

**Dynamic deepwater circulation in the northwestern Pacific during the Eocene: Evidence from Ocean Drilling Program Site 884 benthic foraminiferal stable isotopes ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ )**

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**Supplementary Information**

Supplementary Tables 1 and 2 and Supplementary Figure 1 show the details of the site-specific paleomagnetic-based age model used to determine the age of calcareous nannofossil datums at Sites 1053, 1090, 689, 1218, and 1219 (see Table 1 and Figure 1 of the main text for locations and paleodepths). Only the biostratigraphic datums reported for Site 884B (Barron et al., 1995) (Table 2), with the exception of HO *Ericsonia formosa*, reported in the Ocean Drilling Program Initial Reports (Shipboard Scientific Party, 1993), were taken into account in the biostratigraphic datum recalibration presented in this study. We recalibrated the age of eight calcareous nannoplankton datums (Table 2, Figure 2, Supplementary Tables 1 and 2, and Supplementary Figure 1). Among these datums, we do not use HO *Isthmolitus recurvus*, HO *Discoaster saipanensis*, or HO *Chiasmolithus grandis* because of the uncertainty in their recalibrated ages:

1) HO *I. recurvus* (677.33 compacted mbsf – compacted meters below seafloor; recalculated age 32.33 Ma – millions of years ago). Among the sites considered in this study, Site 689 is the only site in which this datum was reported (Supplementary Tables 1 and 2 and Supplementary Figure 1). The recalibrated age for this datum (32.33 Ma) is consistent with the range given by Berggren et al. (1995) (31.8-33.1 Ma), but Berggren et al. (1995) noted this datum as one of the most inconsistent datums. Because of this and the lack of additional information for this datum at the sites considered in this study, we do not include HO *I. recurvus* in the final age model for Site 884B.

2) HO *D. saipanensis* (685.05 compacted mbsf; recalculated age 34.89 Ma). This datum is consistent in both the equatorial Pacific (Site 1218; 34.25 Ma) and the sub-Antarctic South Atlantic (Site 1090; 34.08 Ma) (Supplementary Tables 1 and 2, and Supplementary Figure 1) and it is close to the calibration of 34.20 Ma given in Berggren et al. (1995). However, as for HO *D. barbadiensis*, Site 1219 records a much older age for HO *D. saipanensis* (36.32 Ma; Supplementary Tables 1 and 2, and Supplementary Figure 1) compared to Site 1218 (34.25 Ma). This datum is not present at Site 689; however, Berggren et al. (1995) assign an age of 35.4 Ma to this datum for the Southern Ocean. For the Site 884B age model used in this study, we use HO *D. barbadiensis* instead of HO *D. saipanensis* because of the better agreement among the recalculated age of HO *D. barbadiensis* at Sites 1053, 1218, and 1219, even though both HO *D. barbadiensis* and HO *D. saipanensis* are associated with a  $\pm 13.83$  m error at Site 1219 (Supplementary Table 1). We note that if HO *D. saipanensis* were included in our age model, it would make the section at  $\sim 695$  cmbsf an extremely condensed section (or a possible unconformity), supporting the Barron et al. (1995) hypothesis of an unconformity at  $\sim 695$  cmbsf; however, this unconformity was not identified by Pak and Miller (1995) or Hague et al. (2012).

3) HO *C. grandis* (768.63 compacted mbsf; recalculated age 37.43 Ma). This datum is consistent at two different sites (Sites 1218 and 1053; 37.84 and 37.90 Ma, respectively) (Supplementary Tables 1 and 2 and Supplementary Figure 1); however, Site 1219 records a much younger age for HO *C. grandis* (36.55 Ma) (Supplementary Tables 1 and 2, and Supplementary Figure 1). At Site 1219, HO *C. grandis* is associated with a much bigger error ( $\pm 15.12$  m) compared to HO *C. grandis* at Sites 1218 and 1053 ( $\pm 0.21$  m and  $\pm 0.65$  m, respectively) (Supplementary Table 1). The uncertainty in the depth of HO *C. grandis* at Site 1219 might be a good reason not to include the recalculated age of HO *C. grandis* at Site 1219 in our biostratigraphic datum recalibration. However, even if we exclude the recalculated age of HO *C. grandis* at Site 1219, there is still almost  $\sim 1$  million year difference between our recalibrated age at Site 1218 and 1053 (37.9 Ma) and the age as given by Berggren et al. (1995) (37.1 Ma). Because of this difference, this datum is not used in the age model for Site 884B; however, we note that if this datum were included in our age model, the section at  $\sim 769$  cmbsf would have been unconformable, supporting the Barron et al. (1995) hypothesis of an unconformity at  $\sim 769$  cmbsf; however, Pak and Miller (1995) or Hague et al. (2012) did not identify an unconformity in this part of the section.

