# *Supplemental Materials* for Convection of North Pacific Deep Water During the Early Cenozoic

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## Paleoceanographic Application of Nd Isotopes

The Nd isotopic composition of seawater, expressed as $\varepsilon_{Nd}$, (the $^{143}Nd/^{144}Nd$ value of a geologic sample normalized to the bulk earth (DePaolo and Wasserburg, 1976)), varies on a basin-scale as well as within individual ocean basins (e.g., Piepgras and Wasserburg, 1987; Piepgras and Jacobsen, 1988; Jeandel, 1993; Jeandel et al., 1998; Amakawa et al., 2000). Surface seawater $\varepsilon_{Nd}$ variations result from differences in weathering of subaerially exposed rocks that drain into a given ocean basin (Goldstein and Jacobsen, 1988). Intermediate- and deep-water masses acquire the isotopic composition of the surface waters in the region of subduction or downwelling (Goldstein and Jacobsen, 1988; Elderfield et al., 1990; Halliday et al., 1992; Sholkovitz, 1993). Subsequently, the initial $\varepsilon_{Nd}$ of a particular water mass may be altered through mixing with other water masses (e.g., Piepgras and Wasserburg, 1982; Piepgras and Wasserburg, 1987; Piepgras and Jacobsen, 1988; Jeandel, 1993; Jeandel et al., 1998; Amakawa et al., 2000) or particle exchange processes (e.g., Lacan and Jeandel, 2001; Siddall et al., 2008); however, provenance information typically is retained because of the short oceanic residence time of Nd (~1000 years; e.g., Tachikawa et al., 1999) relative to oceanic mixing rates (~1500 years; Broecker et al., 1960).

Modern North Atlantic Deep Water (NADW) forms as dense waters from the Nordic Seas ($\varepsilon_{Nd}$ ~-9) flow southward and mix with sinking waters in the Labrador Sea with a surface $\varepsilon_{Nd}$ value as low as ~-26 (Piepgras and Wasserburg, 1987). The resulting water mass has an $\varepsilon_{Nd}$ signature of ~-12 to -13, which can be used to track NADW throughout its deep-sea transit. Modern Southern Ocean waters (both Antarctic Intermediate Water and Antarctic Bottom Water) have a more radiogenic signature than NADW, derived from the mixing of NADW with Pacific waters flowing eastward through the Drake Passage within the Circumpolar current (Piepgras and Wasserburg, 1982). Thus Antarctic waters have an $\varepsilon_{Nd}$ value of ~-9 (Piepgras and Wasserburg, 1982).

The most radiogenic $\varepsilon_{Nd}$ values in the modern oceans occur in the surface waters of the North and South Pacific, which have a characteristically radiogenic signature of ~0 to –4 (Piepgras and Wasserburg, 1982; Piepgras and Jacobsen, 1988; Shimizu et al., 1994). This reflects the average fluvial input to the Pacific of –2.9 to –3.7 (Goldstein and Jacobsen, 1988). But depth profiles of Nd isotopic composition indicate considerable stratification of South Pacific waters compared to the North Pacific. Analyses from the South Pacific indicate very radiogenic surface waters of $\varepsilon_{Nd}$ ~0 underlain by lower $\varepsilon_{Nd}$ values of ~-8 at 4500 m water depth (Piepgras and Wasserburg, 1982). The more negative bottom water signature reflects the northward flow of Antarctic bottom waters into the Pacific (Piepgras and Jacobsen, 1988).

North Pacific depth profiles of Nd isotopic composition differ from those in the South Pacific. While there is a slight trend toward more negative values at depth, much less stratification of $\varepsilon_{Nd}$ values is evident in North Pacific profiles despite the existence of distinct intermediate, deep, and bottom water masses (e.g., Talley, 1993; Tomczak and

Godfrey, 1994). Overall slow deep-water renewal in the North Pacific enables vertical exchange of Nd from Pacific surface waters to overprint the northward advecting Circumpolar Deep-water signal (e.g., Piepgras and Wasserburg, 1982), resulting in relatively radiogenic deep-waters in spite of the absence of large-scale convection in the North Pacific. Some transfer of radiogenic Nd to the deeper portions of the Pacific also results from formation of North Pacific Intermediate Water (e.g., Talley, 1993).

The teeth and bones of fossil fish are useful for paleo-Nd investigations because of their relatively high Nd concentrations (100-1000 ppm) (e.g., Wright et al., 1984; Shaw and Wasserburg, 1985; Staudigel et al., 1985), as well as their resistance to dissolution in corrosive bottom waters. In addition, they are present, albeit rare, in most deep-sea sedimentary sections, providing the opportunity for widespread geographic and stratigraphic coverage within a well-dated biostratigraphic framework. Fish debris acquires enhanced Nd concentrations through post-mortem trapping at the sediment/water interface (e.g., Staudigel et al., 1985; Reynard et al., 1999). Rare earth elements (REEs) are pre-concentrated by settling organic and oxyhydroxide particles, and trapping by fish debris is accomplished via adsorption and substitution on the sea floor (e.g., Reynard et al., 1999). Thus the fossil material records the Nd isotopic composition of oceanic deep and bottom waters (e.g., Wright et al., 1984; Shaw and Wasserburg, 1985; Staudigel et al., 1985; Martin and Haley, 2000; Martin and Scher, 2004; Thomas, 2005). Fish bones record and preserve the same signal as fish teeth (Thomas and Via, 2007).

**<u>Age Models</u>**

Age models were constructed for each site using the most recently published biostratigraphic datums, and linearly interpolating between the closest occurring datums. In most cases the most recently reported datums derive from the shipboard analyses published in the Initial Reports volumes for each site. Sources of the published datums and applied numeric ages from timescales are listed in Supplemental Materials Table DR1. We applied the average of the depths and/or ages when multiple datums with different ages were identified in the same stratigraphic interval. Below we detail the specifics of the age models constructed for each site.

**Site 192 (Hole 192A):** We used the DSDP Leg 19 shipboard nannofossil datums (Creager et al., 1973) and assigned numeric ages from Gradstein et al. (2004).

