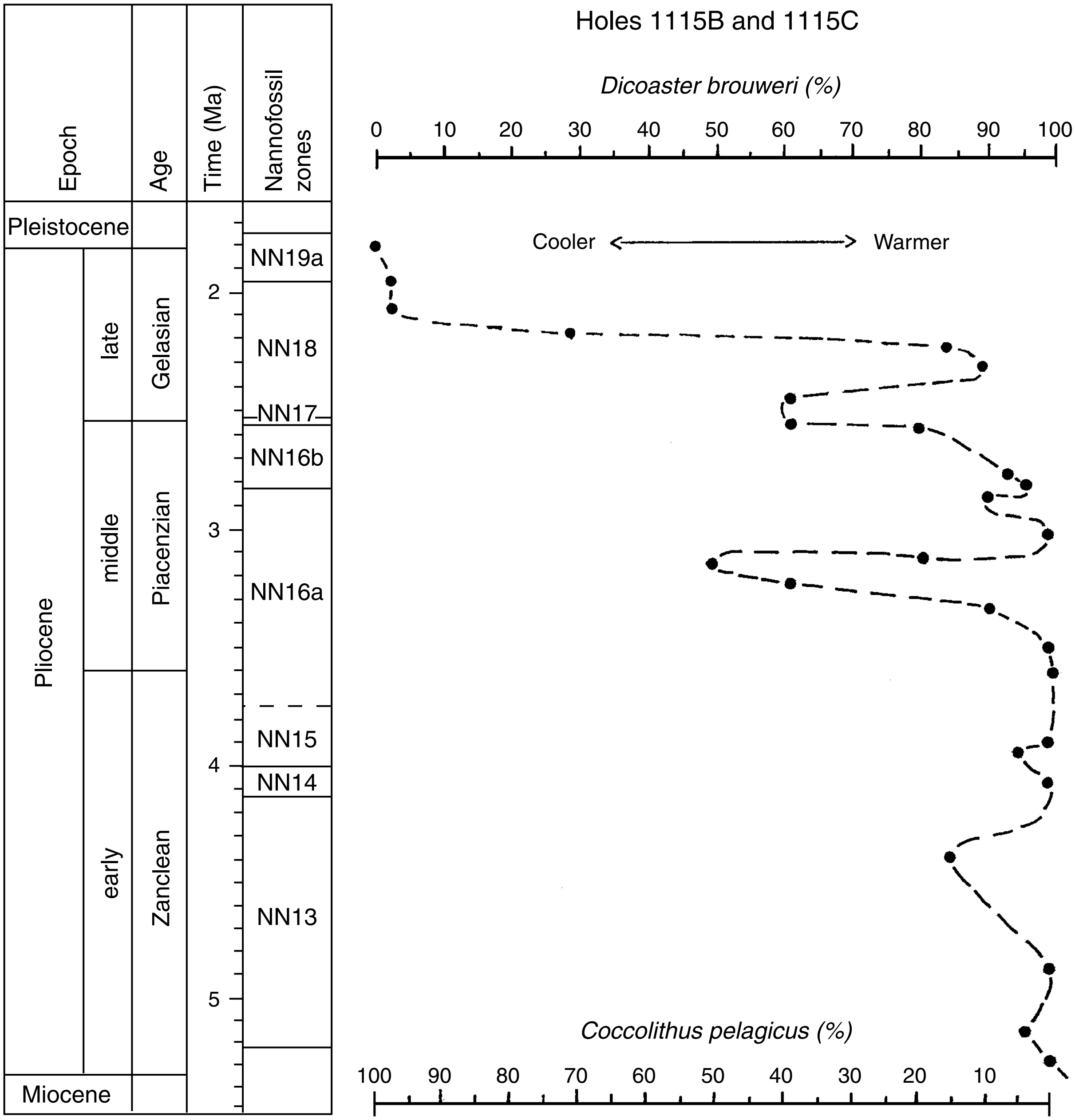

Table T1. Nannofossil, Foraminifer, Magnetochron and $^{40}Ar/^{39}Ar$ Datums, Holes 1115B and 1115C.

Datum event	Depth (mbsf)	Age (Ma)
Top Olduvai	90.5	1.77
Base Olduvai	102.5–103.5	1.95
LAD *Discoaster brouweri*	103.2–106.2	1.95
Top Reunion	118.0	2.14
Base Reunion	119.5	2.15
LAD *Discoaster pentaradiatus*	144.1–147.2	2.52
Gauss/Matuyama boundary	162.0	2.58
FAD *Globorotalia truncatulinoides*	166.2–169.2	2.70
$^{40}Ar/^{39}Ar$	169.3	2.77 ± 0.04
$^{40}Ar/^{39}Ar$	189.6	2.84 ± 0.03
Top Kaena	192.5	3.04
Base Kaena	202.0	3.11
$^{40}Ar/^{39}Ar$	243.4	3.23 ± 0.08
Gilbert/Gauss boundary	386.0–387.0	3.58
FAD *Globorotalia crassaformis*	407.3–412.1	3.80
LCO *Reticulofenestra pseudoumbilicus*	428.7–439.0	3.94
LAD *Discoaster quinqueramus*	514.3–516.4	5.54

Notes: LAD = last appearance datum, FAD = first appearance datum, LCO = last common occurrence.

CHAPTER NOTES*

N1. 19 February 2002—Lackschewitz, K., Bogaard, P.V.D., and Mertz, D.F., 2001. $^{40}Ar/^{39}Ar$ ages of fallout tephra layers and volcaniclastic deposits in the sedimentary succession of the western Woodlark Basin, Papua New Guinea: the marine record of Miocene–Pleistocene volcanism. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: Evidence from Land and Sea,* Spec. Publ.—Geol. Soc. London, 187:373–388.

N2. 19 February 2002—Resig, J.M., Frost, G.M., Ishikawa, N., and Perembo, R.C.B., 2001. Micropaleontologic and paleomagnetic approaches to stratigraphic anomalies in rift basins: ODP Site 1109, Woodlark Basin. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: Evidence from Land and Sea,* Spec. Publ.—Geol. Soc. London, 187:389–404.

*Dates reflect file corrections or revisions.