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SUPPLEMENTARY TABLE 1. COMPLETE BIOSTRATIGRAPHIC DATUM RECALIBRATION FOR OCEAN DRILLING PROGRAM SITES 1053, 1090, 689, 1218, AND 1219.

Ocean Drilling Program Site	Paleomagnetic datum	Depth* (Depth range)	Age (Ma)	Reference	Calcareous nannoplankton datum	Depth* (Depth range)	Reference	Recalculated Age (Ma)
1053A	Top C15n	10.78 (8.95-12.60)	34.66	Ogg and Bardot (2001; reinterpreted by Borrelli et al., 2014)	HO <i>Discoaster barbadiensis</i>	9.80 (9.47-10.12)	Shipboard Scientific Party (1998)	34.57
	Bottom C15n	19.52 (16.84-22.20)	34.94	Ogg and Bardot (2001; reinterpreted by Borrelli et al., 2014)	LO <i>Isthmolithus recurvus</i>	80.73 (75.98-85.47)	Shipboard Scientific Party (1998)	36.18
	Bottom C17n.1n	144.83 (143.23-146.43)	37.47	Ogg and Bardot (2001; reinterpreted by Borrelli et al., 2014)	HO <i>Chiasmolithus grandis</i>	163.23 (162.58-163.88)	Shipboard Scientific Party (1998)	37.90
	Top C17n.2n	148.77 (146.43-151.10)	37.60	Ogg and Bardot (2001; reinterpreted by Borrelli et al., 2014)				
	Bottom C17n.2n	160.41 (160.00-160.82)	37.85	Ogg and Bardot (2001; reinterpreted by Borrelli et al., 2014)				
	Top C17n.3n	164.43 (160.82-168.03)	37.92	Ogg and Bardot (2001; reinterpreted by Borrelli et al., 2014)				
1090	C13r (.14)	247.88 (not provided)	33.70 <sup>+</sup>	Channell et al. (2003)	HO <i>Reticulofenestra umbilicus</i>	221.14 (not provided)	Channell et al. (2003)	Hiatus
	Top C15n	284.00 (not provided)	34.66	Channell et al. (2003)	HO <i>I. recurvus</i>	221.89 (not provided)	Channell et al. (2003)	Hiatus
	Bottom C15n	287.00 (not provided)	34.94	Channell et al. (2003)	HO <i>Ericsonia formosa</i>	221.89 (not provided)	Channell et al. (2003)	Hiatus
	Top C16n.1n	289.00 (not provided)	35.34	Channell et al. (2003)	HO <i>D. saipanensis</i>	262.39 (not provided)	Channell et al. (2003)	34.08
	Bottom C16n.1n	293.50 (not provided)	35.53	Channell et al. (2003)	LO <i>I. recurvus</i>	304.51 (not provided)	Channell et al. (2003)	36.11
	Top C16n.2n	296.00 (not provided)	35.69	Channell et al. (2003)				
	Bottom C16n.2n	309.00 (not provided)	36.34	Channell et al. (2003)				
	Top C17n.1n	319.80 (not provided)	36.62	Channell et al. (2003)				
	Bottom C17n.1n	340.00 (not provided)	37.47	Channell et al. (2003)				