**Site 464:** Essentially no biostratigraphic age control exists for the clay interval investigated from Site 464 (Thiede et al., 1981). Thus we used the highest datum below the base of the clay interval and the lowest datum above the top of the clay interval as the primary age control tie points. The shipboard party assigned an age of 75 Ma to the base of the brown clay at the bottom of Core 10, 89.00 mbsf (Thiede et al., 1981). The upper tie point was particularly problematic. The first occurrence of the radiolarian *S. pentas* (32.00 mbsf, 2.80 Ma) is the lowest biostratigraphic datum above the top of the clay interval, and Thiede et al. (1981) assign the bottom of Section 4 (32.00 mbsf) as the base of the *S. pentas* zone. Theyer and Hammond (1974) list the base of *S. pentas* and *Stichocorys peregrina* as the same zonal boundary, hence age, and Gradstein et al. (2004) assigned the LO of *Stichocorys peregrina* an age of 2.8 Ma. Thus the most easily identifiable upper datum was the LO of *S. pentas* (32.0 mbsf, 2.8 Ma). However, linear interpolation between the 32.0 and 89.0 mbsf resulted in ages too young throughout the entire section (i.e., no sample older than late Paleocene) conflicting with the ichthyolith stratigraphy (Doyle and Riedel, 1981), which nominally identified the K/Pg boundary within Core 8 (between sections 8-2 and 9-1). It is not possible to convert the ichthyolith "datums" directly to accurate ages due to the low sampling resolution as well as the coarse age resolution of the biostratigraphy itself. Arbitrarily assigning numerical ages and specific subseafloor depths to the "datums" is just as imprecise as linear interpolation between only three datums. Thus we included a middle datum (50.00 mbsf, 55.80 Ma) based on the most precisely identified ichthyolith age. The middle datum was assigned using the Paleocene-Eocene boundary age from Gradstein et al. (2004) and by splitting the depth difference between the base of Doyle and Riedel (1981) 6-5, 74-80 sample and the top of the 7-1, 70-77 sample. This resulted in a distribution of ages throughout the section consistent with the qualitative age assignments of Doyle and Riedel (1981).

**Site 465 (Hole 465 and 465A):** Biostratigraphic datums were not published for this site, however, sub-bottom depths and ages were published in the initial reports (Rea and Harrsch, 1981). As more than one sample depth was listed with 57.0 and 58.0 Ma, the depths were averaged for that age.

**Site 883 (Hole 883B)**: We applied calcareous nannofossil datums published in the Leg 145 Initial Reports (Rea et al., 1993) for the Site 883 age model. We applied the numerical age from Gradstein et al. (2004) to the mean of the depth range reported in Rea et al. (1993).

**Site 884 (Hole 884B)**: We assigned ages using Gradstein et al. (2004) to the mean stratigraphic position of calcareous nannofossil datums published in the Leg 145 Initial Reports (Rea et al., 1993). Gradstein et al. (2004) does not assign an age for the LO of *Discoaster saipanensis*, however the age of LO of *Discoaster barbadiensis* from Gradstein et al. (2004) was used for the LO of *Discoaster saipanensis*, as they have the same extinction age.

**Site 1208 (Hole 1208A)**: We used the detailed calcareous nannofossil datums reported in Bralower et al. (2002) for Core 36, and assigned numeric ages from the Gradstein et al. (2004). We omitted the LO *Discoaster barbadiensis*, LO *Chiasmolithus grandis* and FO *Reticulofenestra umbilicus* from the age model, as a hiatus apparently disrupted the stratigraphic sequence of these datums at Site 1208.

**Table DR1**. The datums, ages and sources of the datums used to construct the age model for each new site presented in this study.

**DSDP Hole 192A**

| Specified Sample Interval | Depth (mbsf) | Datum | Datum Source | Age (Ma) | Time Scale |
|---|---|---|---|---|---|
| top Core 1 | 942.00 | top NP 22 | Creager et al. (1973) | 32.40 | Gradstein et al. (2004) |
| base Core 1 | 951.00 | base NP 19 | Creager et al. (1973) | 36.20 | Gradstein et al. (2004) |

| | | | | | |
|---|---|---|---|---|---|
| top Core 2 | 951.00 | top NP 18 | Creager et al. (1973) | 36.20 | Gradstein et al. (2004) |
| base Core 3 | 989.00 | base NP 17 | Creager et al. (1973) | 39.60 | Gradstein et al. (2004) |
| top Core 4 | 1018.00 | top NP 14 | Creager et al. (1973) | 46.60 | Gradstein et al. (2004) |
| base Core 4 | 1027.00 | base NP 12 | Creager et al. (1973) | 52.60 | Gradstein et al. (2004) |

**DSDP Site 464**

| Specified Sample Interval | Depth (mbsf) | Datum | Datum Source | Age (Ma) | Time Scale |
|---|---|---|---|---|---|
| base Core 4 | 32.00 | *S. pentas* | Thiede et al. (1981) | 2.80 | Gradstein et al. (2004) |
| base Core 6 | 50.00 | Paleocene/Eocene | Doyle and Riedel (1981) | 55.80 | Gradstein et al. (2004) |
| base Core 10 | 89.00 | oldest brown clay | Thiede et al. (1981) | 75.00 | Thiede et al. (1981) |

