



Reconstructing benthic carbon oxidation rates using $\delta^{13}\text{C}$ of benthic foraminifers[☆]

Jennifer Holsten^{*}, Lowell Stott, Will Berelson

Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089, USA

Received 4 October 2003; received in revised form 26 April 2004; accepted 6 May 2004

Abstract

In non-bioturbated organic-rich marine sediments, the concentration and carbon isotope gradient of total dissolved carbon dioxide (ΣCO_2) primarily reflects the rate of carbon oxidation and CO_2 diffusion within the sediment pore waters. Here, we investigate whether the calcium carbonate secreted by benthic foraminifers that inhabit discrete depths within the sediments record the pore water $\delta^{13}\text{C}_{\Sigma\text{CO}_2}$ gradient and, hence, can be used as proxies to reconstruct a history of carbon oxidation change. The distribution and live abundance of *Bolivina argentea* s.l., *Bolivina subadvena* s.l. and *Buliminella tenuata* inhabiting the dysoxic marine sediments along the California margin is similar among sites that differ in (ΣCO_2) gradient by up to a factor of three. *Bolivina argentea* inhabits the sediments at the sediment water interface, whereas *B. subadvena* s.l. is most abundant at depths of between 2 and 4 mm. *Buliminella tenuata* is most abundant at deeper depths of between 4 and 6 mm. The $\delta^{13}\text{C}$ of calcite precipitated by these species matches the $\delta^{13}\text{C}$ of the pore water ΣCO_2 at the depth of their maximum live abundance indicating that each species has a preferred depth for calcification. The $\delta^{13}\text{C}$ difference between the species increases as the rate of carbon oxidation increases. These results indicate the carbon isotopic difference between these species in fossil assemblages can be used to estimate changes in the rate of carbon oxidation.

© 2004 Published by Elsevier B.V.

Keywords: benthic carbon oxidation; benthic foraminifers; $\delta^{13}\text{C}$

1. Introduction

A large percentage of the ocean's total marine primary productivity occurs along the ocean margins (Rullkötter, 2000), as does more than 90% of organic carbon burial (Hartnett et al., 1998). The production, oxidation and sequestration of organic carbon along ocean margins have an important impact on global

carbon and oxygen cycles. It is therefore desirable to know how carbon cycling has varied in the past to better assess how the carbon system might respond to changing environmental conditions in the future. There is growing evidence that marine productivity along continental margins and particularly within the major upwelling regions have undergone significant variability in the past (Altabet et al., 1995; Ganeshram et al., 2000; Loubere et al., 2000). Understanding what factors influenced that variability could lead to better assessments of future variability under a warmer global climate.

[☆] Supplementary data associated with this article can be found, in the online version, at doi: 10.1016/j.marmicro.2004.05.006.

^{*} Corresponding author.

The biogeochemical cycling of carbon in marine sediments generates chemical and isotopic gradients that are incorporated into the calcite tests of benthic foraminifera that inhabit these environments. Benthic foraminifera appear to be particularly sensitive to biogeochemical variability. A few studies have documented changes in community structure among infaunal species that are found in the low oxygen environments along the NE Pacific margin (Bernhard and Reimers, 1991; Corliss and Silva, 1993; Bernhard et al., 1997; Cannariato et al., 1999). Efforts are also being made to determine what role symbiosis possibly plays in facilitating the infaunal habitat particularly where the sediments are dysoxic to anoxic (e.g. Bernhard et al., 2000). However, relatively few studies have attempted to document how biogeochemical variability such as changes in carbon oxidation is incorporated into foraminiferal shell chemistry. Here, we are interested in the stable isotope geochemistry of infaunal benthic foraminifera common to the dysoxic marine sediments occurring in basins along the northeastern Pacific margin. We attempt to understand the factors that influence the incorporation of ^{12}C and ^{13}C carbon into the calcium carbonate tests of several common infaunal species. This is important because there is evidence of significant environmental variability along the California margin in the past and there have been varying interpretations of the carbon isotopic record that accompanied this environmental variability (Stott et al., 2000; Kennett et al., 2000; Stott et al., 2002).

It has been shown previously that the pore water ΣCO_2 gradient and the $\delta^{13}\text{C}_{\Sigma\text{CO}_2}$ of the pore waters vary systematically over the uppermost portion of the sediment column in dysoxic, non-bioturbated marine sediments (Berelson and Stott, 2003). The chemical and isotopic gradients within these sediments are controlled primarily by the rate of carbon oxidation and the rate of CO_2 diffusion (Berelson and Stott, 2003). It has also been shown that several of the most abundant benthic foraminiferal species inhabiting the sediment of the Santa Monica and Santa Barbara Basins along the California margin have specific depth habitat preferences (Stott et al., 2000; Stott et al., 2002; Berelson and Stott, 2003). The calcium carbonate precipitated by these foraminifera takes on a $\delta^{13}\text{C}$ that corresponds to that of pore water ΣCO_2 , and this value varies with the depth within the sediment where the test is precipitated. Therefore, the $\delta^{13}\text{C}$ of fossil calcite

could be used as a proxy for reconstructing the history of pore water ΣCO_2 gradient variability and hence, changing carbon oxidation patterns in these environments. The present study attempts to calibrate this foraminiferal proxy in environments along the north-eastern Pacific margin that have differing carbon accumulation and carbon oxidation rates.

