Marine Micropaleontology 70 (2009) 89–101

Contents lists available at ScienceDirect

Marine Micropaleontology

journal homepage: www.elsevier.com/locate/marmicro

Carbon and oxygen isotope geochemistry of live (stained) benthic foraminifera from the Aleutian Margin and the Southern Australian Margin

Chandranath Basak [a,1], Anthony E. Rathburn [a,d,*], M. Elena Pérez [a,b], Jonathan B. Martin [c], Jared W. Kluesner [a,2], Lisa A. Levin [d], Patrick De Deckker [e], Joris M. Gieskes [d], Michelle Abriani [a]

[a] Indiana State University, Geology Program, Science Building 179, Terre Haute, IN 47809, USA
[b] Department of Palaeontology, The Natural History Museum, Cromwell Rd., London, SW7 5BD, UK
[c] Department of Geological Sciences, University of Florida, Gainesville, Florida 32611, USA
[d] Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0218, USA
[e] Department of Earth and Marine Sciences, The Australian National University, Canberra 0200, Australia

ARTICLE INFO

Article history:
Received 18 September 2007
Received in revised form 27 October 2008
Accepted 4 November 2008

Keywords:
stable isotopes
benthic foraminifera
δ13C
δ18O
deep sea ecology
microhabitats
Aleutian Margin
Australian Margin
SE Indian Ocean

ABSTRACT

Comparisons of ambient bottom-water geochemistry and stable isotopic values of the tests of living (stained) calcareous benthic foraminifera from the North Pacific (on the Aleutian Margin, water depth 1988 m) and Murray Canyons group in the Southern Indian Ocean (Australian Margin, water depths 2476 m and 1634 m) provide modern environmental analogs to calibrate paleoenvironmental assessments. Consistent with the hypothesis that microhabitat preferences influence foraminiferal isotopic values, benthic foraminifera from both margins were depleted in ^{13}C with respect to bottom-water dissolved inorganic carbon (DIC). The carbon isotope values of deep infaunal foraminifera (*Chilostomella oolina*, *Globobulimina pacifica*) showed greater differences from estimates of those of DIC than shallow benthic foraminifera (*Bulimina mexicana*, *Bolivinita quadrilatera*, *Pullenia bulloides*). This study provides new isotopic and ecological information for *B. quadrilatera*. The mean $\Delta\delta^{13}$C value, defined as foraminiferal δ^{13}C values minus estimated ambient δ^{13}C values from the Aleutian Margin, is 0.97‰ higher for *G. pacifica* than the mean from the Murray Canyon. This difference may result either from genetic or biological differences between the populations or from differences in environmental isotopic influences (such as pore water differences) that were not accounted for in the equilibrium calculations. These analyses provide calibration information for the evaluation of bottom water conditions and circulation patterns of ancient oceans based on fossil foraminiferal geochemistry.

1. Introduction

The geochemistry of cosmopolitan calcareous foraminifera has been a focus of paleoenvironmental studies since researchers recognized that carbon (δ^{13}C) and oxygen (δ^{18}O) isotopic compositions of calcareous microfossils contain information pertaining to the physicochemical environment (Emiliani, 1955; Shackleton, 1974, 1977; Boyle and Keigwin, 1985; Maslin and Swann, 2006). Assessments of isotope data from microfossils, such as foraminifera, require modern analog calibrations of the relationships between living species and ambient conditions (e.g., Duplessy et al., 1970; Grossman, 1984a,b, 1987). Recognition that benthic foraminiferal isotope values are commonly out of isotopic equilibrium with ambient water and that biological and ecological variables may impact the isotopic signatures of foraminifera (e.g., McCorkle et al., 1990, 1997) highlighted the importance of an understanding of isotopic disequilibrium between foraminifera and the wide variety of environments they live in around the globe. Relatively few studies, however, have compared the stable isotopic values of living benthic foraminifera from different regions (e.g., Graham et al., 1981; Grossman, 1984a,b, 1987; McCorkle et al., 1990, 1997; Mackensen et al., 1993, 2000; Rathburn et al., 1996; Corliss et al., 2002; Schmiedl et al., 2004).

In this study, we present the first stable isotope (δ^{18}O and δ^{13}C) values of live (identified through rose Bengal staining) benthic foraminifera from locations in the North Pacific (on the Aleutian Margin, water depth 1988 m) and Murray Canyons group in the Southern Indian Ocean (Australian Margin, water depths 2476 m and 1634 m). Both areas are remote and largely unexplored regions, that have not been investigated until recently. Submarine canyons, adjacent to continents and deep-sea settings with little prior information characterize both regions. These two locations thus allow comparison of carbon and oxygen isotope values of live benthic foraminifera from two unexplored geological settings. Standard

---

[*] Corresponding author. Tel.: +1 812 237 2269; fax: +1 812 237 8029.
E-mail address: arathburn@indstate.edu (A.E. Rathburn).
[1] Present address: Department of Geological Sciences, University of Florida, Gainesville, Florida 32611, USA.
[2] Present address: Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0218, USA.

0377-8398/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.marmicro.2008.11.002

techniques used by previous workers (e.g., Rathburn et al., 1996; McCorkle et al., 1997) were employed to provide reasonable estimates of environmental parameters, which are not available from these locations. By comparing foraminiferal isotope data from remote study sites with those of previous studies, it is possible to obtain better information about isotopic equilibrium–disequilibrium relationships from foraminifera in different hydrographic regimes. Typically there is a narrow range of isotopic values within a species from a given study area regardless of the sediment depth where specimens are found (e.g., McCorkle et al., 1997). We seek to contribute to an understanding of this phenomenon by comparing foraminiferal isotopes from widely separated regions that have not previously been studied.

2. Regional setting

Although submarine canyons are common features of continental margins (Mulder et al., 2004), they have only recently been systematically sampled off the coast of South Australia (Hill et al., 2005) and the Aleutian Islands in the North Pacific (Rathburn et al., in press). In general, canyon systems, including the canyons and the ridges

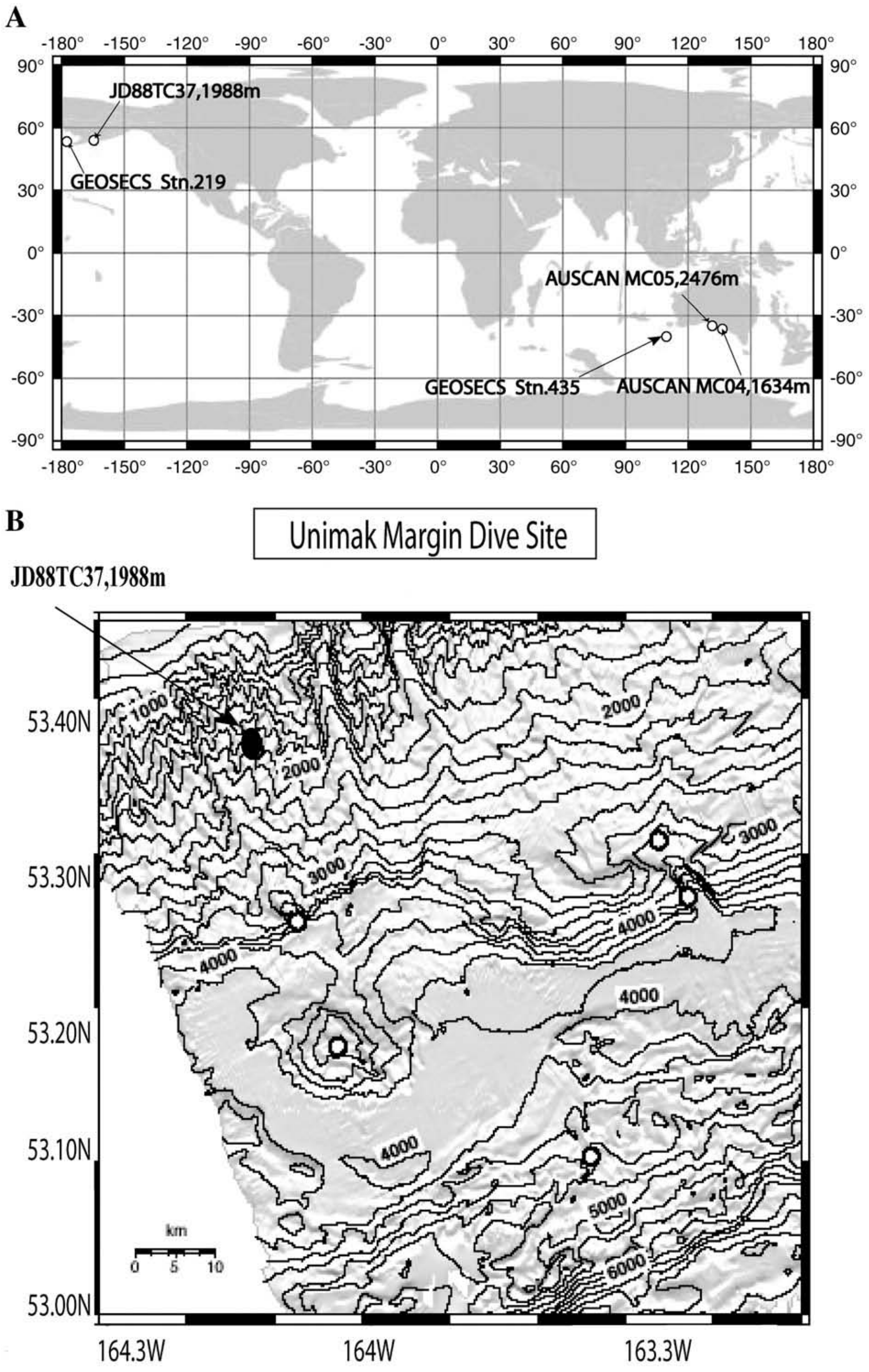

Fig. 1. A) Sampling sites and GEOSECS stations from the North Pacific and SE Indian Ocean; B) Aleutian (Pacific) Margin study area bathymetric chart showing sampling site. Map adapted and modified from Rathburn et al. (in press); C) South Australian Margin study area bathymetric chart showing sampling sites. Map adapted and modified from Hill et al. (2005).