**DSDP Site 465**

| Specified Sample Interval | Depth (mbsf) | Datum | Datum Source | Age (Ma) | Time Scale |
|---|---|---|---|---|---|
| 465, 1-1, 76-78 | 0.77 | n/a | Rea and Harrsch (1981) | 1.00 | Rea and Harrsch (1981) |
| 465, 2-2, 64-68 | 3.15 | n/a | Rea and Harrsch (1981) | 2.50 | Rea and Harrsch (1981) |
| 465, 2-5, 64-66 | 7.65 | n/a | Rea and Harrsch (1981) | 4.00 | Rea and Harrsch (1981) |
| 465, 3-1, 60-62 | 11.11 | n/a | Rea and Harrsch (1981) | 55.00 | Rea and Harrsch (1981) |
| 465, 3-3, 60-62 | 14.11 | n/a | Rea and Harrsch (1981) | 56.00 | Rea and Harrsch (1981) |
| 465, 4-2, 48-50 | 21.99 | n/a | Rea and Harrsch (1981) | 57.00 | Rea and Harrsch (1981) |
| 465, 4-4, 48-50 | 24.99 | n/a | Rea and Harrsch (1981) | 57.00 | Rea and Harrsch (1981) |
| 465, 5-2, 95-97 | 31.96 | n/a | Rea and Harrsch (1981) | 57.00 | Rea and Harrsch (1981) |
| 465, 5-5, 95-97 | 36.46 | n/a | Rea and Harrsch (1981) | 58.00 | Rea and Harrsch (1981) |
| 465, 6-2, 28-30 | 40.79 | n/a | Rea and Harrsch (1981) | 58.00 | Rea and Harrsch (1981) |
| 465, 6-4, 28-30 | 43.79 | n/a | Rea and Harrsch (1981) | 59.00 | Rea and Harrsch (1981) |
| 465, 10-2, 30-32 | 78.81 | n/a | Rea and Harrsch (1981) | 65.00 | Rea and Harrsch (1981) |
| 465, 10-5, 30-32 | 83.31 | n/a | Rea and Harrsch (1981) | 66.00 | Rea and Harrsch (1981) |
| 465A, 1-1, 132-134 | 40.33 | n/a | Rea and Harrsch (1981) | 58.00 | Rea and Harrsch (1981) |
| 465A, 3-2, 18-20 | 59.69 | n/a | Rea and Harrsch (1981) | 64.50 | Rea and Harrsch (1981) |
| 465A, 3-5, 18-20 | 64.69 | n/a | Rea and Harrsch (1981) | 66.00 | Rea and Harrsch (1981) |

**ODP Hole 883B**

| Specified Sample Interval | Mean Depth (mbsf) | Datum | Datum Source | Age (Ma) | Time Scale |
|---|---|---|---|---|---|
| 712.60 - 720.10 mbsf | 716.35 | LO *Discoaster barbadienis* | Rea et al. (1993) | 34.40 | Gradstein et al. (2004) |
| 712.60 - 720.10 mbsf | 716.35 | FO *Isthmolithus recurvus* | Rea et al. (1993) | 36.20 | Gradstein et al. (2004) |
| 729.90 - 739.70 mbsf | 734.80 | LO *Chiasmolithus solitus* | Rea et al. (1993) | 39.80 | Gradstein et al. (2004) |
| 779.20 - 789.20 mbsf | 784.20 | FO *Discoaster sublodoensis* | Rea et al. (1993) | 48.80 | Gradstein et al. (2004) |
| 779.20 - 789.20 mbsf | 784.20 | LO *Tribrachiatus orthostylus* | Rea et al. (1993) | 51.20 | Gradstein et al. (2004) |
| 813.40 - 814.70 mbsf | 814.05 | FO *Discoaster lodoensis* | Rea et al. (1993) | 52.60 | Gradstein et al. (2004) |
| 814.70 - 828.10 mbsf | 821.40 | FO *Discoaster mohleri* | Rea et al. (1993) | 58.40 | Gradstein et al. (2004) |
| 814.70 - 828.10 mbsf | 821.40 | FO *Heliolithus kleinpellii* | Rea et al. (1993) | 59.40 | Gradstein et al. (2004) |

**ODP Hole 884B**

| Specified Sample Interval | Mean Depth (mbsf) | Datum | Datum Source | Age (Ma) | Time Scale |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| 680.60 - 681.10 mbsf | 680.85 | LO *Ericsonia formosa* | Rea et al. (1993) | 33.00 | Gradstein et al. (2004) |
| 690.20 - 699.80 mbsf | 695.00 | LO *Discoaster saipanensis* | Rea et al. (1993) | 34.40 | Gradstein et al. (2004) |
| 757.70 - 767.40 mbsf | 762.55 | FO *Isthmolithus recurvus* | Rea et al. (1993) | 36.20 | Gradstein et al. (2004) |

**ODP Hole 1208A**

| Specified Sample Interval | Depth (mbsf) | Datum | Datum Source | Age (Ma) | Time Scale |
|---|---|---|---|---|---|
| 1208A, 35-5, 10 - 50cm | 321.10 | LO *Reticulofenestra umbilicus* | Bralower et al. (2002) | 32.40 | Gradstein et al. (2004) |
| 1208A, 36-2, 45cm | 326.80 | LO *Tribrachiatus orthostylus* | Bralower et al. (2002) | 51.20 | Gradstein et al. (2004) |
| 1208A, 36-2, 80cm | 327.30 | FO *Discoaster lodoensis* | Bralower et al. (2002) | 52.60 | Gradstein et al. (2004) |
| 1208A, 36-CC, 14cm | 327.60 | FO *Discoaster multiradiatus* | Bralower et al. (2002) | 57.00 | Gradstein et al. (2004) |
| 1208A, 39-CC - 40-CC | 366.10 | FO *Ceratolithoides aculeus* | Bralower et al. (2002) | 79.00 | Gradstein et al. (2004) |

## Analytical Methods

We disaggregated bulk sediment samples in a dilute sodium metaphospate solution and then washed the slurry through a >63 micron sieve. Fish teeth and bones (hereafter referred to as fish debris) were handpicked from the washed samples. Typically we picked ~40-50 pieces of fish debris depending upon the size and abundance in the sample. Traditionally, the Boyle oxidative/reductive cleaning protocol has been used to remove any oxide coating and residual organic matter from the fish debris prior to dissolution (Boyle, 1981; Boyle and Keigwin, 1985). A growing body of work indicates that the oxides coating sediment particles record the Nd isotopic composition of the waters bathing the seafloor (e.g., Martin et al., 2010; Roberts et al., 2010), and this is the same signal recorded by biogenic apatite after early diagenesis.