2. Background

During the Pleistocene, sedimentation within the silled basins along the northeastern Pacific margin alternated between laminated and bioturbated. The warmer intervals appear to have been prone towards accumulation of laminated sediments whereas the colder intervals, including the last glacial maximum, were characterized by bioturbated sedimentation (Kennett et al., 2000). The reason for the alternating sedimentation patterns is not clear. It is possible that ventilation of the silled basins was less vigorous during times when the laminated sediments were accumulating. Reduced ventilation would lead to an exclusion of larger bioturbating animals that require higher dissolved oxygen. Today, ventilation of the silled, dysoxic basins along the California margin occurs seasonally to interannually, depending on the strength of upwelling and intermediate water circulation dynamics (Huyer, 1983; Reimers et al., 1990; Berelson, 1991). Changes in the magnitude or frequency of basin flushing events have been invoked to explain the presence and absence of laminated sediments at times in the past (Reimers et al., 1990; Christensen et al., 1994; Kennett and Ingram, 1995; Behl and Kennett, 1996; Cannariato and Kennett, 1999). However, this idea has been challenged by more recent studies that argue that changes in marine productivity and changes in carbon oxidation may have a more direct impact on the dissolved oxygen concentrations in the silled basins and on the formation of laminated sediments (Stott et al., 2000; Van Geen et al., 2003).

Laminated and bioturbated sedimentation has alternated along the California margin since the Miocene. The most recent shift from laminated to bioturbated sedimentation occurred in association with the 1976 climate change in the North Pacific that affected upwelling and marine productivity along

the margin (Stott et al., 2000). Earlier changes in sedimentation have occurred on decadal, millennial and glacial/interglacial timescales (Christensen et al., 1994; Stott et al., 2000; O'Connell et al., 2001; Kennett and Ingram, 1995; Behl and Kennett, 1996; Cannariato and Kennett, 1999; Van Geen et al., 2003).

In the upwelling waters of the California margin primary productivity and particle fluxes to the sea floor vary seasonally. This affects bottom water chemistry and benthic biological activity (Honjo et al., 1982; Smith et al., 1994; Thunell, 1998). The quantity of organic carbon exported from surface waters and the amount of biogenic material subsequently buried may be both spatially and temporally variable (Hartnett et al., 1998; Thunell, 1998; Van Mooy et al., 2002). At sites along the southern California margin today, there is a trend towards lower organic carbon burial efficiency with increasing productivity and carbon rain rate, which is problematic for paleoceanographic reconstructions (Berelson and Stott, 2003). At the same time, there is a strong correlation between spring sea surface temperature and upwelling-driven productivity (Smith and Eppley, 1982; Roemmich and McGowan, 1995) along the margin that has made it possible to estimate productivity using sea surface temperatures. However, these temperature records are only available for the past several decades and cannot provide a longer term estimate of changes that have occurred on centennial to millennial time scales. A proxy measurement of carbon oxidation using the $\delta^{13}\text{C}$ of fossil benthic foraminifera would therefore be a potentially important tool for deciphering how marine productivity may have affected conditions within the basins through changing carbon rain rates and carbon oxidation within the basins.

McCorkle et al. (1985) estimated organic carbon rain rates from modeled $\delta^{13}\text{C}$ profiles and documented a systematic variation in pore water $\delta^{13}\text{C}$ gradients with varying carbon rain rates. Corliss (1985) documented the microhabitat preferences of several calcareous benthic foraminifera, finding the greatest number of living individuals within a narrow range of sediment depths. Later studies added to these observations with records of combined pore water and foraminiferal $\delta^{13}\text{C}$ as well as in situ live abundance data. The use of $\delta^{13}\text{C}$ differences between benthic species have been used in several previous studies to

investigate changes in pore water gradients and carbon rain rates (Zahn et al., 1986; McCorkle et al., 1990, 1997). Data from a variety of marine environments has shown that benthic foraminifera tend to calcify at specific depths within the sediment pore waters (McCorkle et al., 1990; Corliss and Silva, 1993; Rathburn et al., 1996; McCorkle et al., 1997; Mackensen et al., 2000).

It is important to note that the $\delta^{13}\text{C}$ of calcite precipitated by benthic foraminifera may not reflect equilibrium isotopic values. The $\delta^{13}\text{C}$ of benthic foraminiferal carbonate is a function of biologically mediated fractionation of carbon isotopes during calcification termed "vital effect" and the geochemistry of the ambient pore water (Grossman, 1987; Mackensen et al., 2000). Vital effects typically shift the foraminiferal $\delta^{13}\text{C}$ towards lighter values, but the offset from equilibrium values is generally less than 2‰ (Grossman, 1987). Large negative offsets of up to 6‰ between the $\delta^{13}\text{C}$ values of benthic foraminifera and bottom water ΣCO_2 have been interpreted to be too large to reflect vertical migration or vital effects, and have instead been attributed to the presence of ^{13}C depleted methane that is either oxidized in the pore waters or, in the case of large excursions, the release and oxidation of methane in the water column (Dickens et al., 1995; Kennett et al., 2000; Thomas et al., 2002). Methane is present today in sediments and bottom water all along the northeastern Pacific margin. However, methane that is present near the sediment–water interface occurs at micromolar concentrations in most of these environments (Sansone et al., in press). The portion of this methane that is oxidized within the sediments is negligible and therefore does not influence the $\delta^{13}\text{C}$ of pore water ΣCO_2 or benthic foraminiferal carbonate (Stott et al., 2002; Holsten, 2003). In the present study, we examine more closely the influence of microhabitat preferences and the factors that influence the pore water and foraminiferal $\delta^{13}\text{C}$ values and how these values differ at sites that have undergone different rates of carbon oxidation.