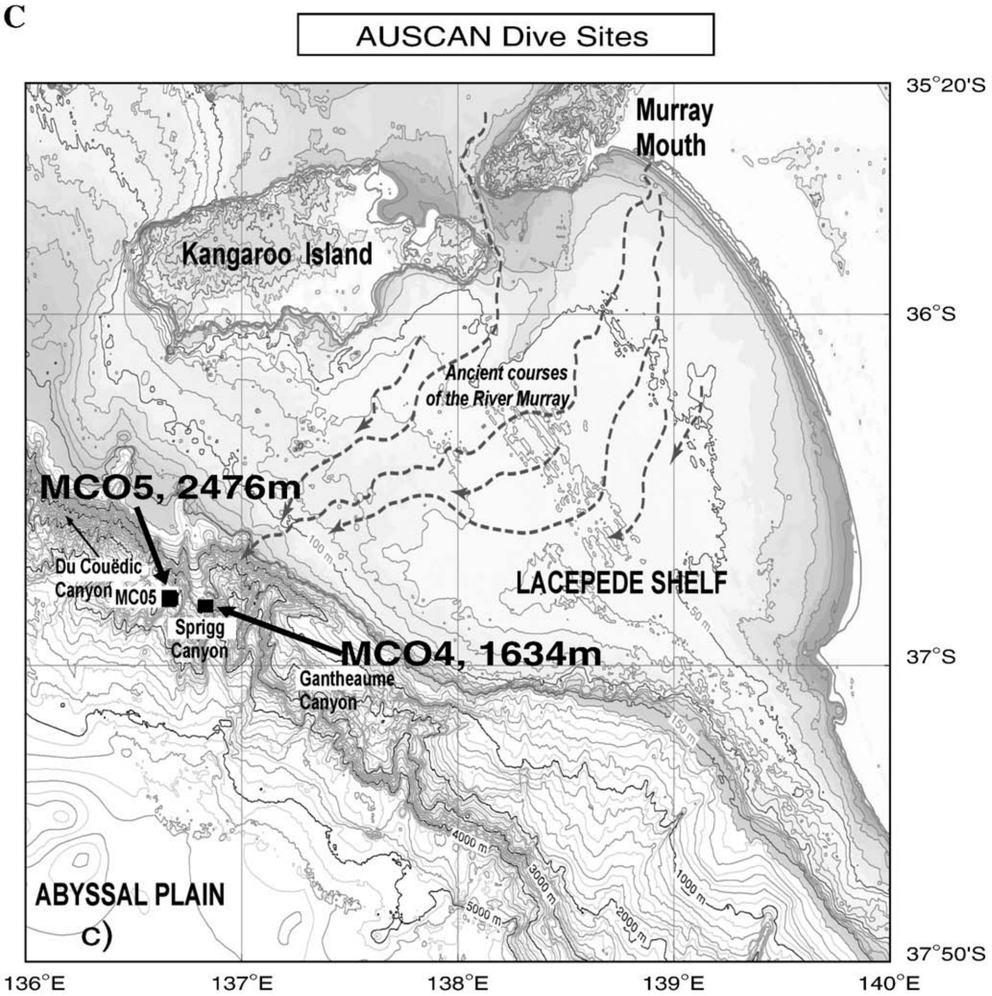

Fig. 1 (*continued*).

between them, are often difficult to sample and are typically not well studied, especially in remote locations. Previous studies of living foraminifera from canyon environments include Jorissen et al. (1994), Schmiedl et al. (2000, 2004), Fontanier et al. (2005), Hess et al. (2005), and Koho et al. (2007).

The seafloor of the North Pacific near the Aleutian Islands is mostly unexplored (Fig. 1A, B). A small region south of Unimak Island was mapped and sampled during a cruise in July 10–23, 2004. During this cruise, multibeam surveys revealed a complex canyon system with thrust faults and a deeply eroded slope. This region is bathed by Pacific Deep Waters (PDW) (Piepgras and Jacobsen, 1988).

The South Australia Margin includes the Murray Canyon Group, located near the mouth of the Murray River, which is characterized by a number of submarine canyons, including the Murray Canyon System (Fig. 1A, C). East flowing Circumpolar Deep Current (CPDW) constitutes the main water mass from the bottom to about 1200 m water depth (Emery and Meincke, 1986; Gingele and De Deckker, 2005). Results presented here are part of a larger international research effort (AUSCAN), which was designed to better understand the geology, biology and oceanography of the region (see Hill et al., 2005).

3. Materials and methods

Samples from the Aleutian Margin were collected during a single cruise on the *R/V Roger Revelle* in 2004 (Fig. 1B). Many of the seafloor samples collected in the region were dominated by agglutinated foraminifera, but push core JD88 TC37 (inner core diameter = 8.3 cm) provided sufficient calcareous foraminifera to be used in this study. Core JD88-TC37 was collected by the remotely operated vehicle (ROV) JASON II from the floor of a canyon (1988 m water depth). The Australian samples were collected using a multicorer (inner core diameter = 9.5 cm) deployed from the *R/V Marion Dufresne* during a cruise conducted in January–March 2003. Samples were obtained at water depths of 2476 m (core MC05) and 1634 m (core MC04) on ridges between canyons of the Murray Canyon Group located 60 km south of Kangaroo Island, Australia (Fig. 1A, C).

3.1. Foraminiferal processing

Each core had clear seawater overlying an undisturbed sediment–water interface, indicating little physical disturbance of the sediment. Only rose Bengal stained foraminifera, interpreted to be living or recently living at the time of collection, were used for isotopic analyses. The uppermost sample included the top 1 cm (0–1 cm), followed by samples every 0.5 cm intervals down to 3 cm. Below 3 cm, samples were collected at 1 cm intervals down to at least 9 cm. Sediments from each sampling interval were preserved in bottles with 200 mL of 4% formaldehyde solution buffered with Mule Team Borax© (diluting 37% formaldehyde solution by a factor of about 10 using filtered seawater) following procedures outlined in Rathburn and Corliss (1994). The volume of the liquid added to each sample bottle was recorded to determine the sediment volume from each interval. In the laboratory, 65 mL of rose Bengal stain solution (1 g/L of 4% formaldehyde) was added to each sample bottle. Rose Bengal staining provides a means to assess protoplasm-containing specimens that were alive or recently alive at the time of collection. This staining technique is commonly used in studies of modern foraminifera and their isotopic signatures, and the advantages and limitations of this technique are well known (e.g., Murray and Bowser, 2000; Bernhard et al., 2006). Once samples had been stained for at least a week, they were wet sieved using 63 µm and 150 µm mesh sieves. The >150 µm fraction of the sediment was used for this study while the 63–150 µm fraction was stored. As a result of the larger volume of sediment in the >150 µm fraction, samples from the Murray Canyon Group, Australia, were wet-split in a modified Otto micro splitter. Each sample was placed in a gridded petri dish with distilled water, and rose Bengal stained benthic foraminifera were wet-picked and sorted onto micropaleontological slides for taxonomic identification and subsequent isotopic analyses.

Only limited ecological information relevant to the isotope values is presented here; a more complete assessment of foraminiferal abundances and ecology will be discussed elsewhere. Vertical distribution profiles are presented as number of individuals (ind.) per 50 cm^3. In accordance with previous studies (e.g., Corliss, 1985; McCorkle et al., 1990, 1997; Rathburn et al., 1996) abundances were plotted at the lowermost boundary of the sample interval. For example, the abundance of foraminifera found in the 0–1 cm interval would be plotted at 1 cm. Although Buzas et al. (1993) pointed out that species occurring in the top 1 cm may be living within the sediment and could be considered “shallow infaunal,” the microhabitat preferences referred to in this study follow those defined in Corliss and Emerson (1990). The term “epifaunal” refers to taxa that primarily reside in the 0–1 cm interval (at or near the sediment water interface), “shallow infaunal” refers to taxa that are able to live deeper in the sediment within the upper few cm, and “deep infaunal” refers to taxa that can have maximum abundances deeper in the sediment.

3.2. Environmental data

Seafloor sediments in the Aleutian Margin study area had total organic carbon (TOC) values between 2.9 and 15.2 mg/g (dry weight) and Carbon/Nitrogen ratios ranging from 8.3 to 9.3. The site at 1988 m also examined in this study had one of the highest TOC values in the study area at 15.2 mg/g and a C/N ratio of 8.5 (Rathburn et al., in press). Chlorophyll a and phaeopigment values of the sediments at this site were the highest in the study area (8.5 µg/g and 25.9 µg/g respectively) reported by Rathburn et al. (in press). Surface primary productivity (represented by mean chlorophyll concentration) near the Aleutian Islands observed from month by month satellite imagery indicates the presence of a prominent seasonality. The range of mean chlorophyll values during June–July (time of collection of cores) is about 3–5 mg/m^3. Estimates of primary productivity calculated using ^{14}C-labeled bicarbonate at eight different light intensities indicated the values to be 910 +/−150 and 770 +/−70 mg $Cm^{-2}day^{-1}$ for June 2001 and 2002 respectively (Mordy et al., 2005). The core from the Aleutian Margin used in this study was collected during the boreal summer so we estimate that the primary productivity was in the range of between 770 and 910 mg $Cm^{-2}day^{-1}$ (Mordy et al., 2005). These values are similar to those of some of the high productivity sites in the Southern California Bight routinely monitored by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program (e.g., ~1072 mg $Cm^{-2}day^{-1}$ (Station 80–55) and ~782 mg $Cm^{-2}day^{-1}$ (Station 83.3–51) in July 2007 (http://www.calcofi.org/newhome/data/2000s.htm).

Surface productivity studies are not available in the Southern Indian Ocean (near the Australian Margin), but comparing the monthly chlorophyll values from satellite images (over a year) (http://marine.rutgers.edu/opp/Chlorophyll/Chlorophyll1.html) there seems to be no seasonal variation. The mean chlorophyll value for February (time of collection of the cores) was around 0.3 mg/m^3. Based on the chlorophyll values, which can be used as an indicator of primary productivity (e.g., Hayward and Venrick, 1998), the overall surface primary productivity of the Australian Margin sites during the time of sampling was lower compared to the surface primary productivity of the North Pacific sites.

Table 1
Description of samples used in this study and estimated bottom water (DIC) carbon isotope and oxygen isotope values for sampling sites

	JD88TC37	AUSCAN MC05	AUSCAN MC04
Core collection method	ROV JASON II	Multicorer	Multicorer
Number of isotopic analyses (C & O)	13	30	11
Latitude	53°36.70 N	36°43.72 S	36°48.77 S
Longitude	164°12.335 W	136°32.81 E	136°48.98 E
Depth (m)	1988	2476	1634
Salinity (psu)	x	34.691	34.549
Temperature(°C)	1.9	02.167	02.727
Oxygen (µmol/kg)	x	183.877	160.87*
Bottom water $\delta^{13}C_{b.w}$ used for all calculation purposes (‰)	−0.5	0.37	0.25
Bottom water $\delta^{18}O_{b.w,SMOW}$ used for all calculation purposes (‰)	−0.15	0.08	0.06

* Oxygen value from Levitus atlas.

We cannot reasonably estimate the influences of lateral transport in the canyon systems off southern Australia and the North Pacific. These are relatively unexplored areas, and, except for the cruises where the study material was collected, not much other relevant work has been done in these regions. Since core locations on the Australian Margin are on canyon ridges, lateral transport is probably not a major factor influencing these sediments. Lateral transport may be a factor for the site of the Aleutian Margin core, but this is not easy to ascertain quantitatively.

3.3. Stable isotope analyses

Living (Rose Bengal stained) specimens of calcareous benthic foraminifera without any signs of chemical or physical alterations were selected for stable isotope analyses. We were careful to use specimens of comparable size from the >150 µm fraction to avoid any isotopic effects due to ontogenetic variation. Each specimen was subjected to two steps of cleaning following procedures outlined in Rathburn et al. (2003). The first step involved mechanically cleaning the specimen by repeated rinses in distilled water and reagent grade methanol followed by ultrasonication to remove adhering detrital material (Rathburn and De Deckker, 1997). The second step included removal of the organic matter by soaking the specimens in 15% hydrogen peroxide for 15 minutes followed by rinsing with methanol (Rathburn and De Deckker, 1997; Rathburn et al., 2003; Martin et al., 2004). Three specimens of *Globobulimina pacifica* and two specimens of *Globobulimina* spp. from the Australian Margin were broken using a metal probe and the isotopic numbers for these specimens are reported as an average of the two analyses of the broken test.

Cleaned foraminifera were then treated with anhydrous phosphoric acid at 73 °C and analyzed using a Kiel III device connected to a Finnigan MAT 252 isotope ratio mass spectrometer in the Department of Geological Sciences at the University of Florida. Depending on the size of the tests, broken tests or single tests were included in the analyses. Data are reported with respect to PDB standard. Precision of the technique was measured with an internal standard of Carrera Marble calibrated with NSB-19, and found to be ±0.04‰ for $\delta^{18}O$ and ±0.08‰ for $\delta^{13}C$.