We compared a subset of “cleaned” versus “un-cleaned” fish debris (identified as “C” and “UC” respectfully). We analyzed two splits from at least two samples at each site (one that underwent the rigorous Boyle oxidative/reductive cleaning step “C” and one that underwent two rinses in ethanol and two rinses in ultrapure (Milli-Q) water “UC” to remove any adhering debris. Results of the comparison indicate that the cleaned and uncleaned samples record the same value (Table DR2). The difference between $\varepsilon_{Nd}(t)$

values for paired cleaned and uncleaned samples ranges from 0.03 to 0.53 epsilon units, with an average difference of 0.15. In addition to the small difference between the cleaned and uncleaned fish debris, there was no systematic offset between the two (i.e., cleaned values were not consistently higher or lower than the uncleaned values). The average difference between cleaned and uncleaned splits (0.15 epsilon units) is comparable to the external analytical precision (12ppm or ~0.24 epsilon units, 2$\sigma$), and to replicate analyses of similarly prepared samples. Based on these results we eliminated the reductive/oxidative cleaning step from the remainder of the samples and interpret the data from both cleaned and uncleaned samples as the ancient water mass composition. For sample intervals with C and UC analyses (as well as replicates) we used the average of the multiple splits for the time-series.

**Table DR2**. Paired analyses of cleaned and uncleaned fish debris.

| Sample | Cleaned $\varepsilon_{Nd}(t)$ | Uncleaned $\varepsilon_{Nd}(t)$ |
|---|---|---|
| 192A, 1-1, 52-55 | -3.5 | -3.6 |
| 192A, 2-1, 66-68 | -3.1 | -3.4 |
| 464, 6-2, 97-99 | -3.1 | -3.0 |
| 464, 6-6, 64-66 | -1.3 | -1.9 |
| 464, 7-1, 50-52 | -2.0 | -2.1 |
| 464, 7-3, 137-139 | -0.8 | -0.6 |
| 464, 9-6, 85-87 | -5.5 | -5.6 |
| 465, 2-1, 122-124 | -3.8 | -3.6 |
| 465, 5-5, 100-102 | -2.9 | -2.9 |
| 465A, 3-1, 25-27 | -3.9 | -3.8 |
| 465A, 3-2, 37-39 | -4.0 | -3.7 |
| 883B, 83-2, 75-77 | -2.1 | -1.9 |
| 883B, 84-1, 75-77 | -1.9 | -1.9 |
| 884B, 74-5, 80-82 | -1.7 | -1.9 |
| 884B, 75-6, 45-47 | -2.4 | -2.5 |
| 1208A, 36-2, 15-17 | -4.5 | -4.6 |
| 1208A, 36-2, 28-30 | -4.5 | -4.4 |

After removing the detrital material, the fish debris was dissolved and processed through RE Spec cation exchange chemistry to isolate the bulk REE, followed by methyllactic acid chemistry to chromatographically separate Nd from the rest of the REE. Finally, we loaded samples in 2N HCl on a (Re) filament and analyzed the Nd isotopic composition as Nd+ using double filaments (sample loaded only on the evaporation filament). Replicate samples, at least two from each site, were analyzed to verify that the Nd values are reproducible. Replicate analyses of the JNdi standard yield a value of 0.512104 (n = 50 during this study) with an external reproducibility of 12ppm (2σ). The Triton factory accepted value and TAMU Triton measured value for the La Jolla standard is 0.511846, which converts to 0.512104 based on the work of Tanaka et al. (2000). The typical lab blank (column chemistry) is 20 pg and is considered negligible.

A representative set of samples was powdered for detrital silicate analysis (Table DR4). The detrital silicate fraction was chemically isolated from carbonate, biogenic apatite, and the oxide/hydroxide using two procedures: the "HH" procedure using chelated hydroxylamine hydrochloride (.02M in 25% acetic acid chelated with Na-EDTA) modified from Gutjahr et al. (2007), and the "traditional" dust extraction procedure using sodium citrate/sodium dithionite (e.g., Hovan, 1995).

For the "HH" procedure, we decarbonated the samples using 50 ml of 2.7% acetic acid buffered with Na acetate (pH 5) for 2 hours on a shaker table. After carbonate digestion, samples were centrifuged and the supernatant discarded. The leaching procedure was repeated until all carbonate was digested. Following complete digestion, samples were rinsed three times in Milli-Q water. To leach the oxide fraction, we added 14 ml of 0.02M HH solution and allowed the samples to react for 1.5 hours on a shaker table.  After centrifuging, the supernatant was retained and and 40ml of fresh HH solution was added to the samples for the long (24 hour) extraction.  Following the long extraction, samples were centrifuged, the supernatant discarded, and rinsed three times in Milli-Q water.  The residual samples were dried and powdered.

The sodium citrate/dithionite procedure used the same carbonate removal step as described in the "HH procedure" above.  To remove the oxide fraction, we added 20 ml of .3M sodium citrate to each sample, then 2.5 ml of 1M sodium bicarbonate solution.  The tubes were then heated in a water bath for 10-15 minutes.  Then we added ~1g of sodium dithionite to the tubes and stirred.  After reacting for 5 minutes we added hot .15M sodium citrate solution to total 40 ml in the tubes.  Samples were centrifuged, solution decanted, and the extraction procedure was repeated three more times with a hot .3M sodium citrate rinse between extractions #2 and #3.  Following extraction #4, samples were rinsed three times in Milli-Q, dried and powdered.

After extraction the detrital silicate was digested in HF-$HNO_3$ and HCl before separation and analysis as described above.

$\varepsilon_{Nd}(t)$ values were calculated using the numerical ages determined with the age models detailed above. For fish debris, we applied a typical $^{147}Sm/^{144}Nd$ value of 0.13 after Thomas et al. (2008). We adopted the $^{147}Sm/^{144}Nd$ value of 0.109 for determination of the silicate $\varepsilon_{Nd}(t)$ values based on upper crustal average concentrations of Sm and Nd (Taylor and McClennan, 1995).