3. Study area

Samples used for the present investigation were collected from the California Borderland Province

with a multicorer during the CALMEX cruise (R/V New Horizon in November 2001). Core locations ranged in depth from 430 to 910 m (Fig. 1, Table 1). The California Borderland Province is characterized by a series of tectonically formed, progressively shallower sills that intersect the well-defined oxygen minimum zone of the Pacific Intermediate Water (PIW). The water flowing over the sills and into the basin is therefore depleted in oxygen and subsequent geochemical processes within the basin further draw down the oxygen. Additional cores from the Magdalena basin and Matzatlan margin, which underlie dysoxic intermediate waters that flow along continental slope, were also included.

The oceanographic conditions that exist at intermediate water depths along the California margin have been studied extensively by the California Cooperative Oceanic Fisheries Investigation (CALCOFI). Lynn and Simpson (1987) present a detailed description of its physical characteristics. Lower temperature (15°C), low salinity (<33.5 PSU) and high oxygen content (>5 ml/l) characterize surface water. Bottom waters along the margin consist of California Undercurrent, a poleward flowing water mass originating from eastern equatorial and North Pacific intermediate waters that is characterized by higher salinity (34–34.5 PSU) and low oxygen (<2 ml/l) concentrations. The lowest levels of dissolved oxygen are found over the continental slope. Anom-

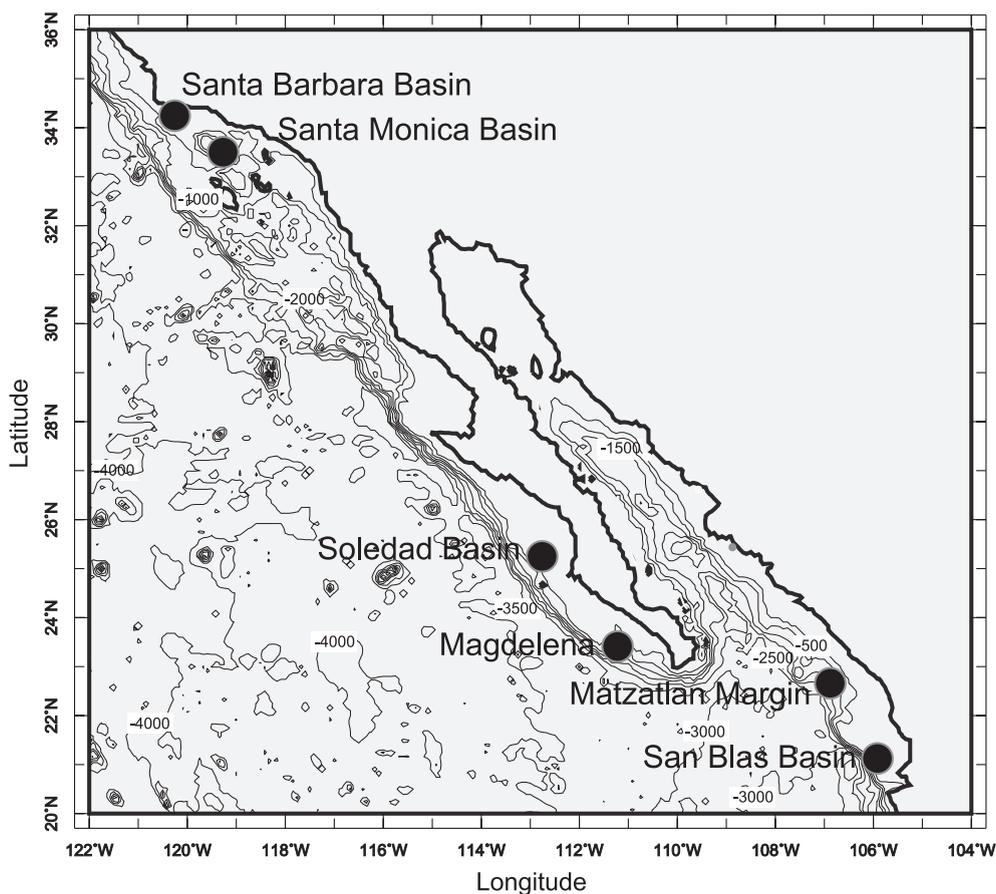


Fig. 1. Dysoxic sites along the northeastern Pacific margin from which multicores were collected during the CALMEX cruise. Additional CALMEX sites in the Gulf of California are not shown.

alously low oxygen concentration can occur seasonally with increased Undercurrent transport from the south. The region along the western Baja and Mexican continental margins is also affected by the seasonality of the California Current system that allows equatorial surface water to flow further north into the Gulf of California in winter (Orozco, 1993; Thunell et al., 1993). The mixing of distinct water masses from the north and south influences the complex hydrography of southern Baja California and the mouth of the Gulf of California.