Table 2
Stable isotopic values for all foraminiferal specimens analyzed in this study

Interval	Taxon	JD88TC37				AUSCAN MC05				AUSCAN MC04			
Cm		$\delta^{13}C$	$\Delta\delta^{13}C$	$\delta^{18}O$	$\Delta\delta^{18}O$	$\delta^{13}C$	$\Delta\delta^{13}C$	$\delta^{18}O$	$\Delta\delta^{18}O$	$\delta^{13}C$	$\Delta\delta^{13}C$	$\delta^{18}O$	$\Delta\delta^{18}O$
0–1.0	*Globobulimina pacifica*	x	x	x	x	−1.56	−1.93	3.81	0.34	x	x	x	x
	Globobulimina pacifica	x	x	x	x	−1.80	−2.18	3.73	0.26	x	x	x	x
	Bulimina mexicana	x	x	x	x	−0.65	−1.02	3.57	0.10	−1.07	−1.32	3.12	0.02
	Hoeglundina elegans	x	x	x	x	1.45	1.08	4.06	0.59	x	x	x	x
	Bolivinita quadrilatera	x	x	x	x	−0.78	−1.15	3.28	−0.19	x	x	x	x
	Bolivinita quadrilatera	x	x	x	x	−1.11	−1.49	3.27	−0.20	x	x	x	x
1.0–1.5	*Bulimina mexicana*	x	x	x	x	−0.78	−1.16	3.02	−0.45	x	x	x	x
	Bulimina mexicana	x	x	x	x	−0.55	−0.93	3.32	−0.15	x	x	x	x
	Globobulimina pacifica	x	x	x	x	−1.00	−1.37	3.54	0.07	x	x	x	x
1.5–2.0	*Globobulimina pacifica*	x	x	x	x	−1.12	−1.50	2.80	−0.67	x	x	x	x
2.0–2.5	*Bulimina mexicana*	x	x	x	x	−0.77	−1.15	3.71	0.24	x	x	x	x
	Bulimina mexicana	x	x	x	x	−1.14	−1.51	3.28	−0.19	x	x	x	x
	Globobulimina pacifica	x	x	x	x	−1.30	−1.67	3.63	0.16	x	x	x	x
	Globobulimina pacifica	x	x	x	x	−1.47	−1.84	3.48	0.01	x	x	x	x
	Globobulimina pacifica	x	x	x	x	−1.54	−1.92	3.79	0.32	x	x	x	x
2.5–3.0	*Globobulimina pacifica*	−1.81	−1.31	3.64	0.29	x	x	x	x	x	x	x	x
	Globobulimina pacifica	−1.12	−0.62	3.76	−0.41	x	x	x	x	x	x	x	x
	Bulimina mexicana	x	x	x	x	−0.94	−1.31	3.33	−0.14	x	x	x	x
	Globobulimina pacifica	−1.59	−1.09	3.64	0.29	−1.65	−2.02	3.66	0.19	x	x	x	x
	Globobulimina pacifica	−2.85	−2.35	2.56	−0.79	−1.80	−2.17	3.55	0.08	x	x	x	x
3.0–4.0	*Chilostomella oolina*	x	x	x	x	−2.22	−2.59	3.52	0.05	−1.93	−2.18	3.24	0.14
	Globobulimina spp.	x	x	x	x	x	x	x	x	−1.29*	−1.39*	3.43*	0.33*
	Globobulimina spp.	x	x	x	x	x	x	x	x	−1.41*	−1.66*	3.40*	0.30*
	Globobulimina pacifica	−1.62	−1.12	3.20	−0.15	−1.66	−2.04	3.44	0.03	x	x	x	x
	Globobulimina pacifica	−1.11	−0.61	3.45	0.10	x	x	x	X	x	x	x	x
	Globobulimina pacifica	−1.82	−1.32	3.46	0.11	x	x	x	X	x	x	x	x
	Globobulimina pacifica	−1.00	−0.50	3.75	0.40	x	x	x	X	x	x	x	x
4.0–5.0	*Globobulimina pacifica*	−1.65	−1.15	3.77	0.42	x	x	x	X	x	x	x	x
	Globobulimina pacifica	−0.79	−0.29	4.21	0.86	x	x	x	X	x	x	x	x
	Globobulimina pacifica	x	x	x	x	−1.95	−2.32	3.70	−0.23	x	x	x	x
	Globobulimina pacifica	x	x	x	x	−1.49*	−1.87*	3.45*	−0.04*	x	x	x	x
	Bulimina mexicana	x	x	x	x	x	x	x	X	−0.59	−0.84	3.09	−0.01
	Bulimina mexicana	x	x	x	x	x	x	x	X	−0.48	−0.73	3.14	0.04
	Bolivinita quadrilatera	x	x	x	x	x	x	x	X	−1.24	−1.49	3.13	0.03
	Chilostomella oolina	x	x	x	x	−2.23	−2.61	3.32	−0.15	x	x	x	x
5.0–6.0	*Globobulimina* spp.	x	x	x	x	−1.72	−2.09	3.72	0.25	x	x	x	x
	Globobulimina spp.	x	x	x	x	−1.73	−2.10	3.59	0.12	x	x	x	x
	Pullenia bulloides	x	x	x	x	x	x	x	X	−1.21	−1.46	3.00	−0.10
	Bulimina mexicana	x	x	x	x	x	x	x	X	−0.91	−1.16	3.01	−0.09
6.0–7.0	*Globobulimina pacifica*	−1.26	−0.76	3.57	0.22	−1.76*	−2.16*	3.46*	−0.06*	x	x	x	x
	Globobulimina pacifica	−0.73	−0.23	3.73	0.38	x	x	x	x	x	x	x	x
	Globobulimina pacifica	−1.49	−0.99	3.56	0.21	−1.45*	−1.82*	3.30*	−0.17*	x	x	x	x

Note that although *H. elegans* is aragonitic, the $\Delta\delta^{18}O$ value (0.59‰) reported here for this species is based on the calcite equation (for comparison with previous studies). Accounting for the range of analytical error in the aragonite equation, the calculated range of $\Delta\delta^{18}O$ values for *H. elegans* in this study is 0.56 to 0.59‰. See text for more details.
'x' = No benthic foraminifera specimens. '*' = Average values of individual foraminifera which were broken into halves for isotope analyses.
S.D values for $\Delta\delta^{13}C$ and $\Delta\delta^{18}O$: Aleutian (Pacific) Margin (*Globobulimina pacifica* = +/−0.56 and +/−0.38); South Australian Margin (*Globobulimina pacifica* = +/−0.25 and +/−0.24, *Bulimina mexicana* = +/−0.24 and +/−0.19, *Bolivinita quadrilatera* = +/−0.20 and +/−0.13, *Chilostomella oolina* = +/−0.26 and +/−0.15, *Globobulimina* spp. = +/−0.26 and +/−0.08).

3.4. Bottom water $\delta^{13}C$ and $\delta^{18}O$

We estimated ambient seawater stable isotopic values of appropriate water column depths using previous geochemical data repositories such as GEOSECS, Levitus and Boyer (1994), Levitus et al. (1994), and the World Ocean Circulation Experiment (WOCE) Database and Atlas. Using these resources to estimate bottom water characteristics is not an unusual procedure, and data from these resources yield reliable estimates (e.g., Rathburn et al., 1996). In the North Pacific Ocean, the $\delta^{13}C$ value of dissolved inorganic carbon (DIC) at a water depth of 1945 m was estimated to be −0.5‰ based on section P17 (the Gulf of Alaska) of the WOCE Atlas. This value is consistent with direct measurements of ambient water DIC $\delta^{13}C$ at 2000 m water depth in the Bering Sea (−0.5‰ unpublished data, Daniel McCorkle, WHOI). Bottom water DIC $\delta^{13}C$ was also estimated to be −0.31 using apparent oxygen utilization (AOU) as explained below. Both the estimated (−0.31‰) and direct (−0.5‰) $\delta^{13}C$ measurements were comparable and we choose to use the later. Our estimated values are within the expected range of DIC $\delta^{13}C$ values based on reported values from the region, and we believe that our estimates for the North Pacific and the Australian Margin are within 0.2‰.

Bottom water DIC $\delta^{13}C_{(b.w.)}$ values were estimated for the South Australian Margin bottom water using the relationship between apparent oxygen utilization (AOU, dissolved oxygen saturation — measured dissolved oxygen levels) and DIC $\delta^{13}C_{(b.w.)}$ in ocean water according to Kroopnick (1985):

$$\delta^{13}C_{(b.w.)} = 1.5 - 0.0075 * AOU \tag{1}$$

Oxygen data collected from the South Australian Margin during the cruise (obtained onboard through oxygen sensors on CTD lowerings) and oxygen values from Levitus and Boyer (1994), Levitus et al. (1994) were used separately to estimate AOU at the water depths of our site. Oxygen saturation at 2476 m and 1634 m was estimated according to (Weiss, 1970). Seasonal changes in sea surface productivity in the area might have an effect on bottom water AOU, but monthly comparisons of surface water chlorophyll data show no

Table 3
Range of $\Delta\delta^{13}C$ and $\Delta\delta^{18}O$ of all specimens of benthic foraminifera used in this study

Microhabitat preference	Taxon	AUSCAN MC 05		AUSCAN MC 04	
		Range $\delta^{13}C$ (‰)	Range $\delta^{18}O$ (‰)	Range $\delta^{13}C$ (‰)	Range $\delta^{18}O$ (‰)
Epifaunal (0–1 cm)	*Hoeglundina elegans**	(1.45)	(3.57)		
Shallow Infaunal (0–2 cm)	*Bulimina mexicana*	(−0.94)–(−0.65)	(3.02)–(3.71)	(−1.07)–(−0.48)	(3.01)–(3.14)
	Bolivinita quadrilatera	(−1.11)–(−0.78)	(3.28)–(3.13)		
	*Pullenia bulloides**			(−1.21)	(3.01)
Deep Infaunal (>4 cm)	*Chilostomella oolina*	(−2.22)–(−2.23)	(3.32)–(3.53)		
	Globobulimina pacifica	(−1.95)–(−1.0)	(2.8)–(3.81)		
	Globobulimina spp.			(−1.73)–(−1.27)	(3.37)–(3.43)

See text for calculation details.
* Single specimen analyzed, so no range could be obtained.

prominent seasonality in this area. So it is reasonable to assume that AOU had been more or less constant at this site. Using the two different calculated AOU values, the bottom water DIC $\delta^{13}C$ values were estimated to be 0.37‰ and 0.25‰ for cores MC05 (2476 m) and MC04 (1634 m) respectively (Table 1).

North Pacific bottom water $\delta^{18}O$ values are available from GEOSECS Station 219 (53.105 N, 177.305 W, about 870 km from the N. Pacific site) and were compared with an unpublished $\delta^{18}O$ profile (data from D. McCorkle, WHOI) from the nearby Bering Sea. At GEOSECS station 219, the oxygen isotopic value was −0.06‰ (SMOW) at 2582 m water depth, but may not be a good approximation because the GEOSECS station is separated from our site by sills. In the Bering Sea, $\delta^{18}O_{SMOW}$ values were found to be −0.15‰ $_{SMOW}$ at 2000 m water depth (D. McCorkle, written communication). In the calculations below, we use the value of −0.15‰ (SMOW) to represent bottom water isotopic composition. Murray canyon *in situ* water $\delta^{18}O$ values (0.08‰ for MC05 and 0.06‰ for MC04; Table 1) were estimated from the nearest GEOSECS Station 435 (39.952 S, 109.970 E, about 2300 km from the Australian sites).