	Top C17n.2n	342.00 (not provided)	37.60	Channell et al. (2003)				
	Bottom C17n.2n	343.50 (not provided)	37.85	Channell et al. (2003)				
	Top C17n.3n	345.00 (not provided)	37.92	Channell et al. (2003)				
689 (Hole B/ Hole D)	<i>Top C12n</i>	104.50 (not provided)	30.48	Florindo and Roberts (2005)	HO <i>R. umbilicus</i>	106.54 (105.79-107.20)	Florindo and Roberts (2005)	31.23
	<i>Bottom C12n</i>	104.90 (not provided)	30.94	Florindo and Roberts (2005)	HO <i>I. recurvus</i>	112.65 (111.90-113.40)	Florindo and Roberts (2005)	32.33
	<i>Top C13n</i>	116.70 (not provided)	33.06	Florindo and Roberts (2005)	LO <i>I. recurvus</i>	132.40 (131.90-132.90)	Florindo and Roberts (2005)	36.04
	<i>Bottom C13n</i>	120.20 (not provided)	33.55	Florindo and Roberts (2005)	HO <i>C. solitus</i>	153.14 (152.39-153.89)	Florindo and Roberts (2005)	39.11
	Top C15n	124.10 (not provided)	34.66	Florindo and Roberts (2005)				
	Bottom C15n	124.80 (not provided)	34.94	Florindo and Roberts (2005)				
	Top C16n.1n	128.25 (not provided)	35.34	Florindo and Roberts (2005)				
	Bottom C16n.2n	134.20 (not provided)	36.34	Florindo and Roberts (2005)				
	Top C17n.1n	135.50 (not provided)	36.62	Florindo and Roberts (2005)				
	Bottom C17n.1n	144.40 (not provided)	37.47	Florindo and Roberts (2005)				
	Top C18n.1n	145.60 (not provided)	38.43	Florindo and Roberts (2005)				
	MECO	162.86 (not provided)	40.00	minimum $\delta^{18}\text{O}$ adjusted to 40 Ma				
1218	Top C12n	200.40 (199.05-201.75)	30.48	Pälike et al. (2005)	HO <i>R. umbilicus</i>	220.85 (220.47-221.23)	Pälike et al. (2005)	32.11
	Bottom C12n	204.67 (204.54-204.80)	30.94	Pälike et al. (2005)	HO <i>E. formosa</i>	231.91 (231.72-232.09)	Pälike et al. (2005)	32.91

Top C13n	233.88 (from Site 1219)	33.06	Pälike et al. (2005)	HO <i>D. saipanensis</i>	244.57 (244.51-244.62)	Pälike et al. (2005)	34.25
Bottom C13n	240.29 (from Site 1219)	33.55	Pälike et al. (2005)	HO <i>D. barbadiensis</i>	245.79 (245.66-245.91)	Pälike et al. (2005)	34.46
Top C15n	246.98 (from Site 1219)	34.66	Pälike et al. (2005)	HO <i>C. grandis</i>	260.27 (260.06-260.48)	Pälike et al. (2005)	37.84
Bottom C15n	247.52 (from Site 1219)	34.94	Pälike et al. (2005)	HO <i>C. solitus</i>	277.82 (276.24-279.40)	Pälike et al. (2005)	40.39
Top C16n.1n	247.94 (from Site 1219)	35.34	Pälike et al. (2005)				
Bottom C16n.1n	249.13 (from Site 1219)	35.53	Pälike et al. (2005)				
Top C16n.2n	249.45 (from Site 1219)	35.69	Pälike et al. (2005)				
Bottom C16n.2n	252.99 (from Site 1219)	36.34	Pälike et al. (2005)				
Top C17n.1n	254.64 (from Site 1219)	36.62	Pälike et al. (2005)				
Bottom C17n.1n	258.40 (from Site 1219)	37.47	Pälike et al. (2005)				
Top C17n.2n	259.35 (from Site 1219)	37.60	Pälike et al. (2005)				
Bottom C17n.2n	260.30 (from Site 1219)	37.85	Pälike et al. (2005)				
Top C17n.3n	260.57 (from Site 1219)	37.92	Pälike et al. (2005)				
Bottom C17n.3n	261.43 (from Site 1219)	38.11	Pälike et al. (2005)				
Top C18n.1n	262.67 (from Site 1219)	38.43	Pälike et al. (2005)				
Bottom C18n.1n	269.97 (from Site 1219)	39.55	Pälike et al. (2005)				
Top C18n.2n	270.34 (from Site 1219)	39.63	Pälike et al. (2005)				
Bottom C18n.2n	273.85 (from Site 1219)	40.13	Pälike et al. (2005)				
Top C19n	291.08 (from Site 1219)	41.26	Pälike et al. (2005)				