**Table DR3**. Fish Debris Nd isotopic data generated in this study. Sample id's followed by "C" indicate cleaned samples, and "rep" indicates a replicate uncleaned fish debris sample. The error is 2σ.

| Sample ID | Depth (mbsf) | Age (Ma) | $^{143}Nd/^{144}Nd$ | Error | $\varepsilon_{Nd}(t)$ |
|---|---|---|---|---|---|
| **Hole 192A** | | | | | |
| 1-1, 52-55 C | 942.52 | 32.62 | 0.512443 | 0.000005 | -3.5 |
| 1-1, 52-55 | 942.52 | 32.62 | 0.512440 | 0.000002 | -3.6 |
| 1-3, 51-53 | 945.51 | 33.88 | 0.512435 | 0.000003 | -3.7 |
| 1-5, 18-20 | 948.18 | 35.01 | 0.512422 | 0.000004 | -3.9 |
| 1-5, 18-20 (rep) | 948.18 | 35.01 | 0.512422 | 0.000003 | -3.9 |
| 2-1, 66-68 C | 951.66 | 36.26 | 0.512462 | 0.000003 | -3.1 |
| 2-1, 66-68 | 951.66 | 36.26 | 0.512449 | 0.000005 | -3.4 |
| 2-1, 66-68 (rep) | 951.66 | 36.26 | 0.512456 | 0.000004 | -3.2 |
| 2-6, 57-59 | 959.07 | 36.92 | 0.512516 | 0.000002 | -2.1 |
| 3-2, 52-54 | 985.02 | 39.24 | 0.512491 | 0.000006 | -2.5 |
| 4-2, 92-94 | 1020.42 | 54.22 | 0.512728 | 0.000009 | +2.2 |
| 4-4, 52-54 | 1023.02 | 62.41 | 0.512517 | 0.000003 | -1.9 |
| | | | | | |
| **Site 464** | | | | | |
| 6-1, 57-59 C | 42.08 | 32.48 | 0.512383 | 0.000004 | -4.7 |
| 6-1, 90-92 | 42.40 | 33.42 | 0.512400 | 0.000005 | -4.4 |
| 6-2, 97-99 C | 43.97 | 38.05 | 0.512465 | 0.000005 | -3.1 |
| 6-2, 97-99 | 43.97 | 38.05 | 0.512468 | 0.000003 | -3.0 |
| 6-3, 100-102 | 45.50 | 42.55 | 0.512394 | 0.000004 | -4.4 |
| 6-4, 80-82 | 46.80 | 46.38 | 0.512465 | 0.000003 | -3.0 |
| 6-5, 44-46 C | 47.95 | 49.76 | 0.512453 | 0.000006 | -3.2 |
| 6-5, 105-107 | 48.55 | 51.53 | 0.512463 | 0.000003 | -3.0 |
| 6-6, 64-66 C | 49.64 | 54.74 | 0.512546 | 0.000006 | -1.3 |
| 6-6, 64-66 | 49.64 | 54.74 | 0.512519 | 0.000003 | -1.9 |
| 6-7, 26-28 C | 50.77 | 56.18 | 0.512527 | 0.000005 | -1.7 |
| 7-1, 50-52 C | 51.50 | 56.54 | 0.512513 | 0.000004 | -2.0 |
| 7-1, 50-52 | 51.50 | 56.54 | 0.512504 | 0.000003 | -2.1 |
| 7-1, 125-127 | 52.25 | 56.91 | 0.512526 | 0.000003 | -1.7 |
| 7-2, 60-62 | 53.10 | 57.33 | 0.512599 | 0.000011 | -0.3 |
| 7-2, 100-102 | 53.50 | 57.52 | 0.512554 | 0.000003 | -1.2 |
| 7-3, 137-139 C | 55.37 | 58.44 | 0.512576 | 0.000007 | -0.7 |
| 7-3, 137-139 | 55.37 | 58.44 | 0.512581 | 0.000016 | -0.6 |
| 7-3, 137-139 (rep) | 55.37 | 58.44 | 0.512579 | 0.000008 | -0.7 |
| 7-4, 70-72 | 56.20 | 58.85 | 0.512583 | 0.000006 | -0.6 |
| 7-5, 125-127 | 58.25 | 59.86 | 0.512612 | 0.000006 | 0.0 |
| 7-6, 120-122 | 59.70 | 60.58 | 0.512554 | 0.000003 | -1.1 |
| 8-2, 70-72 | 62.02 | 61.72 | 0.512527 | 0.000004 | -1.6 |