3.5. Foraminiferal $\delta^{13}C$ and $\delta^{18}O$

In accordance with procedures adopted in McCorkle et al. (1990, 1997) and Rathburn et al. (1996), carbon isotopic values are expressed as the difference between THE VALUES OF the foraminiferal test and those of bottom water DIC ($\Delta\delta^{13}C = \delta^{13}C_{\text{foraminifera}} - \delta^{13}C_{(\text{b.w.})}$), while oxygen isotopic values are expressed as the difference between foraminiferal test $\delta^{18}O$ and the oxygen isotopic value in calcite in equilibrium with bottom water conditions ($\Delta\delta^{18}O = \delta^{18}O_{\text{foraminifera}} - \delta^{18}O_{(\text{e.c.})}$) (Table 2). For comparison purposes, the $\delta^{18}O_{(\text{e.c., SMOW})}$ was converted to $\delta^{18}O_{(\text{e.c., PDB})}$ for a given $\delta^{18}O_{(\text{b.w., SMOW})}$ and temperature T (in degrees Kelvin) using Eqs. (2) and (3). Eq. (2) has been derived using calcite–water fractionation factor from Friedman and O'Neil (1977).

$$\delta^{18}O_{(e.c.,\text{SMOW})} = \left\{ e^{\left((2.78\times10^{3}/T^{2})-(2.89/10^{3})\right)} \times \left(\delta^{18}O_{(b.w.,\text{SMOW})} + 1000\right) \right\} - 1000 \tag{2}$$

$$\delta^{18}O_{(e.c.,\text{PDB})} = \left(0.97006 \times \delta^{18}O_{(e.c.,\text{SMOW})}\right) - 29.94 \tag{3}$$

All species of foraminifera used in this study are calcitic except *Hoeglundina elegans,* which is aragonitic. Although *H. elegans* is aragonitic, most previous studies examining living benthic foraminiferal isotopes (e.g., Rathburn et al., 1996; McCorkle et al., 1997; Fontanier et al., 2006) used the calcite equation to calculate isotopic disequilibrium for this species. We used the same equation as others did so that we could compare our values with theirs. However, we also calculated disequilibrium values for *H. elegans* using the aragonite equation.

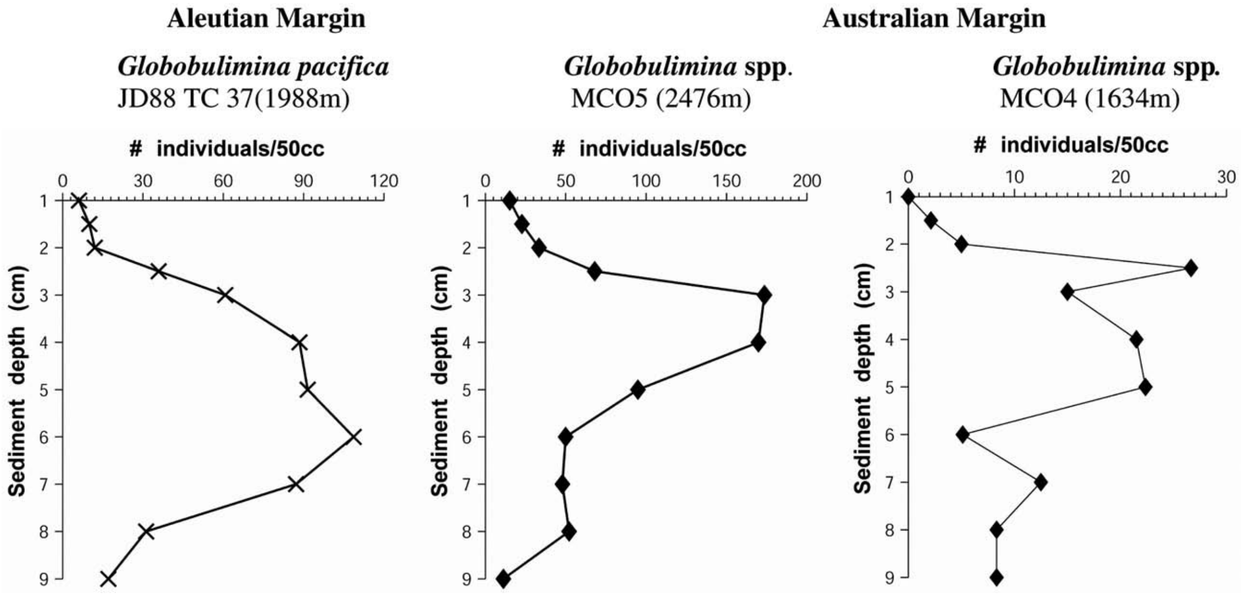

Fig. 2. Vertical distributions of *Globobulimina* (number of foraminifera/50 cm^3) in the > 150 µm fraction relative to sediment depth (in cm). Note the scale change. Values are plotted at the base (lowermost boundary) of the interval from which foraminifera were extracted.

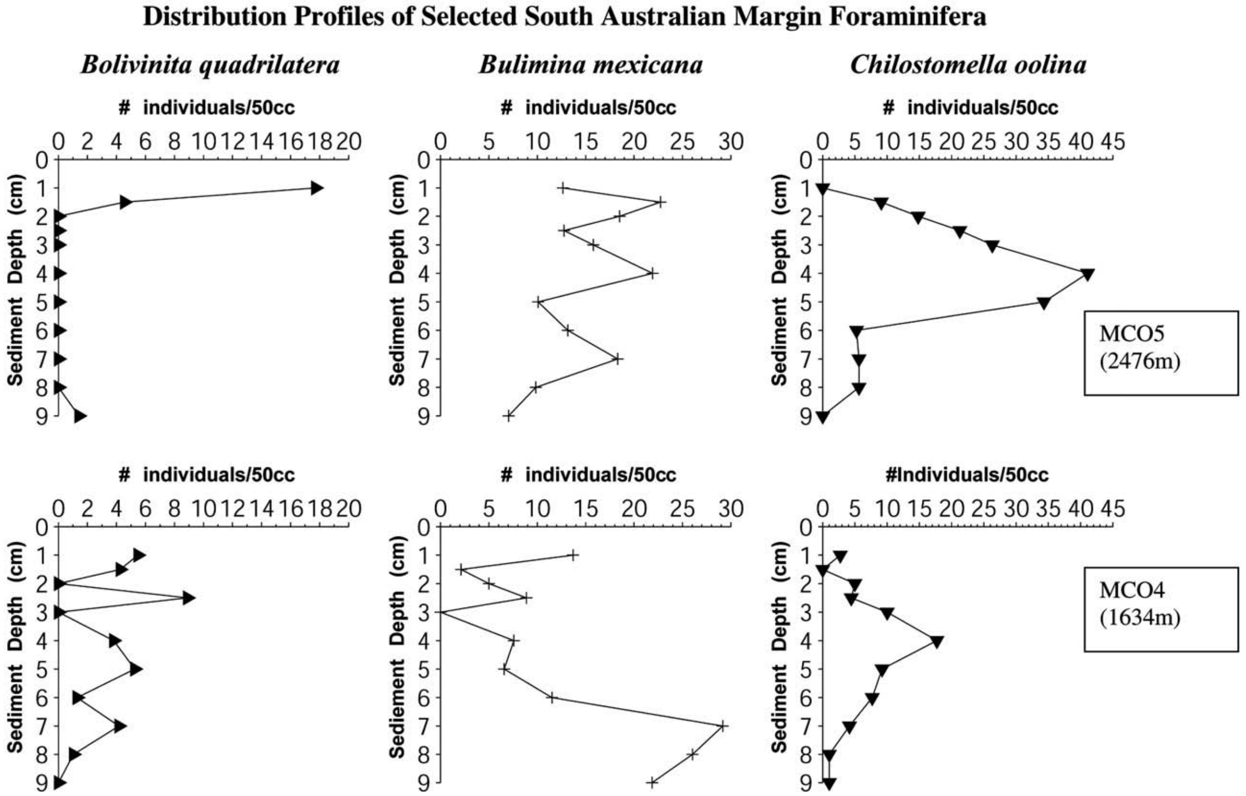

Fig. 3. Vertical distributions of selected species of benthic foraminifera (>150 μm) from core MC05 (2746 m) and MC04 (1634 m) expressed (number of foraminifera/50 cm^3) relative to sediment depth (in cm). Note the scale change. Values are plotted at the base (lowermost boundary) of the interval from which foraminifera were extracted.

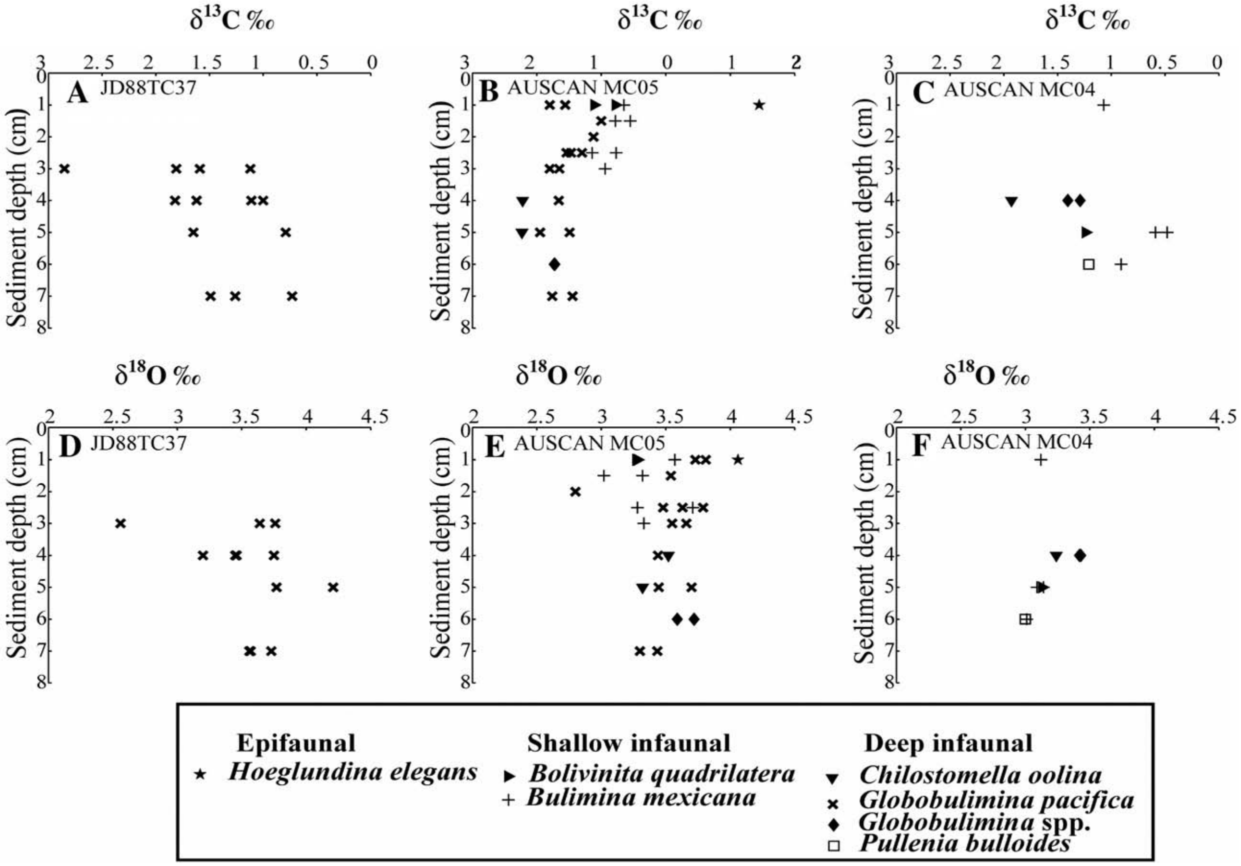

Fig. 4. δ^{13}C and δ^{18}O values (‰, PDB) for benthic foraminiferal species collected from Aleutian Margin [(A, D) 1988 m] and Murray Canyon group [(B, E) 2476 m; (C, F) 1634 m]. Values are plotted at the base (lowermost boundary) of the interval from which foraminifera were extracted.

