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# Early Cenozoic benthic foraminiferal isotopes: Species reliability and interspecies correction factors

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[1] Oxygen and carbon isotope records are important tools used to reconstruct past ocean and climate conditions, with those of benthic foraminifera providing information on the deep oceans. Reconstructions are complicated by interspecies isotopic offsets that result from microhabitat preferences (carbonate precipitation in isotopically distinct environments) and vital effects (species-specific metabolic variation in isotopic fractionation). We provide correction factors for early Cenozoic benthic foraminifera commonly used for isotopic measurements (*Cibicidoides* spp., *Nuttallides truempyi*, *Oridorsalis* spp., *Stensioina beccariiformis*, *Hanzawaia ammophila*, and *Bulimina* spp.), showing that most yield reliable isotopic proxies of environmental change. The statistical methods and larger data sets used in this study provide more robust correction factors than do previous studies. Interspecies isotopic offsets appear to have changed through the Cenozoic, either (1) as a result of evolutionary changes or (2) as an artifact of different statistical methods and data set sizes used to determine the offsets in different studies. Regardless of the reason, the assumption that isotopic offsets have remained constant through the Cenozoic has introduced an ∼1–2°C uncertainty into deep sea paleotemperature calculations. In addition, we compare multiple species isotopic data from a western North Atlantic section that includes the Paleocene-Eocene thermal maximum to determine the most reliable isotopic indicator for this event. We propose that *Oridorsalis* spp. was the most reliable deepwater isotopic recorder at this location because it was best able to withstand the harsh water conditions that existed at this time; it may be the best recorder at other locations and for other extreme events also. *INDEX TERMS:* 3030 Marine Geology and Geophysics: Micropaleontology; 4267 Oceanography: General: Paleoceanography; 4804 Oceanography: Biological and Chemical: Benthic processes/benthos; 4870 Oceanography: Biological and Chemical: Stable isotopes; *KEYWORDS:* isotope correction factors, benthic foraminifera, early Cenozoic, Ocean Drilling Program

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## 1. Introduction

[2] Stable isotope measurements on benthic foraminifera are used routinely to reconstruct past temperatures and circulation patterns in the deep oceans, as well as to infer glacial histories. Paleoceanographic studies rely on the assumption that benthic foraminiferal isotope variations primarily reflect environmental changes: the ambient temperature and the $\delta^{18}$O value of seawater ($\delta^{18}O_{seawater}$) determine the $\delta^{18}$O value recorded in benthic foraminifera ($\delta^{18}O_{calcite}$), whereas the $\delta^{13}$C value is primarily a function of the dissolved inorganic carbon (DIC) $\delta^{13}$C value [e.g., *Urey*, 1947; *Epstein et al.*, 1953; *Emiliani*, 1955; *O'Neil et al.*, 1969; *Graham et al.*, 1981; *McCorkle et al.*, 1990]. A potential complicating factor is that $\delta^{18}$O and $\delta^{13}$C measurements of modern benthic foraminiferal species are often consistently offset from each other and from calcite precipitated in equilibrium with the surrounding water [e.g., *Duplessy et al.*, 1970; *Shackleton*, 1974; *Belanger et al.*, 1981; *Graham et al.*, 1981; *McCorkle et al.*, 1990]. These interspecies isotopic offsets have been attributed to microhabitat preferences (test growth in isotopically distinct environments) [e.g., *Belanger et al.*, 1981; *Corliss*, 1985; *McCorkle et al.*, 1990] and vital effects (species-specific metabolic variation in isotopic fractionation) [e.g., *Duplessy et al.*, 1970; *McCorkle et al.*, 1990].

[3] Deep sea benthic foraminifera have different microhabitat preferences, ranging from deep infaunal (within sediments) to epifaunal (at the sediment-water interface) to elevated substrates [e.g., *Corliss*, 1985; *Gooday*, 1986; *Bernhard*, 1989]. Pore water chemistry differs from overlying seawater chemistry because organic matter decom-

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**Table 1.** Locations, Present Depths, and Paleodepths of Isotope Data Used in This Study

| Site | Present Depth, m | Paleodepth, m | Depth Zone | Paleodepth Reference | Latitude | Longitude | Location |
|---|---|---|---|---|---|---|---|
| 384 | 3909 | 3500–3700 | lower abyssal | *Tucholke and Vogt* [1979] | 40°21.65′N | 51°39.80′W | eastern North Atlantic |
| 401 | 2495 | 2500 | upper abyssal | *Miller and Curry* [1982] | 47°25.65′N | 08°48.62′W | Bay of Biscay |
| 523 | 4562 | 2500–3000 | upper abyssal | *Hsü et al.* [1984] | 28°33.131′S | 02°15.078′W | SE Atlantic |
| 524 | 4796 | 3700 | lower abyssal | *Hsü et al.* [1984] | 29°04.24′S | 03°30.74′E | SE Atlantic |
| 525A | 2467 | 1600–1800 | lower bathyal | *Moore et al.* [1984] | 29°29.055′S | 02°59.12′E | Walvis Ridge |
| 527 | 4428 | 3200–3400 | lower abyssal | *Moore et al.* [1984] | 28°02.49′S | 01°45.80′E | Walvis Ridge |
| 528 | 3800 | 3000–3300 | lower abyssal | *Moore et al.* [1984] | 28°31.49′S | 02°19.44′E | Walvis Ridge |
| 549 | 2515 | 2000–2300 | upper abyssal | *Masson et al.* [1985] | 49°05.28′N | 13°05.88W | Goban Spur |
| 550 | 4420 | 4000–4300 | lower abyssal | *Masson et al.* [1985] | 48°30.91N | 13°26.37′W | Porqupine Abyssal Plain |
| 689B | 2080 | 1400–1650 | lower bathyal | *Kennett and Stott* [1990] | 64°31.009′S | 03°05.996′E | Maud Rise |
| 690 | 2925 | 2250–2490 | upper abyssal | *Kennett and Stott* [1990] | 65°09.63′S | 01°12.30′E | Maud Rise |
| 698 | 2128 | 800–900 | middle bathyal | *Katz and Miller* [1991] | 51°27.51′S | 33°05.96′W | SW Atlantic |
| 699 | 3705.5 | 2700–2900 | upper abyssal | *Katz and Miller* [1991] | 51°32.537′S | 30°40.619′W | SW Atlantic |
| 700 | 3601 | 2250–2600 | upper abyssal | *Katz and Miller* [1991] | 51°31.977′S | 30°16.688′W | SW Atlantic |
| 702 | 3083.7 | 1700–2000 | lower bathyal | *Katz and Miller* [1991] | 50°56.786′S | 26°22.117′W | SW Atlantic |
| 738 | 2252.5 | 1350 | lower bathyal | *Barrera and Huber* [1991] | 62°42.54′S | 82°47.25′E | Kerguelen Plateau |
| 758A | 2934.5 | 2000 | upper abyssal | *Pierce et al.* [1989] | 5°23.049′N | 90°21.673′E | Exmouth Plateau |
| 865 | 1518.4 | 1300–1500 | lower bathyal | *Thomas and Shackleton* [1996] | 18°26.41′N | 179°33.339′W | Allison Guyot |
| 883 | 2384 | 1700–2000 | lower bathyal | *Pak and Miller* [1995] | 51°11.908′N | 167°46.128′E | Detroit Seamount, NW Pacific |
| 884 | 3825 | 3000–3300 | lower abyssal | *Pak and Miller* [1995] | 51°27.026′N | 168°20.228′E | Detroit Seamount, NW Pacific |
| 1051 | 1981 | 1800–2000 | lower bathyal | *Norris et al.* [1998] | 30°03.186′N | 76°21.4712′W | Blake Nose |
| 1052 | 1345 | 1000–2000 | lower bathyal | *Katz et al.* [2001] | 29°57.0906′N | 76°37.5966′W | Blake Nose |