1219	Bottom C19n	293.38 (from Site 1219)	41.52	Pälike et al. (2005)	HO <i>R. umbilicus</i>	156.98 (156.88-157.08)	Pälike et al. (2005)	32.04
	Top C12n	138.45 (137.85-139.05)	30.48	Pälike et al. (2005)	HO <i>E. formosa</i>	167.23 (166.45-168.00)	Pälike et al. (2005)	32.85
	Bottom C12n	143.03 (142.80-143.25)	30.94	Pälike et al. (2005)	HO <i>D. saipanensis</i>	187.22 (173.39-201.04)	Pälike et al. (2005)	36.32
	Top C13n	169.80	33.06	Pälike et al. (2005)	HO <i>D. barbadiensis</i>	187.22 (173.39-201.04)	Pälike et al. (2005)	36.32
	Bottom C13n	173.36	33.55	Pälike et al. (2005)	HO <i>C. grandis</i>	188.51 (173.39-203.63)	Pälike et al. (2005)	36.55
	Top C15n	179.96	34.66	Pälike et al. (2005)				
	Bottom C15n	180.56	34.94	Pälike et al. (2005)				
	Top C16n.1n	181.08	35.34	Pälike et al. (2005)				
	Bottom C16n.1n	182.56	35.53	Pälike et al. (2005)				
	Top C16n.2n	182.96	35.69	Pälike et al. (2005)				
	Bottom C16n.2n	187.36	36.34	Pälike et al. (2005)				
	Top C17n.1n	188.86	36.62	Pälike et al. (2005)				
	Bottom C17n.1n	193.94 (193.89-193.99)	37.47	Pälike et al. (2005)				
	Top C17n.2n	194.89 (194.96-195.09)	37.60	Pälike et al. (2005)				
	Bottom C17n.2n	196.09 (195.84-196.34)	37.85	Pälike et al. (2005)				
	Top C17n.3n	196.44 (196.29-196.59)	37.92	Pälike et al. (2005)				
	Bottom C17n.3n	197.49 (197.29-197.69)	38.11	Pälike et al. (2005)				
	Top C18n.1n	198.97 (198.96-199.24)	38.43	Pälike et al. (2005)				
	Bottom C18n.1n	207.00 (206.87-207.12)	39.55	Pälike et al. (2005)				

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Top C18n.2n	207.47 (207.37-207.57)	39.63	Pälike et al. (2005)
Bottom C18n.2n	211.50 (211.27-211.72)	40.13	Pälike et al. (2005)
Top C19n	224.37 (224.09-224.64)	41.26	Pälike et al. (2005)
Bottom C19n	226.04 (225.89-226.19)	41.52	Pälike et al. (2005)
Top C20n	232.29 (232.19-232.39)	42.54	Pälike et al. (2005)
Bottom C20n	244.12 (243.64-244.59)	43.79	Pälike et al. (2005)

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*Note:* The biostratigraphic datum recalibration is based on a site-specific paleomagnetic-based age model. Paleomagnetic ages are from Cande and Kent (1995). HO=highest occurrence; LO=lowest occurrence; C=chron; MECO=middle Eocene climatic optimum. See Figure 1 and Table 1 for locations and paleodepths, the main text, and the Supplementary information for additional details. The notation "Not provided" is used when the depth range was not noted in the reference used. The notation "from Site 1219" refers to the identification of equivalent levels at Site 1218 for polarity transitions identified at Site 1219.

\* Datum depths: compacted meters below seafloor for Site 1053, meters composite depth for Site 1090, meters below seafloor for Site 689, and revised meters composite depth for Sites 1218 and 1219.