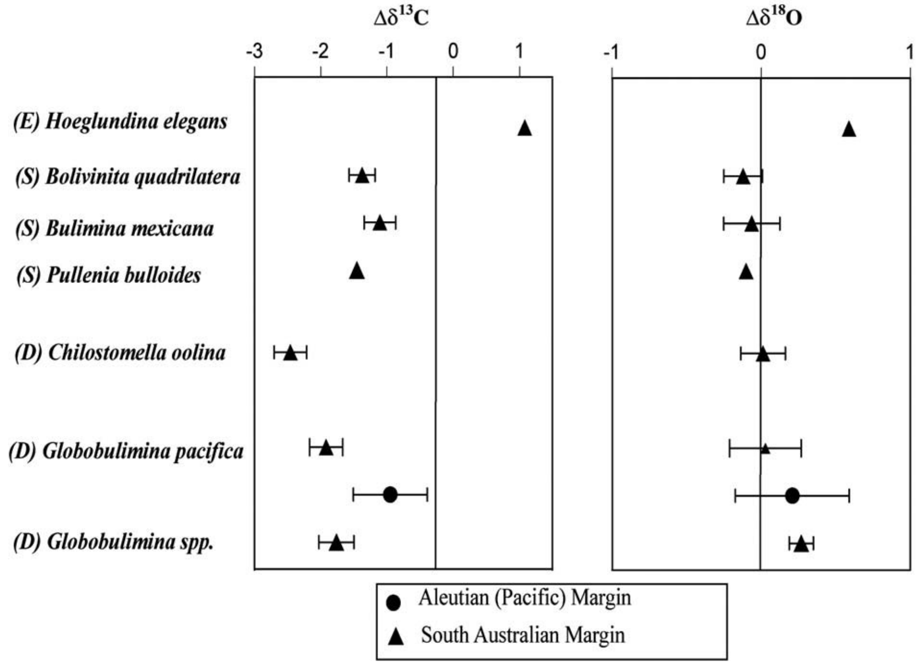

Fig. 5. Dark triangles (▲) and dark circles (●) represent the average $\Delta\delta^{13}C$ and $\Delta\delta^{18}O$ values of species from the South Australian Margin and Aleutian (Pacific) Margin respectively. Error bars indicate standard deviations of the isotopic values. Species have been categorized as epifaunal (E), shallow infaunal (S), and deep infaunal (D). Data points without standard deviation values represent a single isotopic value obtained through analysis of small specimens. *Globobulimina* species that could not be definitely identified as *G. pacifica* or *G. affinis* are grouped together as *Globobulimina* spp. For comparisons with previous studies, $\Delta\delta^{18}O$ (0.59) plotted for the aragonitic species, *Hoeglundina elegans*, has been calculated using a calcite fractionation factor. The $\Delta\delta^{18}O$ calculated for this species using an aragonite fractionation factor ($\alpha_{\text{aragonite–water}}$) produces approximately the same value. See text for more details.

Based on laboratory experiments at temperatures of 0–40 °C, Kim et al. (2007) determined that the aragonite fractionation factor ($\alpha_{\text{aragonite–water}}$) is defined by the equation,

$$1000\ln\alpha_{\text{aragonite–water}} = 17.88 \pm 0.13\left(10^3/T\right) - 31.14F0.46.$$

Taking the maximum allowable analytical error in the fractionation factor into consideration, a range of values was calculated for oxygen isotopes in aragonite in equilibrium with ambient water.

4. Results

Below we present the vertical distribution patterns of taxa and their stable isotope signatures, and only briefly discuss ecological aspects as they pertain to isotopic compositions. The microhabitat preferences (*sensu* Corliss and Emerson, 1990) of the taxa examined in this study are given in Table 3.

4.1. Vertical distribution patterns

To be consistent with previous comparative studies (McCorkle et al., 1997; Rathburn et al., 2003) foraminiferal abundances within the sediments are plotted at the base of the interval sampled. Only foraminiferal species with sufficient numbers (having at least 5 or more specimens for more than one sediment interval) are presented here. In the Murray Canyon Group, these foraminifera include *Bolivinita quadrilatera*, *Bulimina mexicana*, *Chilostomella oolina*, and *Globobulimina* spp. (*G. pacifica* and *G. affinis* combined), but only *G. pacifica* was abundant in the North Pacific core.

Standing stocks of *Globobulimina* spp. in the North Pacific core (61.84 ind./50 cm^2; 0–9 cm) were different from those in the Australian Margin (MC05 = 667.33 ind./50 cm^2, MC04 = 117.10 ind./50 cm^2; 0–9 cm). *Globobulimina* spp. subsurface abundance patterns were also different between and within sites (Fig. 2). Abundance distributions also differed at the two sampled water depths along the Australian Margin for the other three species that were analyzed. At water depths of 2476 m (MC05), *B. quadrilatera* was most abundant at the 0–1 cm sediment interval (18 ind./50 cm^3) and abundances declined sharply down core to 2 cm (Fig. 3). *B. mexicana* had an oscillating pattern down core, with abundance maxima (about 23 ind./50 cm^3) at 1–1.5 cm and 3–4 cm. *C. oolina*, a deep infaunal species, exhibited a subsurface abundance maximum (41 ind./50 cm^3) at 4 cm. At 1634 m water depth (MC04), *B. quadrilatera* displayed an abundance maximum at the surface and at 2–2.5 cm (9 ind./50 cm^3) (Fig. 3). *B. mexicana* exhibited an abundance peak at 0–1 cm (14 ind./50 cm^3) and a second abundance maximum at 6–7 cm (29 ind./50 cm^3). *C. oolina* had a subsurface maximum (18 ind./50 cm^3) at 3–4 cm, similar in pattern, but lower in abundance compared to MC05 (2467 m).

4.2. $\delta^{18}O$ and $\delta^{13}C$ values

4.2.1. Aleutian (Pacific) Margin

Thirteen individuals of *G. pacifica* were measured for their isotopic compositions. The $\delta^{18}O$ values varied between 2.56‰ and 4.21‰ while $\delta^{13}C$ values ranged from 2.85‰ to −0.73‰ (Fig. 4, Table 2). These values yielded $\Delta\delta^{13}C$ values that ranged between −2.35‰ ± 0.56 and −0.23‰ ± −0.56, with an average value of −0.95‰. The $\delta^{18}O$ values are close to calcite oxygen equilibrium values as shown by $\Delta\delta^{18}O$ values that ranged between −0.79‰ ± 0.38 and +0.86‰ ± 0.38 with an average value of +0.21‰.

4.2.2. South Australian Margin

Stable isotopes were measured on 41 individual foraminifera for six different species (*G. pacifica*, *B. mexicana*, *H. elegans, C. oolina*, *Pullenia bulloides*, and *B. quadrilatera*) from the Southern Australian Margin (30 individuals from MC05 and 11 from MC04). These species range in their microhabitat preferences (sensu Corliss and Emerson, 1990) (Table 3)) between epifaunal (*H. elegans*), shallow infaunal (*B. mexicana*, *B. quadrilatera,* and *P. bulloides*), and deep infaunal (*C. oolina* and *G. pacifica*). Ranges of $\delta^{18}O$ and $\delta^{13}C$ values for different species of

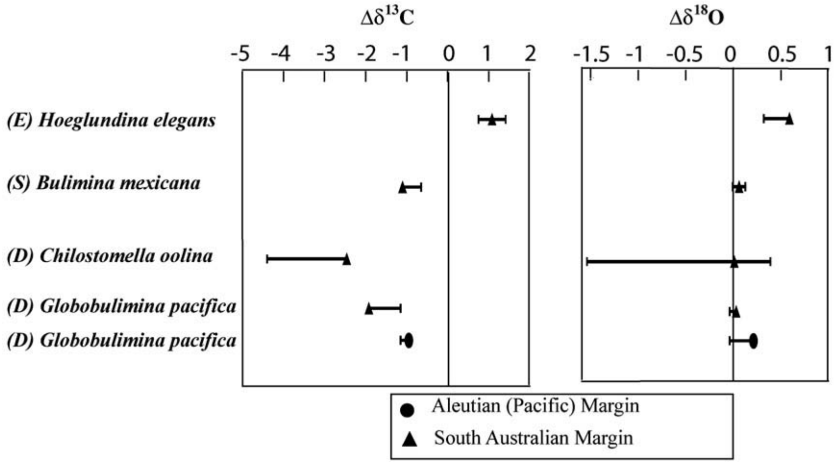

Fig. 6. Comparison of published carbon and oxygen isotope data with mean $\Delta\delta^{13}C$ and $\Delta\delta^{18}O$ from this study. The range of published values for each species is represented as a horizontal bar. Published studies used for this figure include McCorkle et al. (1990, 1997), Rathburn et al. (1996), Corliss et al. (2002), and Fontanier et al. (2006). There are two mean values for *G. pacifica* representing values from the Aleutian (Pacific) Margin and South Australian Margin specimens. The line drawn along the zero mean value denotes the equilibrium value. Letters in parentheses indicate epifaunal (E), shallow infaunal (S) and deep infaunal (D) microhabitat preferences. Note that most of the mean $\Delta\delta^{13}C$ values and some of the mean $\Delta\delta^{18}O$ values reported in this study fall on the extreme edge of the range of published values.

benthic foraminifera are summarized in Table 3. There is no apparent downcore trend in isotope values within a given species (Fig. 4), although deep infaunal taxa have enhanced carbon isotopic disequilibrium values ($\Delta\delta^{13}C$) compared to shallow infaunal taxa. These values are enhanced as much as 1.36‰ between shallow infaunal and deep infaunal species (Fig. 5, Table 3).

Although *H. elegans* is aragonitic, to facilitate comparisons with previous studies, $\Delta\delta^{18}O$ (0.59‰) plotted for this species has been calculated using a calcite fractionation factor ($\alpha_{\text{calcite–water}}$) from Friedman and O'Neil (1977). $\Delta\delta^{18}O$ calculated for *H. elegans* using an aragonite fractionation factor ($\alpha_{\text{aragonite–water}}$) from Kim et al. (2007) produces approximately the same value (using the maximum analytical error in the factor, the value ranges from 0.56‰ to 0.59‰).

5. Discussion

The primary weakness of this study is the paucity of environmental isotope data from which to relate foraminiferal isotope data. We have used available environmental data from previous studies, and use the approach and equations employed by previous workers (e.g., McCorkle et al., 1990; Rathburn et al., 1996) when evaluating foraminiferal isotope data without concurrent measurements of some ambient parameters. This approach has limitations (see Rathburn et al., 1996), but the isotopic estimates we have made are reasonable. We believe the difference between estimated and measured bottom water DIC $\delta^{13}C$ from the North Pacific and the Australian Margin (margin of error in estimated bottom water DIC values) is about 0.2‰. As discussed below, the difference in mean $\Delta\delta^{13}C$ values for *Globobulimina* we observe between sites, however, is much greater than this margin of error (0.97‰). Despite limitations, we believe that our analyses provide insight into the character of relationships between foraminiferal isotopes and ambient conditions. Given the relative scarcity of foraminiferal isotope data from living (stained) benthic foraminifera, these results are presented as an attempt to evaluate isotopic data from these remotely located regions.

Without pore water isotope data, we cannot assess the relationship between the isotopic signatures of infaunal taxa with pore water isotopic compositions. However, the question we pose is: How different are the isotopes of infaunal specimens within and between widely separated environments? Typically there is a narrow range of values within a given study area regardless of the changes in pore water values with depth. We seek to contribute to an understanding of this phenomenon. While it would be very useful to have pore water isotope values, and more data are needed to test our hypotheses, the narrow range of values in some areas compared to others (regardless of pore water values or bottom water estimates) needs to be addressed (see Rathburn et al., 1996, 2003; McCorkle et al., 1997). Most previous papers dealing with infaunal foraminiferal isotopes have correlated the values with bottom water values, and not pore water values, even when isotopic values of pore water DIC were measured (e.g., McCorkle et al., 1990, 1997). We can therefore compare our isotopic data with their results.