The dynamics of surface and intermediate water circulation combine to affect the rates of carbon rain to the sea bed and influence the amount of dissolved oxygen in bottom waters within the Borderland Basins. As a result of this interplay of biology and oceanography, the concentration of dissolved oxygen differs between the basins as does the rate of carbon oxidation within the sediments. These differences produce contrasting profiles of dissolved ΣCO_2 within the uppermost

Table 1
Locations and water depths of multicore sites

Site	Core number	Coordinates	Depth (m)
Santa Barbara Basin	NH01-3-MC13	34°13.61' N, 119°59.42' W	585
	NH01-8-MC2	34°17.83' N, 120°01.36' W	556
Santa Monica Basin	NH01-1-MC1	33°41.06' N, 118°47.24' W	908
	NH01-2-MC1	33°41.71' N, 118°48.17' W	910
Soledad Basin	NH01-10-MC1	25°12.66' N, 112°43.03' W	541
	NH01-11-MC1	25°08.03' N, 112°40.06' W	446
Magdalena	NH01-12-MC1	23°26.60' N, 111°34.20' W	713
	NH01-12-MC2	23°28.27' N, 111°36.70' W	686
Matzatlán margin	NH01-29-MC1	22°40.01' N, 106°28.70' W	442
	NH01-30-MC1	22°38.26' N, 106°31.60' W	600
San Blas Basin	NH01-31-MC1	21°15.32' N, 105°57.42' W	430
	NH01-32-MC1	21°10.22' N, 105°53.47' W	450

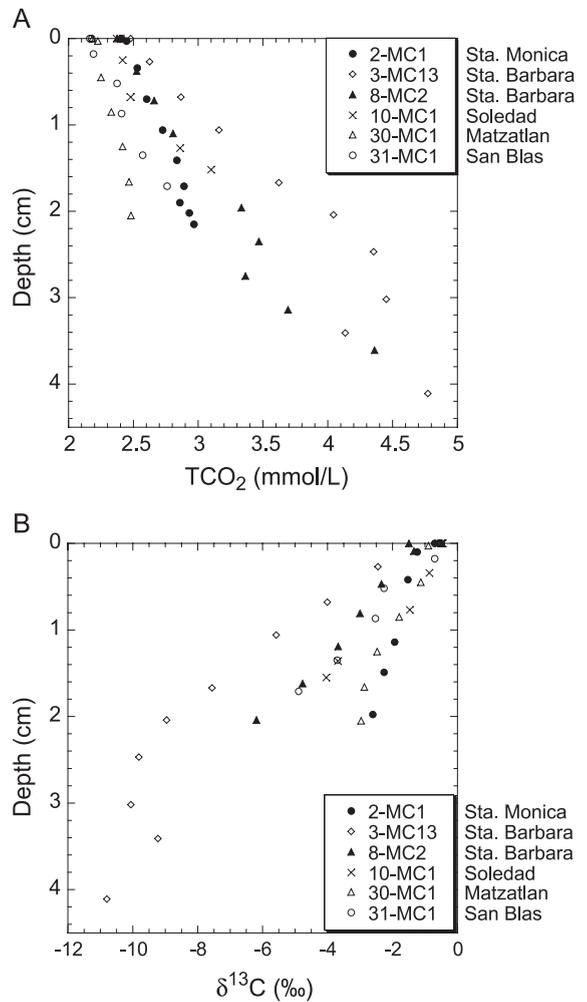


Fig. 2. (A) Pore water ΣCO_2 gradients from several sites along the northeastern Pacific margin. A range of environments that differ in carbon accumulation rates are represented. Carbon accumulation rates have been published for the Santa Barbara Basin (~ 5 mmol C/m² day; Reimers et al., 1996) and for the Matzatlán margin (~ 1 mmol C/m² day; Ganeshram et al., 1999). (B) $\delta^{13}\text{C}_{\Sigma\text{CO}_2}$ gradients corresponding to the ΣCO_2 gradients presented in (a). $\delta^{13}\text{C}$ gradients for 3-MC13, 30-MC1 and 31-MC1 were predicted using Eq. (1) (see text).

section of the sediment columns within the basins (Fig. 2).

4. Methods

The multicores collected during the 2001 CALMEX cruise were sampled every millimeter through the top

1–2 cm by extruding the sediments from the multi-core immediately after the core was recovered. The depth horizon assigned to each extruded sample has an estimated error of approximately 1 mm. Extruded samples were washed over a >63- μm screen with tap water and the living (rose Bengal stained) benthic foraminiferal were counted from the entire sample. Abundance data are presented as numbers of living (rose Bengal stained) specimens per gram of dried sediment (greater than 63- μm fraction). In the present study results are presented for the three most common species, *Bolivina argentea* s.l., *Bolivina subadvena* s.l. and *Buliminella tenuata*. Analytical methods for the stable isotope and ΣCO_2 determinations are those as described in Stott et al. (2002) and Berelson and Stott (2003). The analytical precision of the ΣCO_2 measurements was <1%. The stable isotope results are reported in per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB). Pore water samples were collected using a whole core squeezer (Bender et al., 1987) to obtain millimeter-scale samples from near the sediment–water interface. This device pushes a piston down into the sediment column and pore water is forced through a hole in the piston. The volume of water collected relates to the travel of the piston. The location of a particular split of water is established by relating sample volume expressed to core area and sediment porosity. Porosity was measured on an adjacent core by standard weight loss methods. At some sites, pore waters were expressed from 2 to 4 cm sections of core by squeezing the sediments between two plates like a hockey-puck. The allocation of sediment into the squeezing apparatus took place in an argon glove bag. The $\delta^{13}\text{C}_{\text{DIC}}$ of deep waters was not measured from Niskin bottles. In most cases, the water overlying the sediments in the multicores was sampled for determining the $\delta^{13}\text{C}_{\text{DIC}}$ of bottom waters. The precision of 26 standard water samples analyzed in conjunction with pore water samples was $\pm 0.3\%$ for $\delta^{13}\text{C}$.