position within the sediments changes the carbon isotopic signature [e.g., *Bender et al.*, 1977; *Froelich et al.*, 1979; *Emerson et al.*, 1980]. The oxidation of organic matter within sediments lowers the DIC $\delta^{13}$C value of the pore water; therefore, pore water $\delta^{13}$C profiles tend to decrease with subseafloor depth. Isotopic analyses of modern benthic foraminifera show that epifaunal forms such as *Planulina* spp. and *Cibicidoides* spp. more closely reflect seawater $\delta^{13}$C values, whereas infaunal taxa such as *Bulimina* spp. and *Uvigerina* spp. reflect the lower $\delta^{13}$C values of the pore water [*McCorkle et al.*, 1990]. High productivity in surface waters can result in high concentrations of organic matter in the sediments, further driving down pore water $\delta^{13}$C values. Because of this, infaunal taxa tend to make good paleoproductivity indicators but are not reliable water mass tracers [e.g., *Mackensen et al.*, 2000; *Shackleton et al.*, 2000]. Isotopic values of epifaunal species (such as *Planulina wuellerstorfi*) also can be affected by high productivity rates [e.g., *Mackensen et al.*, 2000].

[4] Ideally, each isotopic record will be generated from a single benthic foraminiferal species that has been calibrated to equilibrium values for the $\delta^{18}$O and $\delta^{13}$C of the ambient seawater. For the Paleocene and Eocene, equilibrium values must be assigned based on the assumption that one or more species secrete their tests in equilibrium with the ambient conditions or that the offset observed in the modern ocean is constant through time for extant species. If there are insufficient specimens of a single species available, then isotope records often are spliced together using interspecific or intergeneric data. It is necessary to compensate for isotopic offsets by determining a correction factor that can be used to adjust one species' isotopic values to the values of a second species used as a proxy for calcite precipitated in equilibrium with ambient seawater conditions (temperature and $\delta^{18}O_{seawater}$ for $\delta^{18}O_{calcite}$ (e.g., *Uvigerina* [*Shackleton*, 1974] or DIC $\delta^{13}C_{seawater}$ for $\delta^{13}C_{calcite}$ (e.g., *Cibicidoides* [*Belanger et al.*, 1981; *Graham et al.*, 1981]). These interspecies corrections rely on offsets that are consistent and reliable through time and space, regardless of the physical or biological processes responsible for the isotopic offsets.

[5] In this paper, we analyze isotopic offsets among early Cenozoic (Paleocene and Eocene) benthic foraminifera with more robust statistical methods and larger data sets than were used in previous studies. In addition, we compare multiple species isotopic data from the Paleocene-Eocene thermal maximum/carbon isotope excursion (PETM/CIE) to determine the most reliable deepwater isotopic recorder for this transient event based on consistency with coeval core records. Our goal is to provide the best correction factors available and the means to generate the most reliable early Paleogene benthic foraminiferal isotopic record possible, regardless of the metabolic or environmental conditions responsible for the interspecies isotopic offsets.

## 2. Methods

[6] Paleocene and Eocene isotopic data generated on benthic foraminifera were compiled from published sources that include analyses generated from at least two of the following taxa for at least one sample level: *Cibicidoides* spp., *Nuttallides truempyi*, *Oridorsalis* spp., *Stensioina beccariiformis*, *Hanzawaia ammophila*, and *Bulimina* spp. (Table 1; Appendix A[1]). Additional unpublished data are included from this paper's coauthors (Appendix A). Data sets span 25 m.y., all ocean basins, and a wide range of paleodepths. Only well preserved specimens were used for isotopic analysis; only coeval, in situ isotopic data pairs were used in the statistical analyses. Data sets were divided according to paired analyses (e.g., *Cibicidoides* spp. -

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[1] Supporting appendix is available via Web browser or via Anonymous FTP from ftp://ftp.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

*Nuttalli destruempyi*, *Cibicidoides* spp. - *Oridorsalis* spp.). Isotope values of modern *Cibicidoides* spp. are consistently offset from seawater equilibrium $\delta^{18}$O and $\delta^{13}$C [e.g., *Graham et al.*, 1981], and interspecies offsets have been consistent through time [e.g., *Graham et al.*, 1981; *Shackleton and Opdyke*, 1973; *Shackleton et al.*, 1984]. Hence *Cibicidoides* spp. is traditionally used as the standard to which other taxa are calibrated; this convention is followed in this study. In addition, empirical relationships among the other taxa in this study are determined.

[7] Previous studies have determined interspecies isotopic offsets either by: (1) averaging the difference between data pairs [*Shackleton et al.*, 1984] or (2) using ordinary least squares (OLS) linear regressions [*Katz and Miller*, 1991; *Pak and Miller*, 1992; *Charisi and Schmitz*, 1996]. The result of an OLS linear regression is the standard equation for a line:

$$y = mx + b, \tag{1}$$

where x = independent variable, y = dependent variable, m = slope, and b = y-intercept. Previous studies have assumed that m = 1 and the y-intercept is an adequate correction factor [*Katz and Miller*, 1991; *Pak and Miller*, 1992; *Charisi and Schmitz*, 1996], and corrected the dependent variable using the equation:

$$y - b = x, \tag{2}$$

without (1) testing the validity of the assumption that the slope of the regression line is 1, and (2) recalculating the y-intercept to account for the assumed slope of 1. If the slope is incorrectly assumed to be 1, then there will be a systematic over- or under-correction above and below the mean. If the slope cannot be shown to be 1, then the dependent variable should be corrected using the equation:

$$(y - b)/m = x. \tag{3}$$

[8] The validity of OLS linear regression analysis has limitations: (1) it depends on the normal distribution of the standard errors; and (2) it is sensitive to data outliers. These limitations can be minimized by assuming normal distribution of errors and removing visible outliers from the data set (typically at the 3-sigma (99%) or 2-sigma (95%) confidence intervals); however, removing outliers yields results that may be subject to skepticism even if the predictive usefulness of these results is valid. As an objective alternative to OLS analysis, we use the least median of squares (LMS)-based MM estimator [*Yohai*, 1987] and the RIPE (Robust Inference Plus Estimation) program of Andre Lucas (http://staff.feweb.vu.nl/alucas/) in this study. This method is robust to outliers in both the independent and dependent variables and does not depend on the assumption of normally distributed errors; therefore, it is not necessary to exclude any data from the analysis.

[9] In this study, a correction factor is determined to be necessary if the slope $\neq$1 and the intercept $\neq$0 (within the 95% confidence interval). For regressions with a slope that statistically = 1 within the 95% confidence interval, a new intercept ("adjusted y-intercept") is calculated with the slope forced to be 1. The adjusted slope and intercept (Table 2) yield the best correction factor equation, with the combined 95% confidence limits of the slope and intercept providing a confidence limit of at least 90% on the correction factor. Additional steps will result in an accumulated error that makes a valid prediction unlikely; in other words, it is not valid (1) to correct from species A to species B, and from species B to species C, and then (2) assume that species A can be corrected to species C by combining the two correction factors.

[10] The LMS method and the larger data sets used in this study provide more robust correction factors (in comparison to previous publications) for early Paleogene benthic foraminiferal isotopic calibrations. The larger data sets also allow us to examine subsets to determine whether species isotopic offsets differ with paleodepth, age, or ocean basin.