Isotopic differences between foraminifera and ambient water DIC may be influenced by a number of variables, including depth in the sediment where foraminifera live, the isotopic composition of dissolved inorganic carbon (DIC), and biological functioning (i.e., vital effects) (e.g., McCorkle et al., 1990; Rathburn et al., 1996, 2003; Erez et al., 2002; Erez, 2003). A number of hypotheses have been proposed to explain benthic foraminiferal isotopic disequilibrium. For example, disequilibrium between benthic foraminifera and ambient pore water may result from accretion of test carbonate (growth) in very restricted microhabitats (e.g., McCorkle et al., 1997; Rathburn et al., 2003), or ontogenetic changes that alter isotopic composition (Schmiedl et al., 2004). Alternatively, foraminifera may calcify their tests at shallower microhabitat depths with isotopically heavier $\delta^{13}C_{DIC}$ than where they commonly live (e.g., McCorkle et al., 1997). Ambient pore water composition is not likely to be the sole control of foraminiferal isotopic composition, however, as individuals of any given species have similar carbon isotope values, regardless of the sediment depth where they are found (e.g., Rathburn et al., 1996; McCorkle et al., 1997). In addition, seasonal studies of vertical distribution patterns and extreme disequilibrium between foraminiferal isotopic signatures and $\delta^{13}C_{DIC}$ in methane seep habitats indicate that migration within the sediments cannot completely account for foraminiferal isotopic disequilibrium (Rathburn et al., 2003). Furthermore, epifaunal species, such as *Cibicides wuellerstorfi* in the Southern Ocean (Mackensen et al., 1993) and *H. elegans* in the North Atlantic (Corliss et al., 2002) can be out of isotopic equilibrium with bottom water $\delta^{13}C_{DIC}$ in areas with high surface productivity, although no appreciable influence of primary productivity was found to control $\delta^{13}C$ values of *C. wuellerstorfi* off Morocco (Eberwein and Mackensen, 2006). The magnitude of isotopic effects derived from sources other than ambient isotopic conditions can be determined by subtracting ambient isotopic values from measured foraminiferal isotopic values (e.g., McCorkle et al., 1990, 1997). These calculations have provided valuable information about the isotopic heterogeneity between populations from different regions, particularly of live (stained)

Table 4
Mean $\Delta\delta^{13}C$ and $\Delta\delta^{18}O$ from this study and other similar studies

Microhabitat preference	Taxon	Aleutians		Murray Canyon		Published studies	
		Average $\Delta\delta^{13}C$	Average $\Delta\delta^{18}O$	Average $\Delta\delta^{13}C$	Average $\Delta\delta^{18}O$	Average $\Delta\delta^{13}C$	Average $\Delta\delta^{18}O$
Epifaunal (0–1 cm)	*Hoeglundina elegans*			1.08	0.59	1.03(2340 m)(1*)	
						2.22(3010 m)(1*)	
						0.85(2)	0.32(2)
Shallow Infaunal (0–2 cm)	*Bulimina mexicana*			−1.1	−0.06	−0.65(3*)	0.005(3*)
						−1.14(5*)[single specimen]	−0.07(5*)
	Bolivinita quadrilatera			−1.38	−0.12		
	Pullenia bulloides			−1.46	−0.10	−1.36(5*)	0.06 (5*)
Deep Infaunal (>4 cm)	*Chilostomella oolina*			−2.46	0.01	−2.65(5*)	−1.52(5*)
						−2.15(5**)	−0.05(5**)
						−4.04(4)	0.38(4)
	Globobulimina pacifica	−0.95	0.21	−1.92	0.03	−1.14(3*)	−0.04(3*)

See text for calculation details.
(1*) Corliss et al. (2002) (North Atlantic), (2) Fontanier et al. (2006), (3*) McCorkle et al. (1997) (California margin), (4) McCorkle et al. (1990), (5*)Rathburn et al. (1996) (Sulu sea), (5**) Rathburn et al. (1996) (South China sea).

benthic foraminifera, in part because they lack diagenetic overprinting (e.g., Rathburn et al., 1996).

Results of previous work suggest foraminiferal isotopic signatures are controlled by microhabitat preferences and ambient water geochemistry (e.g., McCorkle et al., 1990), ontogenetic changes (e.g., Schmiedl et al., 2004), and food preferences (e.g., Mackensen et al., 2006). Although there has been a considerable amount of work on deep-sea foraminifera, stable isotopic data are limited for several important deep-sea species, particularly deep infaunal taxa (such as *Globobulimina* and *Chilostomella*) from remote regions. To our knowledge, the stable isotope data for *B. quadrilatera* presented here are the only stable isotope data available for this species, although limited vertical distribution data of this species have been reported previously in Fontanier et al. (2003) in the Bay of Biscay and Heinz et al. (2005) from methane seeps. There is still much that is not understood about the relationships between environmental and ecological factors and stable isotopic signatures (e.g., Rathburn et al., 2003; Martin et al., 2004). Consequently, a worldwide data set of isotope data from living foraminifera is needed to more confidently interpret paleoceanographic signals recorded in foraminiferal tests.

5.1. Vertical distribution patterns

Observations of the vertical distribution patterns of living benthic foraminifera provide information on preferred habitat depth and can be used to infer how ambient conditions may influence their isotopic compositions (e.g, McCorkle et al., 1990). Although depth distributions for most taxa examined in this study have been observed elsewhere, little is known about the vertical distribution patterns of *B. quadrilatera*. In the South Australian Margin, *B. quadrilatera* preferred a shallow infaunal habitat (Fig. 2), consistent with the pattern observed for this species by Fontanier et al. (2003) in the Bay of Biscay and by Heinz et al. (2005) in methane seeps in the NE Pacific. Bimodal distribution patterns have been reported for *Bulimina* species, and are discussed in Jorissen (1999). Nevertheless, high infaunal abundances of *B. mexicana* found deep (~6–7 cm) in the cores from the South Australian Margin were unusual for this species (e.g., see Rathburn and Corliss, 1994). Pore water chemistry maybe altered at depth by macrofaunal burrows (e.g., Aller and Aller, 1986; Langer et al., 1989; Thomsen and Altenbach, 1993), allowing typically shallow dwelling foraminifera to live deeper in the sediment. However, no evidence of burrows was noted at the depth of high foraminiferal abundance. Similarly, not all species have the same deep-core pattern, suggesting that macrofaunal burrowing is not the cause of the deep infaunal occurrence of *B. mexicana*. Although bimodal distribution patterns are not uncommon among benthic foraminifera, these results suggest that *B. mexicana* may live at a wider range of sediment depths than previously estimated, and may have similar preferences to those of *B. marginata* and *B. aculeata* (e.g., Rathburn et al., 1996; Jorissen, 1999).

Responses to the availability of food and redox conditions also appear to be important controls on the distribution of foraminifera (e.g. Gooday, 1986; Gooday and Rathburn, 1999; Gooday 2003; Jorissen et al., 2007). For example, the deep infaunal *G. affinis* and *C. oolina* have different diets and ecologies (Fontanier et al., 2003; Nomaki et al., 2005, 2006) and may also respond differently to pore water redox conditions (see Jorissen, 1999). Fresh organic matter may be rapidly buried in areas prone to redeposition of sediments from much shallower environments (e.g., Rathburn et al., 1996) changing both food quality and redox conditions in habitats such as those in submarine canyons. In South Australian sediments, the deep abundance maxima of *C. oolina* and *Globobulimina* spp. (Figs. 2 and 3) suggest that subsurface conditions such as redox conditions and food availability were favorable for these taxa.

Previous authors have suggested that *Globobulimina* species respond to the position of redox boundaries (see Jorissen, 1999). At least one *Globobulimina* species appears to use nitrate to respire, enabling this species to live in anoxic sediments for extended periods (Risgaard-Petersen et al., 2006). Without additional data on the availability and quality of the organic material, ontogenetic differences in distributions, and geochemical preferences/tolerances, we can only speculate how these factors may have influenced foraminiferal distribution in the study areas.

5.2. Foraminiferal $\delta^{13}C$ isotopic composition

Average $\Delta\delta^{13}C$ values from this study are similar to previous work (Fig. 6, Table 4) for some species but differ for other species. For example, the aragonitic species, *Hoeglundina elegans* and the calcareous species *B. mexicana*, have similar isotopic offsets (*H. elegans*=1.08‰, *B. mexicana*=−1.1‰) relative to bottom water DIC as those of previous studies (e.g., Rathburn et al., 1996; McCorkle et al., 1997; Corliss et al., 2002). No comparative data are available for *B. quadrilatera*, although this species has an average isotope value consistent with its shallow infaunal habitat. In contrast with *H. elegans* and *B. mexicana*, *Globobulimina* and *C. oolina* show larger than expected isotopic deviations from bottom water DIC. In the Aleutian Margin, *G. pacifica*, a deep infaunal species, had a mean $\Delta\delta^{13}C$ value of −0.95‰±0.56. On the South Australian Margin, *C. oolina* had a mean $\Delta\delta^{13}C$ value of −2.46‰±0.25. Differences in the biology of *G. pacifica* and *C. oolina* could account for isotopic differences between these species, as they do not have similar values when found within the same interval.

Given the probable variability of isotopic compositions of infaunal microenvironments (pore water DIC) around the world, appreciable heterogeneity might be expected in the $\Delta\delta^{13}C$ values of deep-dwelling

Globobulimina. Since previous workers also used bottom water values to calculate $\Delta\delta^{13}C$ for *Globobulimina*, but found relatively little isotopic heterogeneity within each study area, it is possible to examine, on a more global scale, comparative data sets from widely dispersed locations. An average $\Delta\delta^{13}C$ value of −1.15‰ for *Globobulimina* was reported by McCorkle et al. (1997) from the California margin, while Fontanier et al. (2006) reported the average $\Delta\delta^{13}C$ for *Globobulimina* spp. to be −2.03‰, 3.26‰ and −2.93‰ for three stations from the Bay of Biscay. The mean $\Delta\delta^{13}C$ value for *G. pacifica* from the Southern Australian Margin was −1.92‰, near the lower end of the range of *Globobulimina* spp. values from the Bay of Biscay (Fontanier et al., 2006). Mean $\Delta\delta^{13}C$ of *G. pacifica* from the North Pacific was −0.95‰, similar to the mean value from the California margin (e.g., McCorkle et al., 1997). These wide variations in $\Delta\delta^{13}C$ values within a deep infaunal genus indicate that the low variability of isotopic values commonly observed within study areas may not hold true when more data are viewed on a global scale. Since $\Delta\delta^{13}C$ values are based on the difference between test $\delta^{13}C$ values and bottom water DIC $\delta^{13}C$ values, the influence of pore water DIC is not accounted for. As we might expect, based on the likely variability of redox boundaries, organic input, and pore water isotopic characteristics between study areas, some characteristic of deep sediment habitats influences these taxa differently in different environments. Pore water $\delta^{13}C_{DIC}$ values commonly vary by as much as 2‰ within a given region (see McCorkle et al., 1997), which could be responsible for the observed carbon isotopic variation within an infaunal species living within a wide sediment depth range. Without organic flux or pore water isotope data for the canyon systems off southern Australia and the North Pacific, it is not possible to accurately determine the influence of pore water variations, phytodetrital flux or lateral organic flux on foraminiferal isotope signatures in this study. However, as noted by Fontanier et al. (2006), $\delta^{13}C$ values of shallow infaunal taxa are influenced more by changes in phytodetritial flux than those of *Globobulimina*. This limited correspondence in phytodetrital flux and deep infaunal $\delta^{13}C$ values may account for the disequilibrium of *Globobulimina* $\delta^{13}C$ values in some regions, but should reduce isotopic variability within *Globobulimina* species (since phytodetrital flux variation is a primary factor influencing pore water DIC carbon isotopic gradients).