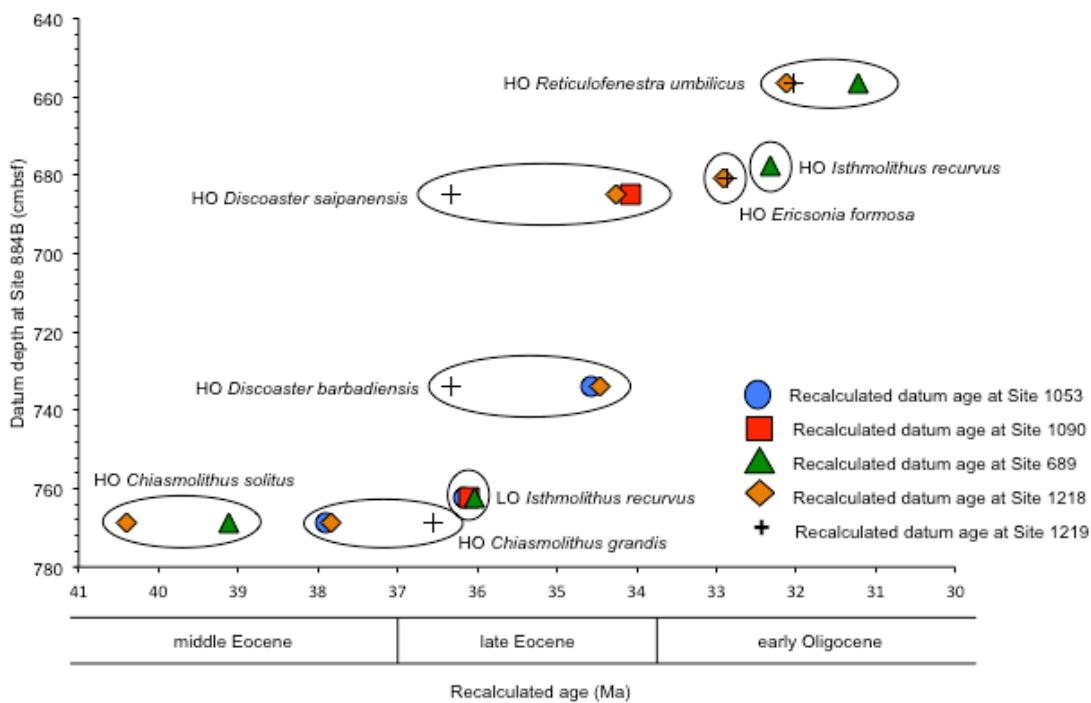
<sup>†</sup>Estimated age based on the estimated depth of the Eocene/Oligocene boundary at Site 1090.

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SUPPLEMENTARY TABLE 2. SUMMARY OF RECALCULATED AGES FOR THE BIOSTRATIGRAPHIC DATUMS FROM OCEAN DRILLING PROGRAM SITE 884.

Ocean Drilling Program Site	<i>Reticulofenestra umbilicus</i> (HO)	<i>Isthmolithus recurvus</i> (HO)	<i>Ericsonia formosa</i> (HO)	<i>Discoaster saipanensis</i> (HO)	<i>D. barbadiensis</i> (HO)	<i>I. recurvus</i> (LO)	<i>Chiasmolithus grandis</i> (HO)	<i>C. solitus</i> (HO)
Site 1053					34.57	36.18	37.90	
Site 1090				34.08		36.11		
Site 689	31.23	32.33				36.04		39.11
Site 1218	32.11		32.91	34.25	34.46		37.84	40.39
Site 1219	32.04		32.85	36.32	36.32		36.55	
Recalculated age	31.80	32.33	32.88	34.89	35.12	36.11	37.43	39.75

*Note:* Ages are in Ma. HO=highest occurrence; LO=lowest occurrence. The recalculated age for each biostratigraphic datum is the average of the ages for the biostratigraphic datum at Sites 1053, 1090, 689, 1218, and 1219. We calculate the ages of the biostratigraphic datums at these sites using a site-specific paleomagnetic-based age model. See Figure 1 and Table 1 for locations and paleodepths, text, Supplementary Figure 1, and Supplementary information for additional details.



Supplementary Figure 1. HO=highest occurrence; LO=lowest occurrence; cmbsf=compacted meters below seafloor. Complete biostratigraphic datum recalibration for Ocean Drilling Program Sites 1053, 1090, 689, 1218, and 1219. The age of each biostratigraphic datum at each site is compared to the depth of the datum at Site 884B. The age recalibration is based on a site-specific paleomagnetic-based age model. See Figure 1 and Table 1 for locations and paleodepths, the main text, and the Supplementary Information for additional details.