## 3. Results

### 3.1. Isotopic Correction Factors

[11] Results of the LMS analyses show that the slope statistically equals one and that equation (2) provides a sufficient correction factor in twelve cases out of eighteen comparisons (Figures 1–3; Tables 2 and 3). In three of these twelve cases, the y-intercepts are close enough to zero to require no correction factor (*Cibicidoides* spp. - *S. beccariiformis* $\delta^{18}$O, *N. truempyi* - *S. beccariiformis* $\delta^{18}$O and $\delta^{13}$C). *Nuttallides truempyi* ($\delta$13C), *Oridorsalis* spp. ($\delta^{18}$O and $\delta^{13}$C), *Hanzawaia ammophila* ($\delta^{13}$C), and *Bulimina* spp. ($\delta^{18}$O) can be corrected to *Cibicidoides* spp. values by subtracting the adjusted y-intercept determined from the LMS analysis. Similarly, the y-intercept alone is a sufficient correction factor for *Oridorsalis* spp. - *S. beccariiformis* $\delta^{13}$C, *Nuttallides truempyi* - *Oridorsalis* spp. $\delta^{13}$C, and *Nuttallides truempyi* - *Bulimina* spp. $\delta^{18}$O and $\delta^{13}$C.

[12] Results of the LMS analyses show that the slope does not equal one in six comparisons (i.e., the offsets vary with respect to isotopic value) and that equation (3) should be used to correct the dependent variable (Figures 1–3; Tables 2 and 3). These include *Cibicidoides* spp. - *Bulimina* spp. $\delta^{13}$C, *Cibicidoides* spp. - *N. truempyi* $\delta^{18}$O, *Cibicidoides* spp. - *S. beccariiformis* $\delta^{13}$C, *Cibicidoides* spp. - *Hanzawaia ammophila* $\delta^{18}$O, *Nuttallides truempyi* - *Oridorsalis* spp. $\delta^{18}$O, and *Oridorsalis* spp.-*S. beccariiformis* $\delta^{18}$O. In one case (*Cibicidoides* spp. - *S. beccariiformis* $\delta^{13}$C), the limits of the confidence intervals are too wide to provide any predictive value.

[13] We caution that all of the *Cibicidoides* spp. - *Hanzawaia ammophila* data are from a single location (Site 1052); we cannot confirm that these correction factors are valid elsewhere. Similarly, most of the data for the *Nuttallides truempyi* - *Bulimina* spp. $\delta^{13}$C comparison are from Site 865 and may not be applicable elsewhere (Figure 3; Table 2).

[14] Regressions were determined for data subsets (with sufficient coverage) according to age (Paleocene versus Eocene), paleodepth (bathyal (200–2000 m) versus abyssal (>2000 m)), and location (Atlantic versus Indo-Pacific) (Figures 1–3; Table 2). The difference in correction factors for most of these subsets was less than the machine

**Table 2.** LMS Analyses Were Conducted for Each Data Set Consisting of Paired Benthic Foraminiferal Isotope Analyses[a]

| | | | | Oxygen | | Carbon | |
|---|---|---|---|---|---|---|---|
| Independent Variable | Dependent Variable | Sample Set | N | y = (m ± 2 × SE) × x + (b ± 2 × SE) | Robust R- Squared | y = (m ± 2 × SE) × x + (b ± 2 × SE) | Robust R-Squared |
| Cib | Nutt | All | 247 | y = (.89 ± .04) × x + (−.1 ± .02) | 0.909 | y = (.98 ± .04) × x + (−.32 ± .04) | 0.936 |
| | | All, m = 1 | 247 | | | y = x + (−.34 ± .02) | |
| | | Eocene | 161 | y = (.90 ± .06) × x + (−.1 ± .02) | 0.897 | y = (.91 ± .08) × x + (−.28 ± .06) | 0.872 |
| | | Paleocene | 86 | y = (.85 ± .08) × x + (−.09 ± .04) | 0.776 | y = (.92 ± .08) × x + (−.16 ± .14) | 0.857 |
| | | Bathyal | 130 | y = (.91 ± .06) × x + (−.08 ± .04) | 0.874 | y = (.96 ± .06) × x + (−.3 ± .08) | 0.888 |
| | | Bathyal, m = 1 | 130 | | | y = x + (−.35 ± .04) | |
| | | Abyssal | 117 | y = (.83 ± .08) × x + (−.13 ± .04) | 0.878 | y = (1.01 ± .06) × x + (−.33 ± .06) | 0.972 |
| | | Abyssal, m = 1 | 117 | | | y = x + (−.33 ± .04) | |
| | | Atlantic | 169 | y = (.87 ± .06) × x + (−.1 ± .02) | 0.914 | y = (.98 ± .04) × x + (−.3 ± .06) | 0.952 |
| | | Atlantic, m = 1 | 169 | | | y = x + (−.33 ± .04) | |
| | | Indo-Pacific | 78 | y = (.93 ± .08) × x + (−.1 ± .04) | 0.918 | y = (.9 ± .1) × x + (−.29 ± .08) | 0.812 |
| | | Indo-Pacific, m = 1 | 78 | y = x + (−.1 ± .04) | | | |
| Cib | Orid | All | 32 | y = (1.01 ± .18) × x + (.28 ± .08) | 0.787 | y = (.98 ± .08) × x + (−.69 ± .1) | 0.964 |
| | | All, m = 1 | 32 | y = x + (.28 ± .06) | | y = x + (−.72 ± .06) | |
| | | Eocene | 19 | y = (.91 ± .22) × x + (.26 ± .1) | 0.716 | y = (.94 ± .18) × x + (−.68 ± .14) | 0.918 |
| | | Eocene, m = 1 | 19 | y = x + (.28 ± .08) | | y = x + (−.72 ± .06) | |
| | | Paleocene | 13 | y = (1.08 ± .2) × x + (.29 ± .12) | 0.850 | y = (.93 ± .18) × x + (−.56 ± .4) | 0.916 |
| | | Paleocene, m = 1 | 13 | y = x + (.27 ± .1) | | y = x + (−.71 ± .14) | |
| Cib | Sbecc | All | 33 | y = (.99 ± .14) × x + (−.05 ± .1) | 0.699 | y = (.63 ± .28) × x + (.46 ± .66) | 0.675 |
| | | All, m = 1 | 33 | y = x + (−.04 ± .08) | | | |
| Cib | Hanz | All | 111 | y = (.62 ± .16) × x + (.16 ± .12) | 0.347 | y = (.92 ± .08) × x + (.02 ± .1) | 0.892 |
| | | All, m = 1 | 111 | | | y = x + (−.08 ± .02) | |
| Cib | Bul | All | 130 | y = (.92 ± .04) × x + (.33 ± .08) | 0.684 | y = (.57 ± .28) × x + (−.16 ± .36) | 0.281 |
| | | All, m = 1 | 130 | y = x + (.28 ± .02) | | | |
| | | Site 865 | 39 | y = (1.07 ± .1) × x + (.35 ± 06) | 0.941 | y = (.96 ± .1) × x + (−.06 ± .38) | 0.543 |
| | | Site 865, m = 1 | 39 | y = x + (.37 ± .06) | | | |
| | | Site 1052 | 90 | y = (.77 ± .16) × x + (.44 ± .12) | 0.684 | y = (1.24 ± .1) × x + (−1.1 ± .12) | 0.893 |
| Nutt | Orid | All | 94 | y = (.79 ± .06) × x + (.36 ± .04) | 0.925 | y = (1.0 ± .06) × x + (−.45 ± .06) | 0.955 |
| | | All, m = 1 | 94 | | | y = x + (−.46 ± .04) | |
| | | Eocene | 66 | y = (.79 ± .1) × x + (.36 ± .08) | 0.818 | y = (.92 ± .08) × x + (−.45 ± .06) | 0.809 |
| | | Eocene, m = 1 | 66 | | | y = x + (−.47 ± .06) | |
| | | Paleocene | 28 | y = (.8 ± .32) × x + (.36 ± .06) | 0.198 | y = (1.06 ± .2) × x + (−.53 ± .32) | 0.786 |
| | | Paleocene, m = 1 | 28 | y = x + (.33 ± .08) | | y = x + (−.43 ± .08) | |
| | | Bathyal | 37 | y = (.81 ± .14) × x + (.35 ± .04) | 0.798 | y = (1.01 ± .12) × x + (−.5 ± .18) | 0.928 |
| | | Bathyal, m = 1 | 37 | | | y = x + (−.49 ± .08) | |
| | | Abyssal | 57 | y = (.8 ± .1) × x + (.37 ± .1) | 0.689 | y = (1.02 ± .08) × x + (−.44 ± .06) | 0.801 |
| | | Abyssal, m = 1 | 57 | | | y = x + (−.44 ± .06) | |
| Nutt | Sbecc | All | 102 | y = (.98 ± .22) × x + (.01 ± .04) | 0.276 | y = (.95 ± .12) × x + (.07 ± .18) | 0.865 |
| | | All, m = 1 | 102 | y = x + (.01 ± .04) | | y = x + (0 ± .06) | |
| | | bathyal | 72 | y = (.54 ± .32) × x + (.02 ± .06) | 0.273 | y = (1 ± .16) × x + (.03 ± .33) | 0.855 |
| | | bathyal, m = 1 | 72 | | | y = x + (−.03 ± .08) | |
| | | abyssal | 30 | y = (1.18 ± .16) × x + (.1 ± .08) | 0.589 | y = (.88 ± .22) × x + (.13 ± .36) | 0.910 |
| | | abyssal, m = 1 | 30 | | | y = x + (−.06 ± .06) | |
| Nutt | Bul | All | 56 | y = (.95 ± .08) × x + (.4 ± .04) | 0.824 | y = (.87 ± .4) × x + (.23 ± .1) | −0.407 |
| | | All, m = 1 | 56 | y = x + (.39 ± .08) | | y = x + (.19 ± .08) | |
| | | Site 865 | 43 | y = (1.01 ± .18) × x + (.44 ± .08) | 0.801 | y = (1.0 ± .14) × x + (.25 ± .08) | 0.024 |
| | | Site 865, m = 1 | 43 | y = x + (.44 ± .08) | | y = x + (.25 ± .06) | |
| Orid | Sbecc | All | 19 | y = (.85 ± .06) × x + (−.26 ± .08) | 0.606 | y = (.88 ± .14) × x + (.61 ± .2) | 0.704 |
| | | All, m = 1 | | | | y = x + (.48 ± .1) | |