| | | | | | |
|---|---|---|---|---|---|
| 8-2, 84-86 | 62.16 | 61.79 | 0.512545 | 0.000003 | -1.3 |
| 9-1, 4-6 | 70.04 | 65.67 | 0.512373 | 0.000001 | -4.6 |
| 9-1, 95-97 | 70.95 | 66.11 | 0.512371 | 0.000002 | -4.7 |
| 9-4, 92-94 | 71.95 | 66.61 | 0.512367 | 0.000002 | -4.7 |
| 9-6, 46-48 | 73.86 | 67.55 | 0.512342 | 0.000004 | -5.2 |
| 9-6, 85-87 C | 74.25 | 67.74 | 0.512328 | 0.000015 | -5.5 |
| 9-6, 85-87 | 74.25 | 67.74 | 0.512322 | 0.000012 | -5.6 |
| 9-6, 85-87 (rep) | 74.25 | 67.74 | 0.512345 | 0.000003 | -5.1 |
| **Hole 465** | | | | | |
| 3-1, 100-102 | 11.50 | 55.13 | 0.512471 | 0.000005 | -2.8 |
| 4-3, 55-57 | 23.55 | 56.77 | 0.512463 | 0.000006 | -2.9 |
| 5-3, 127-129 | 33.77 | 57.61 | 0.512462 | 0.000004 | -3.0 |
| 5-5, 100-102 C | 36.50 | 57.83 | 0.512465 | 0.000014 | -2.9 |
| 5-5, 100-102 | 36.50 | 57.83 | 0.512463 | 0.000002 | -2.9 |
| 6-5, 78-80 | 45.78 | 59.34 | 0.512451 | 0.000005 | -3.2 |
| 6-5, 78-80 (rep) | 45.78 | 59.34 | 0.512451 | 0.000007 | -3.2 |
| 10-2, 75-77 | 79.25 | 65.10 | 0.512392 | 0.000006 | -4.3 |
| 10-5, 83-85 | 83.28 | 65.99 | 0.512390 | 0.000003 | -4.3 |
| **Hole 465A** | | | | | |
| 3-1, 25-27 C | 58.25 | 64.02 | 0.512411 | 0.000011 | -3.9 |
| 3-1, 25-27 | 58.25 | 64.02 | 0.512416 | 0.000008 | -3.8 |
| 3-1, 76-78 | 58.76 | 64.19 | 0.512428 | 0.000004 | -3.6 |
| 3-1, 76-78 (rep) | 58.76 | 64.19 | 0.512422 | 0.000005 | -3.7 |
| 3-2, 37-39 C | 59.87 | 64.55 | 0.512407 | 0.000011 | -4.0 |
| 3-2, 37-39 | 59.87 | 64.55 | 0.512419 | 0.000005 | -3.7 |
| 3-3, 35-37 | 61.35 | 65.00 | 0.512429 | 0.000007 | -3.5 |
| 3-3, 68-70 | 61.68 | 65.10 | 0.512439 | 0.000005 | -3.3 |
| 3-4, 84-86 | 63.34 | 65.60 | 0.512414 | 0.000002 | -3.8 |
| 3-5, 33-35 | 64.33 | 65.89 | 0.512408 | 0.000002 | -3.9 |
| 3-5, 66-68 | 64.66 | 65.99 | 0.512416 | 0.000006 | -3.8 |
| **Hole 883B** | | | | | |
| 75-2, 20-22 | 714.03 | 34.73 | 0.512475 | 0.000006 | -2.9 |
| 76-1, 52-54 | 720.62 | 36.34 | 0.512534 | 0.000003 | -1.7 |
| 76-5, 94-96 | 727.04 | 37.91 | 0.512486 | 0.000007 | -2.7 |
| 77-1, 31-33 | 730.21 | 38.68 | 0.512502 | 0.000005 | -2.3 |
| 77-4, 50-52 | 734.90 | 39.82 | 0.512504 | 0.000004 | -2.3 |
| 79-2, 20-22 | 751.20 | 43.19 | 0.512506 | 0.000005 | -2.2 |
| 79-3, 65-67 | 753.15 | 43.59 | 0.512502 | 0.000004 | -2.3 |
| 82-1, 60-62 | 779.80 | 49.09 | 0.512521 | 0.000003 | -1.9 |
| 82-1, 60-62 (rep) | 779.80 | 49.09 | 0.512531 | 0.000003 | -1.7 |
| 82-7, 21-23 | 788.41 | 50.37 | 0.512561 | 0.000006 | -1.1 |
| 83-2, 75-77 C | 791.45 | 50.63 | 0.512507 | 0.000005 | -2.1 |

| | | | | | |
|---|---|---|---|---|---|
| 83-2, 75-77 | 791.45 | 50.63 | 0.512517 | 0.000006 | -1.9 |
| 83-2, 75-77 (rep) | 791.45 | 50.63 | 0.512507 | 0.000005 | -2.1 |
| 84-1, 75-77 C | 799.95 | 51.37 | 0.512519 | 0.000005 | -1.9 |
| 84-1, 75-77 | 799.95 | 51.37 | 0.512517 | 0.000004 | -1.9 |
| 85-1, 60-62 | 809.50 | 52.20 | 0.512506 | 0.000004 | -2.1 |
| 85-4, 20-22 | 813.60 | 52.56 | 0.512487 | 0.000003 | -2.5 |
| 86-2, 20-22 | 820.20 | 57.87 | 0.512732 | 0.000004 | +2.3 |
| 86-5, 5-7 | 824.55 | 61.60 | 0.512799 | 0.000003 | +3.7 |
| 87-1, 97-99 | 829.07 | 65.47 | 0.512789 | 0.000003 | +3.5 |
| 87-2, 75-77 | 830.25 | 66.49 | 0.512730 | 0.000004 | +2.4 |
| **Hole 884B** | | | | | |
| 74-5, 80-82 C | 687.40 | 33.65 | 0.512538 | 0.000002 | -1.7 |
| 74-5, 80-82 | 687.40 | 33.65 | 0.512525 | 0.000003 | -1.9 |
| 74-5, 80-82 (rep) | 687.40 | 33.65 | 0.512532 | 0.000004 | -1.8 |
| 75-6, 45-47 C | 698.15 | 34.48 | 0.512501 | 0.000004 | -2.4 |
| 75-6, 45-47 | 698.15 | 34.48 | 0.512495 | 0.000002 | -2.5 |
| 75-6, 45-47 (rep) | 698.15 | 34.48 | 0.512496 | 0.000003 | -2.5 |
| 77-6, 25-27 | 717.25 | 34.99 | 0.512447 | 0.000004 | -3.4 |
| 80-1, 85-87 | 739.25 | 35.58 | 0.512549 | 0.000001 | -1.4 |
| 82-1, 55-57 | 758.25 | 36.09 | 0.512514 | 0.000002 | -2.1 |
| 82-5, 70-72 | 764.40 | 36.25 | 0.512529 | 0.000004 | -1.8 |
| 83-2, 24-26 | 769.14 | 36.38 | 0.512513 | 0.000004 | -2.1 |
| 83-7, 28-30 | 776.03 | 36.56 | 0.512516 | 0.000003 | -2.1 |
| 84-5, 56-58 | 783.56 | 36.76 | 0.512519 | 0.000003 | -2.0 |
| 88-1, 100-102 | 816.60 | 37.64 | 0.512508 | 0.000003 | -2.2 |
| 89-1, 65-67 | 825.75 | 37.88 | 0.512590 | 0.000007 | -0.6 |
| 90-1, 93-95 | 835.53 | 38.14 | 0.512429 | 0.000004 | -3.8 |
| 90-1, 93-95 (rep) | 835.53 | 38.14 | 0.512434 | 0.000003 | -3.7 |
| **Hole 1208A** | | | | | |
| 36-2, 3-5 | 326.43 | 49.77 | 0.512383 | 0.000002 | -4.6 |
| 36-2, 15-17 C | 326.55 | 50.16 | 0.512387 | 0.000004 | -4.5 |
| 36-2, 15-17 | 326.55 | 50.16 | 0.512382 | 0.000004 | -4.6 |
| 36-2, 28-30 C | 326.68 | 50.58 | 0.512386 | 0.000003 | -4.5 |
| 36-2, 28-30 | 326.68 | 50.58 | 0.512393 | 0.000004 | -4.4 |
| 36-2, 46-48 | 326.86 | 51.37 | 0.512442 | 0.000004 | -3.4 |
| 36-2, 46-48 (rep) | 326.86 | 51.37 | 0.512439 | 0.000003 | -3.4 |
| 36-2, 55-57 | 326.95 | 51.62 | 0.512452 | 0.000005 | -3.2 |
| 36-2, 88-90 | 327.28 | 52.54 | 0.512431 | 0.000001 | -3.6 |
| 36-2, 88-90 (rep) | 327.28 | 52.54 | 0.512430 | 0.000008 | -3.6 |
| 36-CC, 20-21 C | 327.61 | 57.01 | 0.512421 | 0.000012 | -3.8 |
| 37-2, 40-42 C | 336.40 | 62.03 | 0.512393 | 0.000018 | -4.3 |
| 38-2, 41-43 C | 346.01 | 67.52 | 0.512406 | 0.000016 | -4.0 |