Benthic foraminifera were cleaned prior to isotopic analysis by soaking in sodium hypochlorite for 24 h, then rinsed repeatedly in DI water and finally with methanol before being dried in an oven at 40 °C. The $\delta^{13}\text{C}$ of the benthic foraminifera was determined using 10–15 *Bolivina argentea* s.l., 20–30 *Buliminella tenuata* and 60–80 *Bolivina subadvena* s.l. speci-

mens. The analytical precision of the USC calcite standard (ULTISS marble) run in conjunction with foraminiferal samples was $\pm 0.1\%$ for $\delta^{13}\text{C}$.

Previous work has shown that the $\delta^{13}\text{C}$ of pore water ΣCO_2 can be modeled using a simple isotope mass balance that combines CO_2 derived from the oxidation of marine photosynthate organic carbon (-17% to -21%) with bottom water ΣCO_2 and its $\delta^{13}\text{C}$ (Stott et al., 2002; Berelson and Stott, 2003). This combination can be represented as:

$$(\Sigma\text{CO}_{2\text{b.w.}})(\delta^{13}\text{C}_{\text{b.w.}}) + (\Sigma\text{CO}_{2\text{p.w.}} - \Sigma\text{CO}_{2\text{b.w.}}) \times (\delta^{13}\text{C}_{\text{org}}) = (\Sigma\text{CO}_{2\text{p.w.}})(\delta^{13}\text{C}_{\text{p.w.}}) \quad (1)$$

where (b.w.) indicates a bottom water value and (p.w.) refers to a pore water value at a chosen sediment depth. While this calculation is useful for estimating the $\delta^{13}\text{C}$ of pore water ΣCO_2 at a specific sediment depth, it does not account for any interaction between discrete sediment depth horizons, such as diffusion and reaction processes that influence the overall shape of the pore water profile. It also assumes that the CO_2 added to pore waters is derived only from the oxidation of photosynthate carbon with a specific carbon isotopic composition. We test the validity of this assumption and assess whether there is an additional source of isotopically distinct CO_2 by applying a diffusion-reaction model that estimates the isotopic composition of carbon added to the pore water (e.g. McCorkle et al., 1985; Stott et al., 2002; Berelson and Stott, 2003).

5. Depth distribution and $\delta^{13}\text{C}$ of living foraminifera

The live (stained) benthic foraminifera inhabiting the sediments of the basins along the California margin are partitioned within the sediments (Fig. 3). Each of three species studied display a persistent preference for a shallow, intermediate or a deeper habitat within the sediments. The maximum abundance of live *Bolivina argentea* persistently occurs near the sediment–water interface, usually within the top millimeter at each site we sampled. Live *Buliminella tenuata* are most abundant at depths of between 3 and 6 mm in the Santa Monica, Magdalena and