[a] Additional LMS analyses were conducted for data subsets where possible. x = independent variable, y = dependent variable, m = slope, b = intercept, N = number of paired isotope comparisons, SE = standard error. 2 × SE establishes the 95% confidence interval for slope and intercept. The combined 95% confidence limits of the slope and intercept provide a confidence limit of at least 90% on the correction factor. Additional steps will result in an accumulated error that makes a valid prediction unlikely; in other words, it is not valid (1) to correct from species A to species B, and from species B to species C, and then (2) assume that species A can be corrected to species C by combining the two correction factors.

precision of the mass spectrometer (±0.1‰), making the correction factor for the entire data set applicable regardless of age, paleodepth, or location (Figures 1–3; Table 2; see section 4). However, analyses of several subsets provided correction factors for individual locations that differed from the overall correction factors (Figures 2–3; Table 2; see section 4). No meaningful correction factor could be established for the bathyal subset of *Nuttallides truempyi - S. beccariiformis* $\delta^{18}$O because these data are distributed in a circular region with no obvious linear trend (Figure 3; Table 2).

### 3.2. PETM/CIE Isotopes: Species Reliability

[15] Site 1051 (Blake Nose, western North Atlantic) provides a detailed record that includes four benthic foraminiferal isotopic records spanning the CIE (*Cibicidoides* spp., *N. truempyi*, *Oridorsalis* spp., and *Stensioina beccariiformis*) and a bulk sediment isotope record from many of

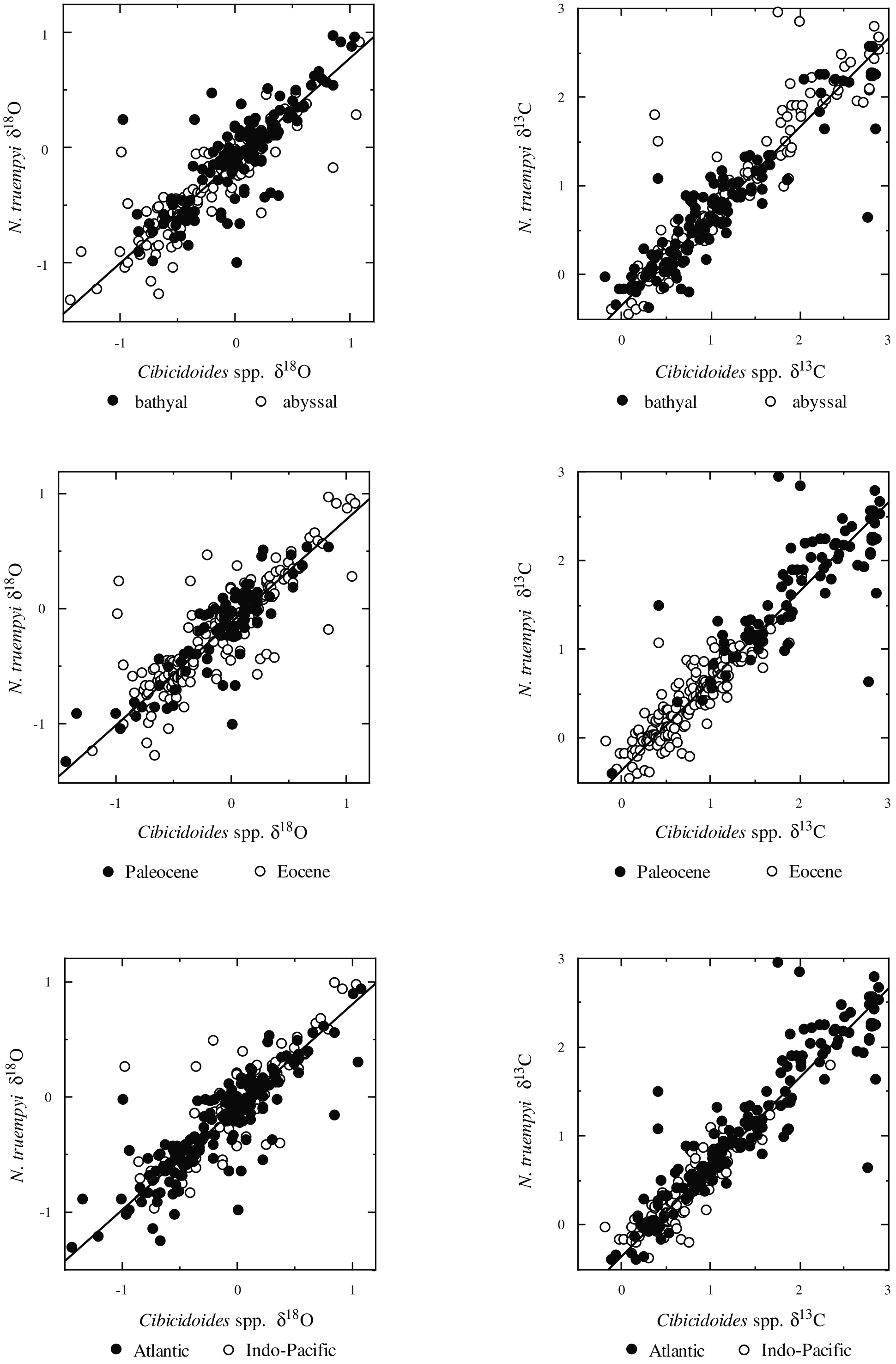

**Figure 1.** Paired isotope analyses of *Cibicidoides* spp. and *N. truempyi*. LMS regression line is for the entire data set; data plotted are divided by age, paleodepth, and ocean basin. See Tables 2 and 3 for associated statistics.