Although variations in pore water chemistry influence the isotopic values of foraminifera living within the sediment, *G. pacifica* and other taxa in MC05 have nearly constant $\delta^{13}C$ values regardless of the sediment depth where they were found. As mentioned previously, a narrow range of isotope values of a given species has been noted by previous studies of benthic foraminifera, but the causes are unknown (e.g., Rathburn et al., 1996; McCorkle et al., 1997). $\delta^{13}C$ values of *G. pacifica* had a wide range on the Aleutian Margin, but the isotopic variation was not associated with sediment depth (Fig. 4). Since isotopic variation of individuals is not related to the sediment depth where they are found living, it seems reasonable to assume that microhabitat preference alone (including tracking of redox boundaries) is not sufficient to explain isotopic disequilibrium and isotopic variability between species. If differences in organic flux do not appreciably affect *Globobulimina* carbon isotopic compositions as implied by Fontanier et al. (2006), and isotopic heterogeneity between individuals of a given study area remains low regardless of sediment depth, some other factor(s) must account for isotopic differences within this taxon. These are important considerations and warrant further investigation.

The more traditional explanations of infaunal isotopic homogeneity within species, such as pore water DIC influences, calcification in a narrow zone, and averaged isotopic values over the life span of an individual (see review in Jorissen, 1999) have recently been augmented with suggestions of other potential influences on foraminiferal isotopic compositions, such as food preferences (e.g., Rathburn et al., 1996; Mackensen et al., 2006), "nano-environments" (on the order of microns) that are different than the average surroundings (e.g., Rathburn et al., 2003), and the influence of symbionts. Bernhard et al. (2001) noted that individuals of the same species from two different habitats did not both have endobionts. We might expect more isotopic variability between individuals of some taxa if endobionts (symbionts?) in benthic foraminifera influence carbonate isotopic composition, as is the case with planktonic foraminifera. Given the potential processes affecting foraminiferal isotopic compositions, biological influences need to be understood to more confidently interpret paleoenvironmental conditions from foraminiferal carbon isotopic signatures in the geologic record.

5.3. Foraminiferal $\delta^{18}O$ isotopic composition

Schmiedl et al. (2004) hypothesized that food availability and interspecific competition at different subsurface habitat depths increased metabolic rates of epifaunal and shallow infaunal benthic foraminifera and produced a negative relationship between $\delta^{18}O$ values of benthic foraminifera and their microhabitat preferences. Schmiedl et al. argued that deep infaunal foraminifera feed on more degraded organic matter, resulting in a lower metabolic rate, which influences calcite precipitation. Studies by McCorkle et al. (1990, 1997), Rathburn et al. (1996) and Fontanier et al. (2006), however, did not report a systematic relationship between foraminiferal $\delta^{18}O$ and the sediment depth where the foraminifera lived, arguing against a metabolic control over foraminiferal $\delta^{18}O$ values.

Despite greater than expected variability, comparisons of AUSCAN and Aleutian foraminiferal $\Delta\delta^{18}O$ with depth also show no relationship between $\Delta\delta^{18}O$ and sediment habitat depth of the studied species (Fig. 5), supporting the inference that metabolic rate does not influence $\delta^{18}O$ values. Benthic foraminiferal $\Delta\delta^{18}O$ values from both study sites showed limited downcore and inter-specific variations similar to previous benthic foraminiferal $\delta^{18}O$ studies (e.g., McCorkle et al., 1997) (Fig. 6 and Table 4). Mean $\Delta\delta^{18}O$ values of *G. pacifica* from this study (0.21‰±0.38 from the Aleutian core and 0.029‰±0.24 for the core from the South Australian sector) were in general agreement with values (−0.04‰±0.09) reported by McCorkle et al. (1990). Variations in *Globobulimina* oxygen isotope values from this study are larger than those observed in previous work (Fig. 6). Standard deviations are ±0.38 ($n=13$) for specimens from the Aleutian Margin, ±0.24 ($n=17$) for the specimens from the South Australian Margin, and ±0.09 ($n=21$) for data from McCorkle et al. (1997), reflecting wider natural variability in individuals of $\delta^{18}O$ of *G. pacifica* than previously reported.

Oxygen isotopic values of deep sea benthic foraminifera commonly have a very narrow range within a species. In the Australian Margin, *C. oolina*, was nearly at equilibrium with bottom water $\delta^{18}O$ values with a mean $\Delta\delta^{18}O$ value of 0.01‰. Previously reported $\Delta\delta^{18}O$ values for *C. oolina* are variable, ranging from +0.37‰ in the Atlantic (McCorkle et al., 1990), to −1.5‰ in the Sulu Sea and −0.05‰ in the South China Sea (Rathburn et al., 1996). It is unclear what controls the differences in disequilibrium of different individuals of this species. Since these differences occur in a single species, taxonomy alone cannot account for isotopic disequilibrium, because vital effects should alter isotopic compositions of specimens equally within species. Consequently, ecological and/or metabolic differences are likely to influence the compositions of these individuals.

6. Conclusions

The $\delta^{13}C$ values for shallow (*B. mexicana*, *B. quadrilatera*, *P. bulloides*) and deep infaunal (*C. oolina, G. pacifica*) benthic foraminifera agree with the hypothesis that microhabitat preferences influence stable isotopic composition of benthic foraminifera. This study provides new isotopic and ecological information for *B. quadrilatera*. As more isotopic data become available, the causes of homogeneity of isotopic values within study sites, and any heterogeneity of isotopic values between sites need to be addressed. In order to more fully assess the relationship between benthic foraminiferal isotope compositions and ambient conditions, additional comparative work is needed from a wide range of environments. *G. pacifica* δ^{18}O values are in equilibrium with $\delta^{18}O_{e.c.}$ in specimens from the Murray Canyon Group with a slightly wider range of values observed in specimens from the North Pacific. Despite greater than expected variability, comparisons of South Australian and Aleutian Margins foraminiferal $\Delta\delta^{18}$O with depth also show no relationship between $\Delta\delta^{18}$O and sediment habitat depth, supporting the inference that metabolic rate does not influence δ^{18}O values in these regions.

Acknowledgements

Funding for collection and analyses of North Pacific samples was provided by NOAA's National Undersea Research Program through the West Coast and Polar Regions Undersea Research Center at the University of Alaska Fairbanks (NOAA-NURC grant UAF 04-0111 to AER, grant UAF-040109 to JBM, and grant UAF 04-0112 to LAL). The AUSCAN cruise was funded by an Australian National Oceans Office grant as well as ARC grant DP0344932, both awarded to PDD. Funding for AUSCAN cruise participation for AER was provided by a grant from the Indiana State University Research Committee. We sincerely appreciate contributions to the AUSCAN cruise effort by the Institut Polaire Français, The Australian National Oceans Office, Geoscience Australia, and the South Australian Research Development Institute. Special thanks to the crew and the science parties of *R/V Marion Dufresne* and *R/V Roger Revelle* for their help during sample collection. Many thanks to Mike Tyron. We also thank J. Adamic, E. Brouliette, C. Gray and B. Wrightsman for help in the lab and Chuang Xuan for technical assistance. We are grateful for input from Ellen Thomas and three anonymous reviewers whose suggestions and comments greatly improved the paper. Many thanks are due to P. Mondal for her constant support and numerous proof reading sessions.

Appendix A. Taxonomic references

Bolivinita quadrilatera (*Schwager*)=Textilaria quadrilatera *Schwager, 1866*
Bulimina mexicana Cushman, 1922
Chilostomella oolina Schwager, 1878
Hoeglundina elegans (d'Orbigny)=*Rotalia elegans* d'Orbigny, 1826
Globobulimina affinis (d'Orbigny)=*Bulimina affinis* d'Orbigny, 1839
Globobulimina pacifica Cushman, 1927
Pullenia bulloides (d'Orbigny)=Nonionina bulloides d'Orbigny, 1826

References

Aller, J.Y., Aller, R.C., 1986. Evidence for localized and enhancement of biological activity associated with tube a burrow structures in deep-sea sediments at the HEBBLE site, western North Atlantic. Deep-Sea Research 33, 755–790.

Bernhard, J.M., Buck, K.R., Barry, J.P., 2001. Monterey Bay cold-seep biota: Assemblages, abundance, and ultrastructure of living foraminifera. Deep-Sea Research I 48, 2233–2249.

Bernhard, J.M., Ostermann, D.R., Williams, D.S., Blanks, J.K., 2006. Comparison of two methods to identify live benthic foraminifera: A test between Rose Bengal and CellTracker Green with implications for stable isotope paleoreconstructions. Paleoceanography 21, PA4210. doi:10.1029/2006PA001290.

Boyle, E.A., Keigwin, L.D., 1985. A comparison of paleochemical records from the North Atlantic and North Pacific Ocean: changes in deep ocean circulation and chemical inventories. Earth and Planetary Science Letters 76, 135–150.

Buzas, M.A., Culver, S.J., Jorissen, F.J., 1993. A statistical evaluation of the microhabitats of living (stained) infaunal benthic foraminifera. Marine Micropaleontology 29, 73–76.

Corliss, B.H., 1985. Microhabitats of benthic foraminifera within deep-sea sediments. Nature 314 (6010), 435–438.

Corliss, B.H., Emerson, S., 1990. Distribution of rose bengal stained deep-sea benthic foraminifera from the Nova Scotian continental margin and Gulf of Maine. Deep-Sea Research. Part A, Oceanographic Research Papers 37 (3), 381–400.1990/3.

Corliss, B.H., McCorkle, D.C., Higdon, D.C., 2002. A time series study of the carbon isotopic composition of deep-sea benthic foraminifera. Paleoceanography 17 (3). doi:10.1029/2001PA000664.

Duplessy, J.C., Lalou, C., Vinot, A.C., 1970. Differential isotopic fractionation in benthic foraminifera and paleotemperatures reassessed. Science 168 (3928), 250–251.

Eberwein, A., Mackensen, A., 2006. Regional primary productivity differences off Morocco (NW-Africa) recorded by modern benthic foraminifera and their stable carbon isotopic composition. Deep-Sea Research. Part 1. Oceanographic Research Papers 53 (8), 1379–1405.

Emery, W.J., Meincke, J., 1986. Global water masses: summary and review. Oceanologica Acta 9 (4), 383–391.

Emiliani, C., 1955. Pleistocene temperatures. Journal of Geology 63, 538–578.

Erez, J., 2003. The source of ions for biomineralization in foraminifera and their implications for paleoceanographic proxies. In: D., P.M., Yoreo, J.J.D., Weiner, S. (Eds.), Biomineralization. Reviews in Mineralogy & Geochemistry, pp. 115–149.

Erez, J., Bentov, S., Brownlee, C., Raz, M., Rinkevich, B., 2002. Biomineralization mechanisms in foraminifera and corals and their paleoceanographic implications. Geochimica et Cosmochimica Acta 66 (15A), 216-A216 (Suppl. 1).

Fontanier, C., Jorissen, F.J., Chaillou, G., David, C., Anschutz, P., Lafon, V., 2003. Seasonal and interannual variability of benthic foraminiferal faunas at 550 m depth in the Bay of Biscay. Deep-Sea Research. Part 1. Oceanographic Research Papers 50 (4), 457–494.

Fontanier, C., Jorissen, F.J., Chaillou, G., Anschutz, P., Grémare, A., Griveaud, C., 2005. Live foraminiferal faunas from a 2800 m deep lower canyon station from the Bay of Biscay: Faunal response to focusing of refractory organic matter. Deep-Sea Research. Part 1. Oceanographic Research Papers 52 (7), 1189–1227.

Fontanier, C., Mackensen, A., Jorissen, F.J., Anschutz, P., Licari, L., Griveaud, C., 2006. Stable oxygen and carbon isotopes of live benthic foraminifera from the Bay of Biscay: microhabitat impact and seasonal variability. Marine Micropaleontology 58 (3), 159–183.