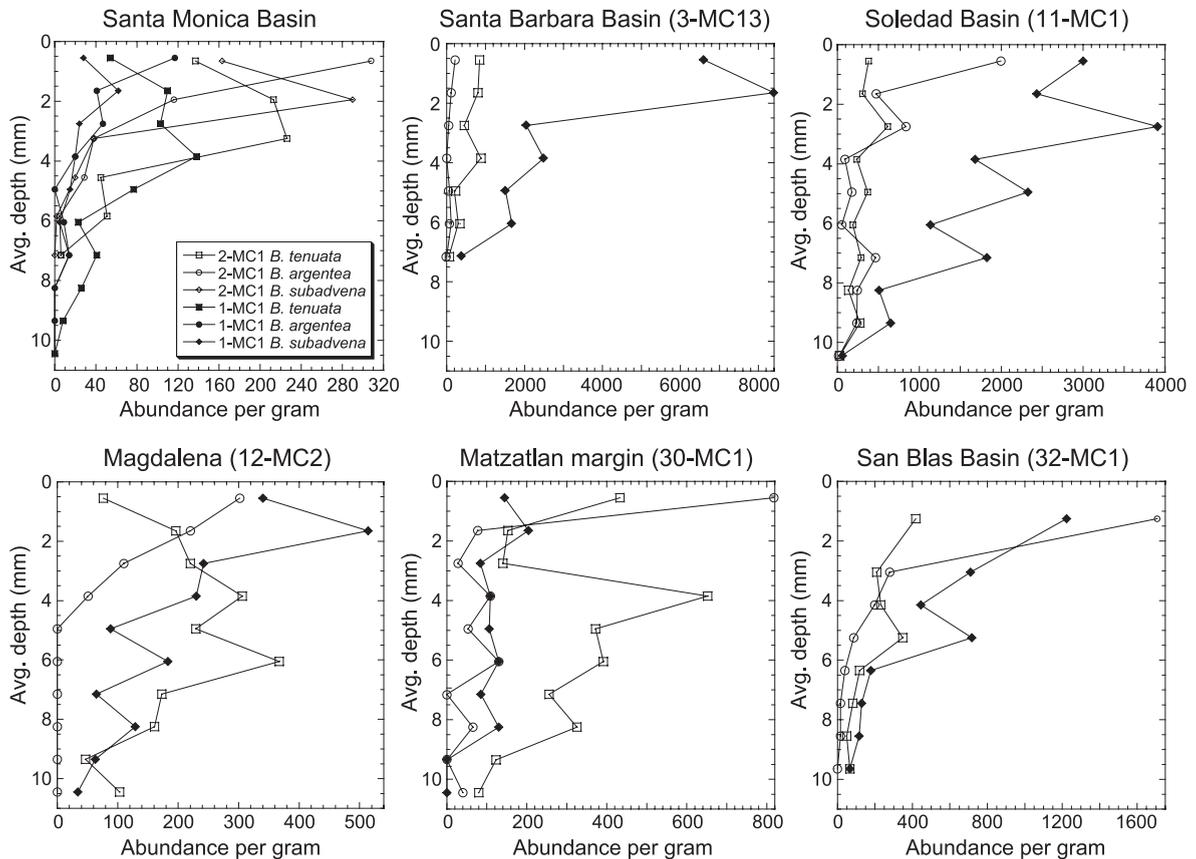


Fig. 3. Live (rose Bengal stained) abundance of benthic foraminifera at six sites along the northeastern Pacific margin. Note differences in scale. All symbols are as shown for Santa Monica Basin. In San Blas Basin, the maximum abundance of *Bolivina subadvena*, usually 1–3 mm, appears to be the same as *Bolivina argentea*. Due to difficulty in sectioning these high porosity sediments at mm resolution, the first sample at this site combines the upper 2.5 mm.

Matzatlan sites (Fig. 3). In the Santa Barbara, Soledad and San Blas Basins, the abundance of *B. tenuata* does not display distinct maxima. At these sites, *B. tenuata* tends to exhibit an overall lower abundance compared to the other sites and the abundance of live individuals remains relatively uniform through the top 4–5 mm and then falls to zero abundance below 5 mm. In an earlier study of live assemblages in the center of Santa Barbara Basin, a similar distribution of *B. tenuata* was also observed (Stott et al., 2002), indicating that this is a persistent pattern.

Bolivina subadvena s.l. was observed to be most abundant at an intermediate depth of between 1 and 3 mm and appears to distribute itself in the sediments between the *Bolivina argentea* s.l. and *Bulminella tenuata* (Fig. 3). A similar distribution

within the sediments has been observed for this species in basins within the Gulf of California (F. Staines-Urias, personal communication). Thus, despite the range of environmental conditions that exist between the basins (e.g. sediment accumulation rates, carbon rain rates, etc.) the species appears to be vertically segregated from the other species at all the sites and the species also distributes itself at approximately the same depth horizons within the sediments.

The segregation of the species reflected in the live abundance data is also evident in the carbon isotopic values of the three species (Fig. 4). *Bolivina argentea* s.l. exhibits $\delta^{13}\text{C}$ values that are similar to pore water values near the sediment water interface. The only exception to this observation is the site 2-MC1 data