the same samples (Figures 4 and 5). 55% of the benthic foraminiferal species disappear in the latest Paleocene at Site 1051 [*Katz et al.*, 1999]. The majority (75%) of these last appearances occur below the onset of the CIE (as recorded in both benthic and bulk sediment isotope records). The remaining 25% last occur above this in a dissolution interval associated with the CIE, with only a few specimens lingering in samples that are dominated by *Bulimina* spp. The relict specimens tend to be partially dissolved with poor to moderate preservation, in contrast to

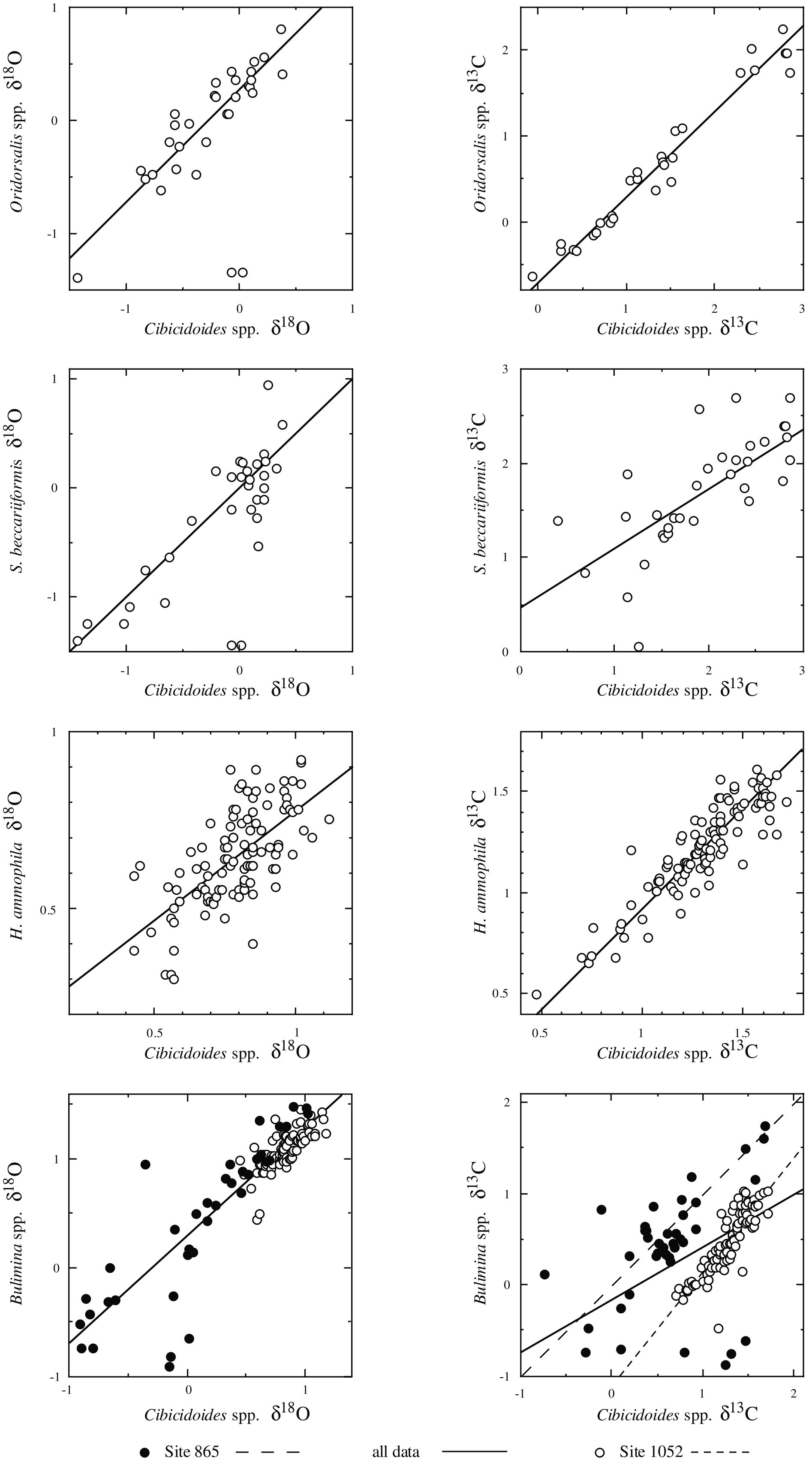

**Figure 2.** *Cibicidoides* spp. isotope analyses paired with *Oridorsalis* spp., *S. beccariiformis*, *H. ammophila*, and *Bulimina* spp. See Tables 2 and 3 for associated statistics.

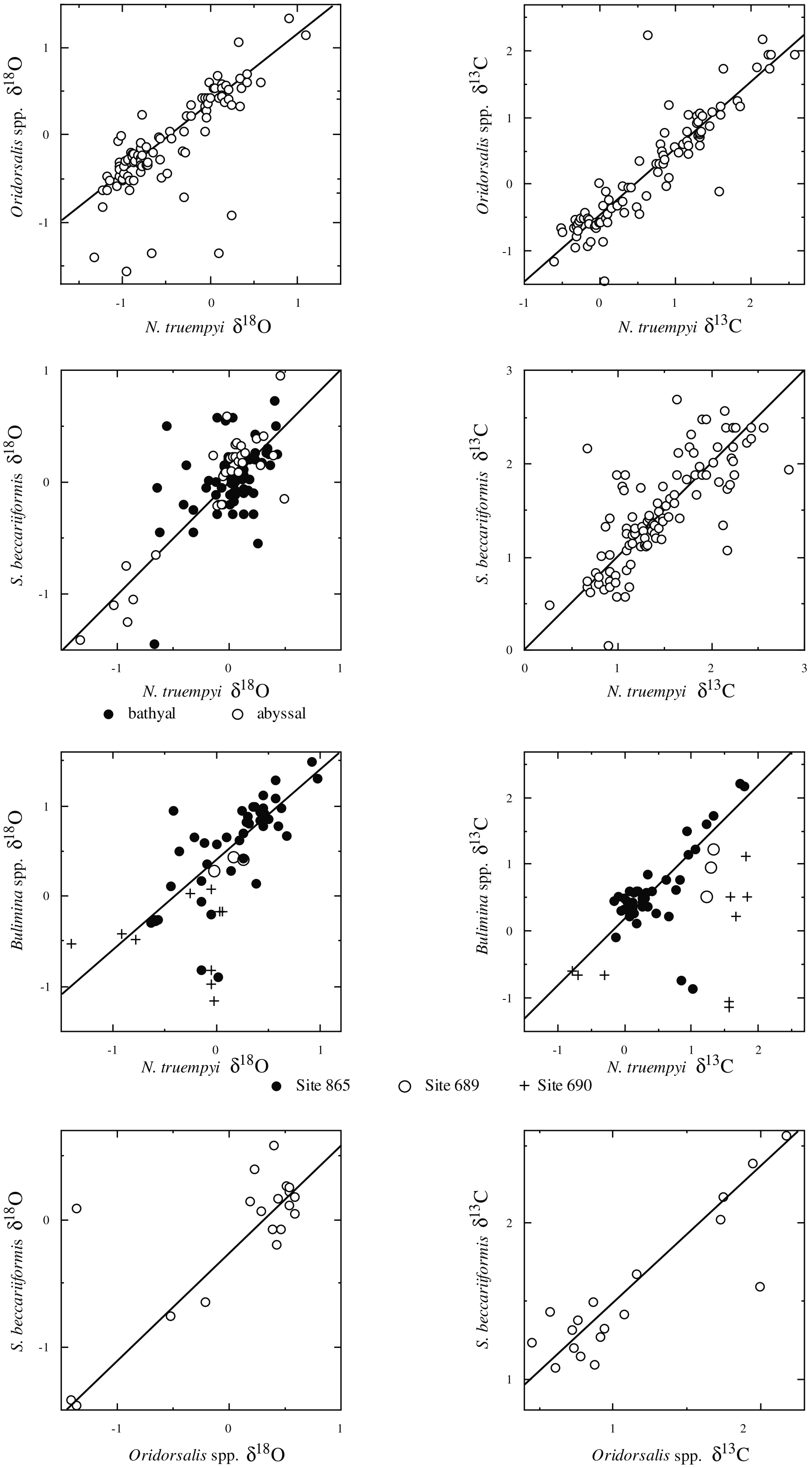

**Figure 3.** *N. truempyi* isotope analyses paired with *Oridorsalis* spp., *S. beccariiformis*, and *Bulimina* spp.; *Oridorsalis* spp. isotope analyses paired with *S. beccariiformis*. See Tables 2 and 3 for associated statistics.