Friedman, I., O'Neil, J.R., 1977. Compilation of stable isotope fractionation factors of geochemical interest, In: Fleischer, M. (Ed.), Data of geochemistry, sixth edition. U.S. Geol. Sur. Prof. Pap. , p. 110.

Gingele, F.X., De Deckker, P., 2005. Late Quaternary fluctuations of palaeoproductivity in the Murray Canyons area, South Australian continental margin. Palaeogeography, Palaeoclimatology, Palaeoecology 220 (3–4), 361–373.

Gooday, A.J., 1986. Meiofaunal foraminiferans from the bathyal Porcupine Seabight (northeast Atlantic): size structure, standing stock, taxonomic composition, species diversity and vertical distribution in the sediment. Deep-Sea Research 33, 1345–1373.

Gooday, A.J., 2003. Benthic foraminifera (Protista) as tools in deep-water palaeoceanography: environmental influences on faunal characteristics. Advances in Marine Biology 46 90 pp.

Gooday, A.J., Rathburn, A.E., 1999. Temporal variability in living deep-sea benthic foraminifera: a review. Earth-Science Reviews 46 (1–4), 187–212.

Graham, D.W., Corliss, B.H., Bender, M.L., Keigwin, J., Lloyd, D., 1981. Carbon and oxygen isotopic disequilibria of recent deep-sea benthic foraminifera. Marine Micropaleontology 6 (5–6), 483–497.

Grossman, E.L., 1984a. Carbon isotopic fractionation in live benthic foraminifera-comparison with inorganic precipitate studies. Geochimica et Cosmochimica Acta 48 (7), 1505–1512.

Grossman, E.L., 1984b. Stable isotope fractionation in live benthic foraminifera from the southern California Borderland. Palaeogeography, Palaeoclimatology, Palaeoecology 47 (3–4), 301–327.

Grossman, E.L., 1987. Stable isotopes in modern benthic foraminifera: a study of vital effect. Journal of Foraminiferal Research 17, 48–61.

Hayward, T.L., Venrick, E.L., 1998. Near surface pattern in the California Current: coupling between physical and biological structure. Deep-Sea Research. Part 2. Topical Studies in Oceanography 45, 1617–1638.

Heinz, P., Sommer, S., Pfannkuche, O., Hemleben, C., 2005. Living benthic foraminifera in sediments influenced by gas hydrates at the Cascadia convergent margin, NE Pacific. Marine Ecology. Progress Series 304, 77–89.

Hess, S., Jorissen, F., Venet, V., Abu-Zied, R., 2005. Benthic foraminiferal recovery after recent turbidite deposition in Cap Breton Bay, Bay of Biscay. Journal of Foraminiferal Research 35 (2), 114–129.

Hill, P.J., Deckker, P.D., Exon, N.F., 2005. Geomorphology and evolution of the gigantic Murray canyons on the Australian southern margin. Australian Journal of Earth Sciences 52 (1), 117–136.

Jorissen, F., 1999. Benthic foraminiferal microhabitats below the sediment–water interface. Modern Foraminifera. Academic Publishers. 181–199 pp.

Jorissen, F., Buzas, M., Culver, S., Kuehl, S., 1994. Vertical distribution of living benthic foraminifera in submarine canyons off New Jersey. Journal of Foraminiferal Research 24 (1), 28–36.

Jorissen, F., Fontanier, C., Thomas, E., 2007. Paleoceanographical proxies based on deep-sea benthic foraminiferal assemblage characteristics. In: Hillaire-Marcel, C., de Vernal, A. (Eds.), Proxies in late Cenozoic plaeoceanography. Elsevier, p. 862.

Kim, S.-T., O'Neil, J.R., Hillaire-Marcel, C., Mucci, A., 2007. Oxygen isotope fractionation between synthetic aragonite and water: Influence of temperature and Mg^{2+} concentration. Geochimica et Cosmochimica Acta 71 (19), 4704–4715.2007/10/1.

Koho, K.A., Kouwenhoven, T.J., de Stigter, H.C., van der Zwaan, G.J., 2007. Benthic foraminifera in the Nazaré Canyon, Portuguese continental margin: Sedimentary environments and disturbance. Marine Micropaleontology 66 (1), 27–51.2007/12.

Kroopnick, P.M., 1985. The distribution of δ^{13}C of Sigma CO_2 in the world oceans. Deep-Sea Research. Part A. Oceanographic Research Papers 32 (1), 57–84.

Langer, M., Hottinger, L., Huber, B., 1989. Functional morphology in low-diverse benthic foraminiferal assemblages from tidal flats of the North Sea. Senckenbergiana Maritima 20 (3–4), 81–99.

Levitus, S., Boyer, T., 1994. Temperature. NOAA Atlas NESDIS 4, vol. 4. U.S. Dept. Commerce.

Levitus, S., Burgett, R., Boyer, T., 1994. Salinity. NOAA Atlas NESDIS 3, vol. 3. US Dept. Commerce.

Mackensen, A., Hubberten, H.W., Bickert, T., Fischer, G., Futterer, D.K., 1993. The $\delta^{13}C$ in benthic foraminiferal tests of *Fontobotia wullerstorfi* (Schwager) relative to the $\delta^{13}C$ of dissolved inorganic carbon in Southern Ocean deep water: implications for glacial ocean circulation models. Paleoceanography 8, 587–610.

Mackensen, A., Schumacher, S., Radke, J., Schmidt, D.N., 2000. Microhabitat preferences and stable carbon isotopes of endobenthic foraminifera: clue to quantitative reconstruction of oceanic new production? Marine Micropaleontology 40 (3), 233–258.

Mackensen, A., Wollenburg, J., Licari, L., 2006. Low $\delta^{13}C$ in tests of live epibenthic and endobenthic foraminifera at a site of active methane seepage. Paleoceanography 21, PA2022. doi:10.1029/2005PA001196.

Martin, J.B., Day, S.A., Rathburn, A.E., Perez, M.E., Mahn, C., Gieskes, J., 2004. Relationships between the stable isotopic signatures of living and fossil foraminifera in Monterey Bay, California. Geochemistry Geophysics Geosystems 5 (4), Q04004. doi:10.1029/2003GC000629.

Maslin, M.A., Swann, G.E.A., 2006. In: Leng, M.J. (Ed.), Isotopes in Marine Sediments. . Isotopes in Palaeoenvironmental Research. Springer, p. 307.

McCorkle, C.D., Keigwin, L.D., Corliss, B.H., Emerson, S.R., 1990. The influence of microhabitats on the carbon isotopic composition of deep-sea benthic foraminifera. Paleoceanography 5 (2), 161–185.

McCorkle, D.C., Corliss, B.H., Farnham, C.A., 1997. Vertical distributions and stable isotopic compositions of live (stained) benthic foraminifera from the North Carolina and California continental margins. Deep-Sea Research. Part 1. Oceanographic Research Papers 44 (6), 983–1024.

Mordy, C.W., Stabeno, P.J., Ladd, C., Zeeman, S., Wisegarver, D.P., Salo, S.A., Hunt, G.L., 2005. Nutrients and primary production along the eastern Aleutian Island Archipelago. Fisheries Oceanography 14 (s1), 55–76.

Mulder, T., Cirag, P., Gaudin, M., Bourillet, J.F., Traniner, J., Normand, A., Weber, O., Griboulard, R., Jouanneau, J.M., P., A., Jorissen, F.J., 2004. Understanding continent–ocean sediment transfer. EOS 85 (257), 261–262.

Murray, J.W., Bowser, S.S., 2000. Mortality, protoplasm decay rate, and reliability of staining techniques to recognize 'living' foraminifera: A review. Journal of Foraminiferal Research 30 (1), 66–70.

Nomaki, H., Heinz, P., Nakatsuka, T., Shimanaga, M., Kitazato, H., 2005. Species-specific ingestion of organic carbon by deep-sea benthic foraminifera and meiobenthos: in situ tracer experiments. Limnology and Oceanography 50 (1), 134–146.

Nomaki, H., Heinz, P., Nakatsuka, T., Shimanaga, M., Ohkouchi, N., Ogawa, N.O., Kogure, K., Ikemoto, E., Kitazato, H., 2006. Different ingestion patterns of $\delta^{13}C$-labeled bacteria and algae by deep-sea benthic foraminifera. Marine Ecology Progress Series 310, 95–108.

Piepgras, D.J., Jacobsen, S.B., 1988. The isotopic composition of neodymium in the North Pacific. Geochimica et Cosmochimica Acta 52 (6), 1373–1381.1988/6.

Rathburn, A.E., Corliss, B.H., 1994. The ecology of living (stained) deep-sea benthic foraminifera from the Sulu Sea. Paleoceanography 9, 87–150.

Rathburn, A.E., De Deckker, P., 1997. Magnesium and strontium compositions of Recent benthic foraminifera from the Coral Sea, Australia and Prydz Bay, Antarctica. Marine Micropaleontology 32 (3–4), 231–248.

Rathburn, A.E., Corliss, B.H., Tappa, K.D., Lohmann, K.C., 1996. Comparisons of the ecology and stable isotopic compositions of living (stained) benthic foraminifera from the Sulu and South China Seas. Deep-Sea Research. Part 1. Oceanographic Research Papers 43 (10), 1617–1646.

Rathburn, A.E., Pérez, M.E., Martin, J.B., Day, S.A., Mahn, C., Gieskes, J., Ziebis, W., Williams, D., Bahls, A., 2003. Relationships between the distribution and stable isotopic composition of living benthic foraminifera and cold methane seep biogeochemistry in Monterey Bay, California. Geochemistry Geophysics Geosystems 4 (12), 1106. doi:10.1029/2003GC000595.

Rathburn, A.E., Levin, L.A., Tryon, M., Gieskes, J.M., Martin, J.B., Pérez, M.E., Fodrie, F.J., Neira, C., Mendoza, G., McMillan, P.A., Kluesner, J., Adamic, J., Ziebis, W. (in press). Geological and biological Heterogeneity of the Aleutian Margin (1965-4800 m). Progress in Oceanography. doi:10.1016/j.pocean.2008.12.002.

Risgaard-Petersen, N., Langezaal, A.M., Ingvardsen, S., Schmid, M.C., Jetten, M.S.M., Op den Camp, H.J.M., Derksen, J.W.M., Pina-Ochoa, E., Eriksson, S.P., Peter Nielsen, L., Peter Revsbech, N., Cedhagen, T., van der Zwaan, G.J., 2006. Evidence for complete denitrification in a benthic foraminifer. Nature 443 (7107), 93–96.

Schmiedl, G., de Bovée, F., Buscail, R., Charrière, B., Hemleben, C., Medernach, L., Picon, P., 2000. Trophic control of benthic foraminiferal abundance and microhabitat in the bathyal Gulf of Lions, western Mediterranean Sea. Marine Micropaleontology 40 (3), 167–188.

Schmiedl, G., Pfeilsticker, M., Hemleben, C., Mackensen, A., 2004. Environmental and biological effects on the stable isotope composition of recent deep-sea benthic foraminifera from the western Mediterranean Sea. Marine Micropaleontology 51 (1–2), 129–152.

Shackleton, N.J., 1974. Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina*: isotopic changes in the ocean during the last glacial. Colloque International du Centre National de la Recherche Scientifique 219, 203–225.

Shackleton, N.J., 1977. ^{13}C in *Uvigerina*: tropical rainforest history and the equatorial Pacific carbonate dissolution cycles. In: Anderson, N., Malahof, A. (Eds.), Fate of Fossil Fuel CO_2 in the Oceans. Plenum, New York, pp. 401–427.

Thomsen, L., Altenbach, A.V., 1993. Vertical and areal distribution of foraminiferal abundance and biomass in microhabitats around inhabited tubes of marine echiurids. Marine Micropaleontology 20 (3–4), 303–309.

Weiss, R.F., 1970. The solubility of nitrogen, oxygen, and argon in water and seawater. Deep-Sea Research 17, 721–735.