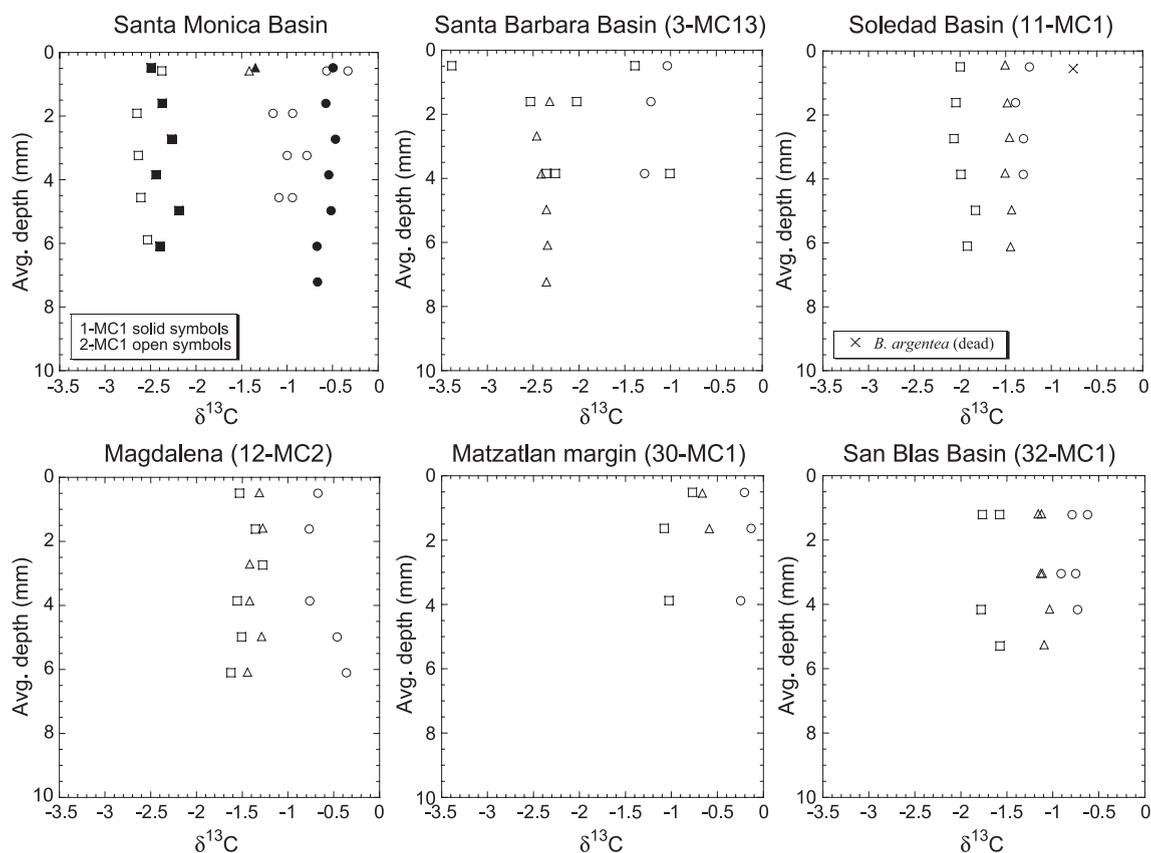


Fig. 4. Measured $\delta^{13}\text{C}$ of benthic foraminifera along the northeastern Pacific margin. Live *Bolivina argentea* (circles), *Bolivina subadvena* (triangles) and *Buliminella tenuata* (squares) record uniform $\delta^{13}\text{C}$ values regardless of sediment depth, with the exceptions of *B. argentea* s.l. from 2-MC1 in Santa Monica Basin and *B. tenuata* in Santa Barbara Basin. Additional symbols are used as indicated. The $\delta^{13}\text{C}$ of dead *B. argentea* s.l. in Soledad Basin is heavier than of living specimens (see text).

where relatively lighter $\delta^{13}\text{C}$ values of *B. argentea* occur below 2 mm. Replicate analyses of the stained specimens from these depths confirms the validity of the isotopic result. As there is no significant difference in ΣCO_2 at 2 mm in 2 MC1 that would explain the isotopic offset it is possible that these *B. argentea* s.l. specimens calcified at deeper horizons within the pore waters. However, samples of living *B. argentea* s.l. that have been collected from this basin other times in the past have not shown such light isotopic values. Hence, the 2-MC1 values below 2 mm are not considered to be representative of the species' calcification depth.

The isotopic values of *Bolivina subadvena* s.l. are lower than those of *Bolivina argentea* s.l. and are consistent with an intermediate depth habitat for

calcification. *Buliminella tenuata* consistently displays the most negative $\delta^{13}\text{C}$ values. Only at the Santa Barbara basin site do the $\delta^{13}\text{C}$ values of *B. tenuata* deviate from this pattern. The abundance data together with the isotopic results support the contention that at sites along the California margin *B. argentea* s.l., *B. subadvena* s.l. and *B. tenuata* segregate themselves vertically within the sediments in a consistent tiered pattern that reflects an apparent preferred depth for growth and calcification. The depth of maximum live abundance of each species varies by only 1–2 mm between basins, which is equivalent to the uncertainty of the sampling. With the exception of *B. tenuata* in Santa Barbara Basin and *B. argentea* s.l. below 2 mm in Santa Monica Site 2-MC1, each of the three species records $\delta^{13}\text{C}$ values

that are consistent with their shallow, intermediate and deeper infaunal habitat preferences.

6. Relationship between $\delta^{13}\text{C}$ of pore water ΣCO_2 and benthic foraminifera

The measured pore water $\delta^{13}\text{C}$ values and those predicted by Eq. (1) are in close agreement at the sites investigated. This observation extends previous results for the Santa Monica and Santa Barbara Basins (Stott et al., 2003) that concluded the primary influence on the pore water and the infaunal benthic foraminiferal $\delta^{13}\text{C}$ values in these basins is the oxidation of photosynthate carbon and the flux of ΣCO_2

through the sediments (Fig. 5). Although the abundance data suggests the species may migrate over small depth ranges during their life cycle, the isotopic results indicate there is narrower range of preferred depths for calcification.

In the Soledad Basin, we believe the anomalously light $\delta^{13}\text{C}$ values compared to the measured and estimated pore water $\delta^{13}\text{C}$ values in the upper millimeter where the species is most abundant is due to an inadvertent inclusion of some *Bolivina subadvena* s.l. specimens in the *Bolivina argentea* s.l. samples. An additional analysis of dead (unstained) *B. argentea* s.l. individuals from the upper millimeter of in the Soledad core exhibits a more positive $\delta^{13}\text{C}$ value of -0.74‰ (Fig. 4) that is similar to that of the pore