**Table DR4**. Detrital silicate Nd isotopic data generated in this study. Sample methods labeled "HH" indicate detrital samples isolated using Na-EDTA 0.02M hydroxylamine hydrochloride in 25% acetic acid, and "C/D" indicates silicates extracted using the Sodium Citrate/Sodium Dithionite procedure. The error is 2σ.

| Sample ID | Depth (mbsf) | Age (Ma) | $^{143}Nd/^{144}Nd$ | Error | $\varepsilon_{Nd}(t)$ | Method |
|---|---|---|---|---|---|---|
| **Hole 192A** | | | | | | |
| 1-3, 51-53 | 945.51 | 33.88 | 0.512642 | 0.000007 | 0.4 | HH |
| 4-2, 92-94 | 1020.42 | 54.22 | 0.513014 | 0.000010 | 7.9 | HH |
| **Site 464** | | | | | | |
| 6-1, 90-92 | 42.40 | 33.42 | 0.512162 | 0.000007 | -8.9 | C/D |
| 6-1, 90-92 | 42.40 | 33.42 | 0.512151 | 0.000008 | -9.1 | HH |
| 6-3, 100-102 | 45.50 | 42.55 | 0.512269 | 0.000006 | -6.7 | HH |
| 7-1, 50-52 | 51.50 | 56.54 | 0.512600 | 0.000003 | -0.1 | HH |
| 7-6, 120-122 | 59.70 | 60.58 | 0.512241 | 0.000023 | -7.1 | C/D |
| 9-6, 46-48 | 73.86 | 67.55 | 0.512026 | 0.000004 | -11.2 | C/D |
| **Hole 883B** | | | | | | |
| 77-4, 50-52 | 734.90 | 39.82 | 0.513063 | 0.000009 | 8.7 | HH |
| 78-3, 65-67 | 743.35 | 41.57 | 0.512746 | 0.000006 | 2.6 | HH |
| 83-2, 75-77 | 791.45 | 50.63 | 0.512465 | 0.000002 | -2.8 | HH |
| 85-4, 20-22 | 813.60 | 52.56 | 0.512173 | 0.000006 | -8.5 | HH |
| 86-1, 20-22 | 818.70 | 56.59 | 0.512724 | 0.000003 | 2.3 | HH |
| **Hole 884B** | | | | | | |
| 79-2, 78-80 | 731.08 | 35.36 | 0.512964 | 0.000006 | 6.8 | HH |
| 80-1, 85-87 | 739.25 | 35.58 | 0.512871 | 0.000007 | 5.0 | C/D |
| 90-1, 93-95 | 835.53 | 38.14 | 0.512088 | 0.000005 | -10.3 | HH |
| **Hole 1208A** | | | | | | |
| 36-2, 3-5 | 326.43 | 49.77 | 0.512218 | 0.000002 | -7.6 | C/D |
| 36-2, 28-30 | 326.68 | 50.58 | 0.512376 | 0.000005 | -4.5 | HH |
| 36-2, 28-30 (rep) | 326.68 | 50.58 | 0.512387 | 0.000002 | -4.3 | HH |
| 36-2, 28-30 | 326.68 | 50.58 | 0.512377 | 0.000002 | -4.5 | C/D |
| 36-2, 46-48 | 326.86 | 51.37 | 0.512112 | 0.000005 | -9.8 | C/D |

**Table DR5**. Compilation of published North Pacific Late Cretaceous – early Paleogene Nd isotope data binned into two time intervals: 54-64 Ma and 33-53 Ma. Crust data from Ling et al. (1997), van de Flierdt et al. (2004), and Ling et al. (2005).