**Table 3.** Isotopic Correction Factors for Paired Species Isotopic Analyses[a]

| Taxa Pairs | | Correction Factor | *Shackleton et al.* [1984] | *Katz and Miller* [1991] | *Pak and Miller* [1992] | *Charisi and Schmitz* [1996] |
|---|---|---|---|---|---|---|
| *Cibicidoides* | O18 | (Nutt + 0.10)/0.89 = Cib | Nutt + 0.15 = Cib | Nutt + 0.1 = Cib | Nutt + 0.12 = Cib | |
| *N. truempyi* | C13 | Nutt + 0.34 = Cib | none needed | Nutt + 0.26 = Cib | Nutt + 0.23 = Cib | |
| *Cibicidoides* | O18 | Orid - 0.28 = Cib | Orid - 0.5 = Cib | | | |
| *Oridorsalis* | C13 | Orid + 0.72 = Cib | Orid + 1.0 = Cib | | | |
| *Cibicidoides* | O18 | Bul - 0.28 = Cib | none needed | | | |
| *Bulimina* | C13 | single site reliability | none needed | | | |
| *Cibicidoides* | O18 | none needed | | | | |
| *S. beccariiformis* | C13 | not reliable | | | | |
| *Cibicidoides* | O18 | (Hanz - 0.16)/.62 = Cib[b] | | | | |
| *H. ammophila* | C13 | Hanz + 0.08 = Cib[b] | | | | |
| *N. truempyi* | O18 | (Orid - 0.36)/0.79 = Nutt | | | | Orid - 0.7 = Nutt |
| *Oridorsalis* | C13 | Orid + 0.46 = Nutt | | | | Orid + 0.46 = Nutt |
| *N. truempyi* | O18 | none needed | | | | |
| *S. beccariiformis* | C13 | none needed | | | | |
| *N. truempyi* | O18 | Bul - 0.39 = Nutt | | | | |
| *Bulimina* | C13 | Bul - 0.19 = Nutt[c] | | | | |
| *Oridorsalis* | O18 | (Sbecc + 0.26)/0.85 = Orid | | | | |
| *S. beccariiformis* | C13 | Sbecc - 0.48 = Orid | | | | |

[a] Cib = *Cibicidoides* spp.; Nutt = *Nuttallides truempyi*; Orid = *Oridorsalis* spp.; Sbecc = *Stensioina beccariiformis*; Hanz = *Hanzawaia ammophila*; Bul = *Bulimina* spp. Correction factors from previous publications are summarized for comparison. These correction factors have not been shown to be valid for younger or older time periods, and should not be used for post-Eocene or pre-Cenozoic data without further study.

[b] All data is from Site 1052; it has not been established whether this correction factor is valid at other locations.

[c] Most data is from Site 865; it has not been established whether this correction factor is valid at other locations.

the generally good preservation observed in the specimens of in situ *Bulimina* spp. [*Katz et al.*, 1999]. In order to establish whether these relict specimens represent true highest occurrences rather than bioturbated older specimens, oxygen and carbon isotope analyses were run on the classic pre-extinction event marker species *Stensioina beccariiformis* (Figures 4 and 5). Only two samples yielded sufficient numbers of well preserved *S. beccariiformis* for isotopic analyses; both samples yield pre-excursion $\delta^{18}$O and $\delta^{13}$C values (Figures 4 and 5; ~512.6 mbsf). The low benthic foraminiferal numbers, poor preservation, and pre-excursion isotopic values indicate that *S. beccariiformis* and other relict specimens are most likely older specimens that were bioturbated upsection and mixed with in situ faunas. Similarly, corroded specimens of *S. beccariiformis* and *N. truempyi* were found above the extinction event at Southern Ocean Site 690 [*Thomas and Shackleton*, 1996; *Thomas et al.*, 2000].

[16] At Site 1051, *Oridorsalis* spp. $\delta^{18}$O and $\delta^{13}$C values decreased by ~1.5‰ and ~2.5‰, respectively, in the latest Paleocene [*Katz et al.*, 1999]. A feature that stands out in these isotope records is the apparent lag in the *N. truempyi* isotopic shift relative to the level of the bulk sediment and *Oridorsalis* spp. isotopic shifts (Figures 4 and 5). Like *S. beccariiformis* and other relict Paleocene taxa in this part of the section, *N. truempyi* may have been unable to survive in the changing water conditions at the Blake Nose, and specimens at the onset of the CIE may be reworked in the same manner as *S. beccariiformis*. The level at which dissolution becomes less severe in the sediments at Site 1051 is the level at which the negative shift in *N. truempyi* isotope values begins, and may indicate a time when deep-water conditions more favorable to *N. truempyi* allowed this species to return to this location.

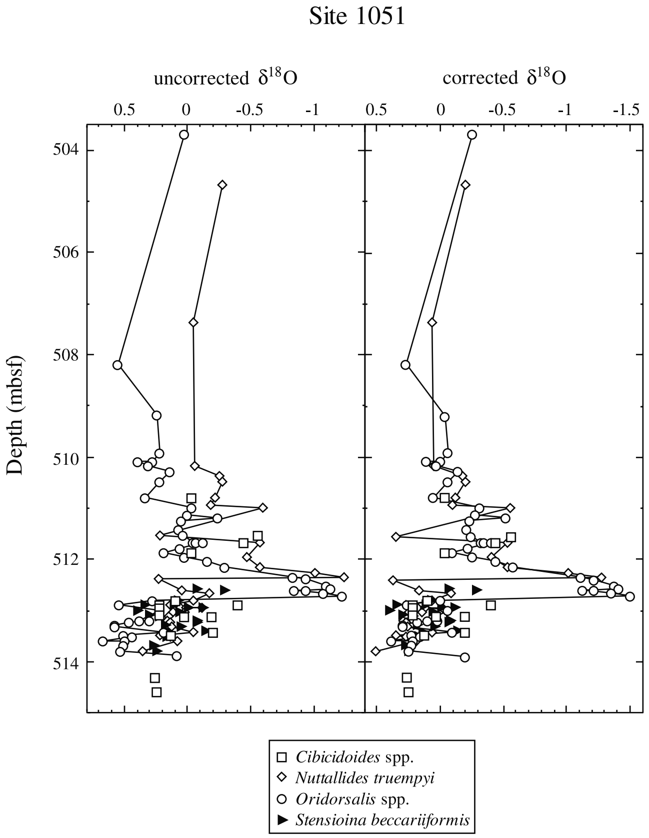

**Figure 4.** Uncorrected $\delta^{18}$O values from Site 1051 (*Cibicidoides* spp., *N. truempyi, Oridorsalis* spp., *S. beccariiformis*) compared with isotope data corrected to *Cibicidoides* spp. based on correction factors provided in Table 3.