| Site/Crust | Latitude | Longitude | Depth (m) | 33-53Ma | 54-64Ma |
|---|---|---|---|---|---|
| 192 | 53°00.57'N | 164°42.81'E | 3014 | -3.2 | 0.2 |
| 464 | 39°51.64'N | 173°53.33'E | 4637 | -3.7 | -1.2 |
| 465 | 33°49.23'N | 178°55.14'E | 2161 | | -3.1 |
| 883 | 51°11.898'N | 167°46.128'E | 2396 | -2.1 | 3.0 |
| 884 | 51°27.026'N | 168°20.228'E | 3826 | -2.2 | |
| 1208 | 36°7.6301´N | 158°12.0952´E | 3346 | -4.0 | -4.0 |
| 1209 | 32°39.1001´N | 158°30.3560´E | 2387 | -3.4 | -3.2 |
| 1211 | 32°0.1300´N | 157°50.9999´E | 2918 | -3.8 | -3.5 |
| 1215 | 26°01.77'N | 147°55.99'W | 5396 | -3.4 | -4.2 |
| 1217 | 16°52.02´N | 138°06.00´W | 5342 | -4.4 | -4.3 |
| 1219 | 7°48.019´N | 142°00.940´W | 5063 | -4.6 | |
| 1221 | 12°01.999´N | 143°41.572´W | 5175 | -4.3 | -4.5 |
| | | | | | |
| D137-01 | 1°08´S | 168°04´W | 7100 | -5.2 | |
| CB12 | 17°59´N | 178°39´E | 2381 | -3.9 | -4.1 |
| CLD01 | 21°45´N | 160°44´E | 2210 | -4.2 | -4.2 |
| CJ01 | 17°59´N | 177°42´W | 3082 | -4.2 | -4.4 |
| VA13/2 | 9°18´N | 146°03´W | 4800 | -4.7 | -4.6 |
| CD29-2 | 16°42´N | 168°14´W | 2300 | -4.7 | -5.2 |
| D11-1 | 11°39´N | 161°41´E | 1800 | -4.2 | -4.5 |

**Background Information Regarding the Model Simulations**

The coupled integration of the NCAR CCSM3 for early Paleogene conditions has been shown to produce reasonable simulations of the cooler parts of the early Paleogene, including the Paleocene (Huber, 2009) and the mid-to-late Eocene (Liu et al., 2009; Ali and Huber, 2010) (Figure DR1). In the simulations, deep water forms primarily in the North and South Pacific and flows through the abyss following the basic physical constraint of conservation of potential vorticity, which establishes a Stommel and Arons (1960) circulation over much of the oceans away from boundaries and substantial topography, and following contours of f/h, where f is the Coriolis parameter and h is the water depth (Andersson and Veronis, 2004) in regions of substantial topography, such as the mid-Pacific ridge (Figure 3). Obvious differences occur in regions of bathymetric variation not captured in the model boundary conditions.

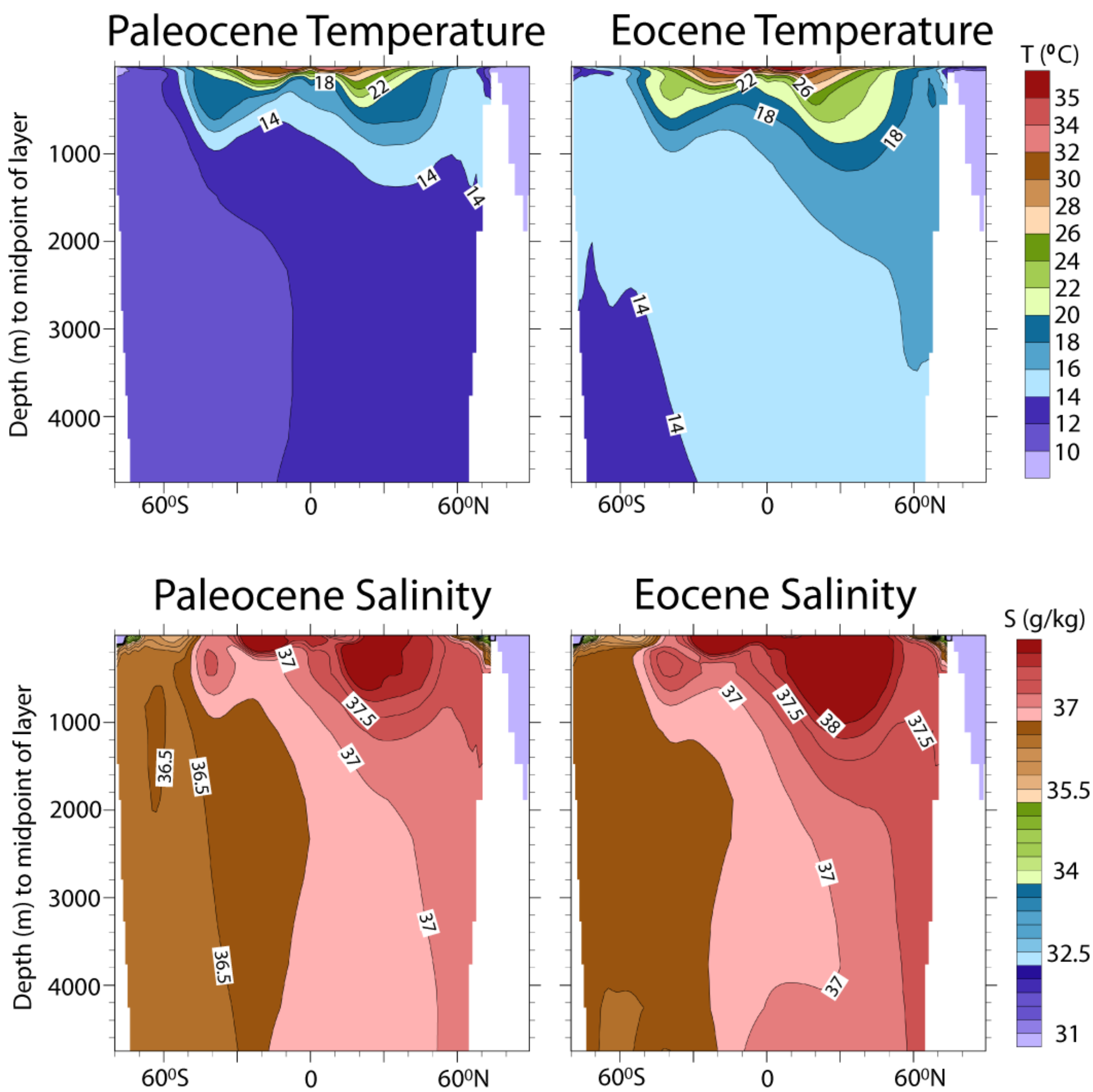


Figure S1.

Figure DR1. Simulated temperature and salinity for the Paleocene and Eocene runs.

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