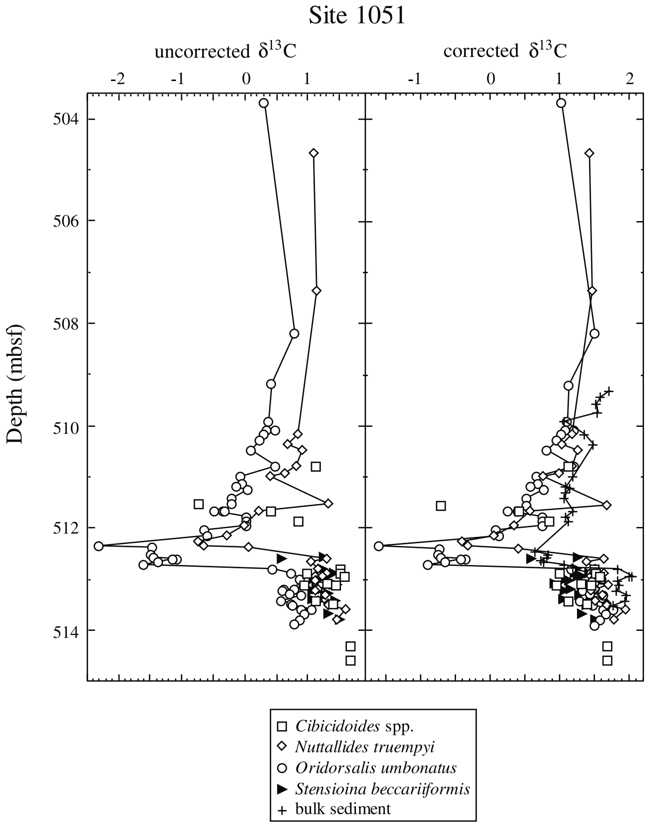

**Figure 5.** Uncorrected $\delta^{13}C$ values from Site 1051 (*Cibicidoides* spp., *N. truempyi, Oridorsalis* spp., *S. beccariiformis*) compared with isotope data corrected to *Cibicidoides* spp. based on correction factors provided in Table 3.

[17] At Sites 689, 690, and 865, *N. truempyi* is absent from early postextinction faunas, attributed in part to decreased dissolved oxygen levels and/or carbonate corrosivity at this time [*Thomas*, 1989, 1998; *Thomas and Shackleton*, 1996]. Tethyan sections yield similar results, with the temporary near-disappearance of *N. truempyi* coinciding with the benthic foraminiferal extinction event (BFEE) and brief (3000 year) period of oxygen deficiency [*Speijer et al.*, 1997]. In contrast, *N. truempyi* abundances increased after the BFEE and record post-CIE values at Walvis Ridge Sites 525 and 527 [*Thomas and Shackleton*, 1996].

[18] In contrast to *N. truempyi*, *Oridorsalis* spp. is a shallow infaunal taxon [*Rathburn and Corliss*, 1994] that may have been protected against the moderate dissolution and harsh environmental conditions of the CIE. In fact, *Oridorsalis* spp. was only a minor component in Paleocene benthic foraminiferal faunas; it became a major faunal component above the BFEE throughout the bathyal and abyssal Atlantic (Zone P6a [*Tjasma and Lohmann*, 1983; *Thomas and Shackleton*, 1996]) and increased in abundance in parts of the Pacific [*Pak and Miller*, 1992, 1995; *Kaiho et al.*, 1996; E. Thomas, unpublished data, 2003]. Harsh deepwater conditions may have restricted *N. truempyi* while favoring the opportunistic, shallow infaunal *Oridorsalis* spp. worldwide during the CIE. Therefore, *Oridorsalis* spp. may be the most reliable deepwater stable isotopic indicator for the PETM/CIE, and by extension, for other extreme events.

## 4. Discussion

### 4.1. Environmental Influence on Isotope Signature

[19] Paleoceanographic studies rely on the assumption that benthic foraminiferal isotopes reflect environmental conditions. The isotopic comparisons presented here demonstrate that a large range of benthic foraminiferal species can be used as faithful proxies of environmental change for both $\delta^{18}O$ and $\delta^{13}C$. In this study, LMS analysis shows that twelve out of eighteen species comparisons yield regressions with a statistical slope of 1; the other six species comparisons yield linear regressions with slopes that deviate from 1 (Figures 1–3; Tables 2 and 3). Analyses of data subsets (age, paleodepth, or ocean basin; Figures 1–3; Table 2) show that difference in correction factors for most of these subsets was less than the machine precision of the mass spectrometer (±0.1‰), showing that the correction factor for the entire data set is applicable regardless of age, paleodepth, or location in most cases. These analyses are valid over ~25 m.y., through a large global temperature change (~10°C), and span bathyal to abyssal depths in all ocean basins. This demonstrates that environmental parameters (temperature, $\delta^{18}O$ water, and DIC $\delta^{13}C$) exerted the primary influence on these stable isotopic signatures through the Paleocene and Eocene.

[20] Local conditions and/or analyzing different species within a single genus may account for isotopic offsets that vary with respect to isotopic value (i.e., the slope deviates from 1) in six comparisons (Figures 2 and 3; Table 2). LMS analyses of several data subsets demonstrate that a correction factor at an individual location may differ from the overall correction factor. Most notably, the infaunal *Bulimina* spp. records the $\delta^{13}C$ of pore waters rather than of seawater, and hence varies at different locations. For example, subdividing the *Cibicidoides* spp. - *Bulimina* spp. $\delta^{13}C$ data set resulted in different correction factors for Site 865 (equatorial Pacific, 1300–1500 m paleodepth) and Site 1052 (western North Atlantic, 1000–1500 m paleodepth) (Figure 2; Table 2). Similarly, most of the data for the *Nuttallides truempyi* - *Bulimina* spp. $\delta^{13}C$ comparison are from Site 865, and the resulting correction factor may not be valid for the sparse data from Sites 689 and 690 (Figure 3; Table 2).

### 4.2. Interspecies Isotopic Offsets Through the Cenozoic

[21] Paleoceanographic reconstructions assume that a species' isotopic offset with respect to both equilibrium and other species is constant through time. For example, *Planulina wuellerstorfi* has become the preferred species for middle Miocene to Recent isotopic studies because it is thought to reliably record DIC $\delta^{13}C_{seawater}$ values and to record $\delta^{18}O_{calcite}$ values that are constantly offset from equilibrium through time [e.g., *Graham et al.*, 1981; *Shackleton et al.*, 1984]. *Oridorsalis* spp. $\delta^{18}O$ values

record equilibrium $\delta^{18}O_{seawater}$ values, with the $\Delta\delta^{18}O_{calcite}$ values of *Oridorsalis* spp. - *P. wuellerstorfi* remaining ~0.64 ‰ [*Graham et al.*, 1981; *Shackleton et al.*, 1984; *Shackleton and Hall*, 1997] and $\Delta\delta^{18}O_{calcite}$ values of *Oridorsalis* spp. - *Cibicidoides* spp. remaining ~0.5‰ [*Shackleton et al.*, 1984; *Shackleton and Hall*, 1997] through the Neogene. In contrast, our Paleocene and Eocene *Oridorsalis* spp. - *Cibicidoides* spp. comparisons show that this difference was 0.28‰ (Table 3).

[22] Similarly, the isotopic offsets between *Cibicidoides* spp. and *Nuttallides* spp. also appear to have shifted through time. *Shackleton et al.* [1984] found that Paleogene through Neogene *Nuttallides* spp. is enriched by 0.15‰ in $\delta^{18}O$ and is equivalent in $\delta^{13}C$ relative to *Cibicidoides* spp., *Cibicidoides mundulus*, and *Cibicidoides havanensis*. In contrast, Paleocene and Eocene *N. truempyi* is depleted by ~0.1‰ in $\delta^{18}O$ (with the slope of the regression = 0.89) and 0.23–0.34‰ in $\delta^{13}C$ relative to *Cibicidoides* spp. [*Katz and Miller*, 1991; *Pak and Miller*, 1992; this study] (Table 3). An important implication of these offsets is that a slope <1 indicates that *N. truempyi* (the dependent variable) does not record the full range in $\delta^{18}O$ (and therefore temperature) recorded by *Cibicidoides* spp. (the independent variable).

[23] These apparent changes in interspecies $\delta^{18}O$ offsets may be the result of evolutionary changes in different species of *Cibicidoides*, *Nuttallides*, and *Oridorsalis* through the Cenozoic (e.g., post-Eocene *Nuttallides umbonifera* versus pre-Oligocene *Nuttallides truempyi*). Alternatively, the shifting offsets may be an artifact of different statistical methods and data set sizes used to determine the offsets in different studies. Regardless of the reason for these changes, the interspecies $\delta^{18}O$ offset is significant because it introduces at least 1–2°C uncertainties into Cenozoic paleotemperature calculations. *Miller et al.*'s [1987] and *Zachos et al.*'s [2001] Cenozoic $\delta^{18}O$ syntheses are based on *Cibicidoides* spp. and assume that the $\delta^{18}O$ values were constantly offset from equilibrium by 0.64‰ for the entire Cenozoic. These syntheses show peak warmth in the early Eocene with deepwater temperatures of 12°C [*Zachos et al.*, 2001] to 14°C [*Miller et al.*, 1987]. However, if (1) *Oridorsalis* $\delta^{18}O$ values accurately record equilibrium $\delta^{18}O$ values through the entire Cenozoic and (2) the Paleocene and Eocene *Oridorsalis* spp. - *Cibicidoides* spp. offset is 0.27‰ (Table 3), then temperature estimates based on *Cibicidoides* spp. [*Miller et al.*, 1987; *Zachos et al.*, 2001] are ~1–2°C too low for the Paleocene to Eocene. Similarly, the 0.4‰ correction for *Nuttallides* spp. used by *Zachos et al.* [2001] also would yield temperature reconstructions on the order of 1 to 2°C too low. The magnitude of the change in the interspecies isotopic offset is fairly small in comparison to the total amplitude of Cenozoic deepwater isotopic changes.

### 4.3. Species Reliability

[24] Traditionally, *Cibicidoides* species has been considered to be the most reliable isotopic recorder through time. Paleotemperature calculations and paleoceanographic reconstructions depend on this assumption. However, results presented here show that interspecies isotopic offsets may have changed over time, casting doubt on this assumption for Paleocene and Eocene sections. *Oridorsalis* spp. $\delta^{18}O$ values record equilibrium $\delta^{18}O_{seawater}$ values in the modern ocean [*Graham et al.*, 1981; *Shackleton et al.*, 1984] and appears to be the most reliable isotopic recorder during the transient conditions of the PETM. However, it is clear that the $\delta^{13}C$ offset between *Oridorsalis* spp. and *Cibicidoides* spp. (and other species) has changed through time (e.g., during the Miocene) [*Woodruff et al.*, 1981; *Vincent et al.*, 1980]. Most previous studies have used *Cibicidoides* as a standard, assuming that *Oridorsalis* changed its "vital effects" or infaunal depth habitat preference through time. This study shows that *Oridorsalis* spp. provides an excellent recorder for the early Paleogene. Although *Oridorsalis* spp. morphology remains remarkably stable through the Cenozoic and Upper Cretaceous, the correction factors established here cannot be extrapolated to the younger record with certainty. Additional calibration studies are needed for late Paleogene to Neogene sections to establish whether *Oridorsalis* spp. provides a reliable recorder for the entire Cenozoic.

## 5. Summary and Conclusions

[25] We provide correction factors for early Cenozoic (Paleocene and Eocene) benthic foraminifera that commonly are used for isotopic measurements using more robust statistical techniques than were applied in previous studies [*Shackleton et al.*, 1984; *Katz and Miller*, 1991; *Pak and Miller*, 1992; *Charisi and Schmitz*, 1996]. These new correction factors (Table 3) provide the means to generate more robust early Paleogene benthic foraminiferal isotopic records, regardless of the metabolic differences or environmental conditions that are responsible for the observed isotopic offsets. We caution that these correction factors have not been shown to be valid for younger or older time periods, and should not be used for post-Eocene or pre-Cenozoic data without further study.

[26] The best approach to generating an accurate isotopic record is to use a single benthic foraminiferal species for the entire section studied. If there are insufficient numbers of a single species to do this, then data from different species may be spliced together using the correction factors provided here. If possible, these correction factors should be compared with interspecies offsets from the location that is being studied.

[27] The isotopic comparisons presented here demonstrate that a large range of benthic foraminiferal species yield reliable $\delta^{18}O$ and $\delta^{13}C$ proxies of environmental change. These isotopic offsets appear to have changed through the Cenozoic, perhaps as a result of evolutionary changes or differing habitat preferences in different species within a genus. Alternatively, the change in offsets may be an artifact of different statistical methods used in different studies. The magnitude of the change in the interspecies isotopic offset is fairly small compared to the total amplitude of Cenozoic deepwater isotopic changes, yet this change introduces ~1–2°C uncertainties into Cenozoic paleotemperature calculations.

[28] Faunal and isotopic records indicate that *Oridorsalis* spp. may provide the most reliable deepwater isotopic

recorder for the onset of the CIE, and by extension, for other extreme events. This is supported by: (1) the decline or disappearance of *N. truempyi* from the Southern Ocean, Tethys, and Blake Nose at the onset of the CIE [*Thomas*, 1989; *Thomas and Shackleton*, 1996; *Speijer et al.*, 1997; this study]; (2) the presence of reworked *N. truempyi* and *S. beccariiformis* at the Blake Nose [this study] and reworked *N. truempyi* in the Southern Ocean [*Thomas*, 1989; *Thomas et al.*, 2000] at the onset of the CIE; and (3) the Atlantic-wide increase in *Oridorsalis* spp. abundances in the early Eocene [*Tjasma and Lohmann*, 1983; *Thomas and Shackleton*, 1996], accompanied by *Oridorsalis* spp. abundance increases in parts of the Pacific [*Pak and Miller*, 1992, 1995; *Kaiho et al.*, 1996; E. Thomas et al., unpublished data, 2003].

## Appendix A

[29] Isotopic analyses generated for two or more of the following taxa from at least one sample level were used to determine correction factors: *Cibicidoides* spp., *Nuttallides truempyi*, *Oridorsalis* spp., *Stensioina beccariiformis*, *Hanzawaia ammophila*, and *Bulimina* spp. Data sources are as follows: 1, *Miller et al.* [1987]; 2, *Corfield and Norris* [1996]; 3, *Pak and Miller* [1992]; 4, *Pak* [1996]; 5, *Oberhansli et al.* [1984]; 6, *Shackleton et al.* [1984]; 7, *Charisi and Schmitz* [1996]; 8, *Kennett and Stott* [1990]; 9, *Thomas and Shackleton* [1996]; 10, *Thomas et al.* [1999]; 11, *Katz and Miller* [1991]; 12, M. E. Katz and J. D. Wright (unpublished data, 2000); 13, *Barrera and Huber* [1991]; 14, *Zachos et al.* [1993]; 15, *Bralower et al.* [1995]; 16, *Zachos et al.* [2001]; 17, *Pak and Miller* [1995] (*Cibicidoides* spp. are unpublished); 18, *Katz et al.* [1999]; 19, D. K. Pak and M. E. Katz (unpublished data, 1999); 20, N. J. Shackleton (unpublished data, 1999).

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