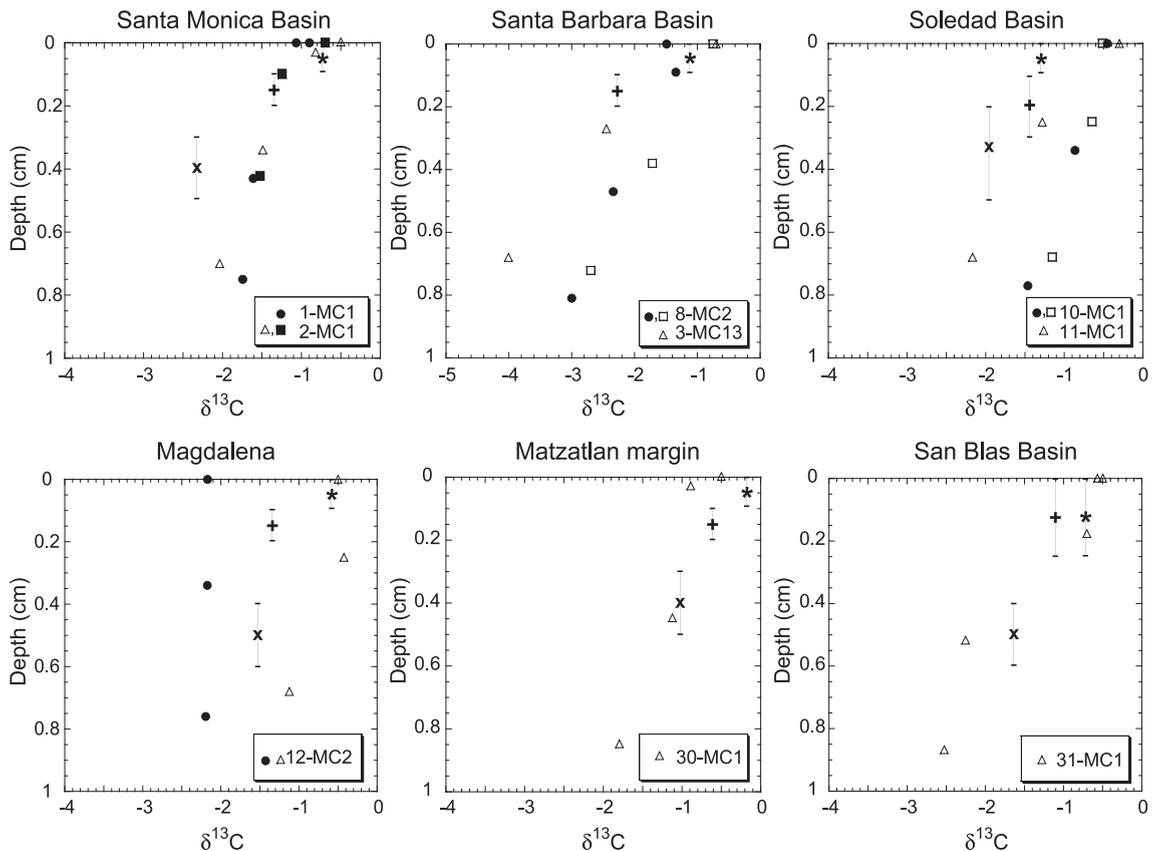


Fig. 5. Pore water $\delta^{13}\text{C}_{\Sigma\text{CO}_2}$ in the upper cm of sediment measured at six sites along the northeast Pacific margin and values predicted using Eq. (1) (see text). Open symbols represent predicted values. Solid symbols show values measured from indicated cores. Average measured $\delta^{13}\text{C}$ of benthic foraminifera; asterisks = *Bolivina argentea*, plus symbols = *Bolivina subadvena* and \times symbols = *Buliminella tenuata*. Note the difference in the $\delta^{13}\text{C}$ scale for Santa Barbara Basin. The error bars indicate the estimated uncertainty in the depth range of maximum abundance.

waters at the depth of maximum live abundance for *B. argentea* s.l.

The nearly vertical pore water $\delta^{13}\text{C}$ profile in the Magdalena core is indicative of bioturbation and bio-irrigation. There were no laminations visible in the 12-MC2 multicores at the time of collection. Nor were laminations observed in the x-radiographs of other cores from this site. Pore water $\delta^{13}\text{C}$ values are not reported for the Matzatlan margin and San Blas Basin because the samples were damaged during storage. It is difficult therefore to compare the $\delta^{13}\text{C}$ of pore water ΣCO_2 directly with the foraminiferal measurements for these sites. However, the benthic foraminiferal $\delta^{13}\text{C}$ values from these sites do match pore water values that are estimated from a reaction diffusion model (e.g. Stott et al., 2003) (Fig. 5). These estimates assume the average bottom water $\delta^{13}\text{C}_{\text{DIC}}$ is -0.5% . Small discrepancies between foraminiferal and the modeled pore water $\delta^{13}\text{C}$ profile at both sites are within 0.2% to 0.3% , which reflects the degree of uncertainty in the model and in the value assumed for bottom water $\delta^{13}\text{C}$.

The depth of primary calcification is estimated for each of the three species by matching the foraminiferal $\delta^{13}\text{C}$ value to that of pore water $\delta^{13}\text{C}_{\text{DIC}}$ (Table 2), or the model-predicted value of pore water $\delta^{13}\text{C}_{\text{DIC}}$. On this basis, *Bolivina argentea* s.l. consistently calcifies within the upper millimeter of sediment (the depth of calcification is not predicted for the Soledad Basin). *Bolivina subadvena* s.l. records the most uniform $\delta^{13}\text{C}$ values of the three species, illus-

trated by the very narrow range of $\delta^{13}\text{C}$ values throughout the sediment column at each of the study sites. Its abundance pattern indicates a primary depth habitat at an intermediate depth of between 1 and 3 mm. This is similar to the depth that is predicted from its $\delta^{13}\text{C}$ value (~ 2.4 mm). Likewise, the greatest numbers of living *Buliminella tenuata* are observed at between 4 and 6 mm, and the average depth of calcification based on its $\delta^{13}\text{C}$ value is 5.5 mm.

The close correspondence between the isotopic value of benthic foraminifera and the pore water at the depth of the species average maximum live abundance implies the $\delta^{13}\text{C}$ of fossil *Bolivina argentea* s.l., *Bolivina subadvena* s.l. and *Buliminella tenuata* can provide a good estimate of the pore water $\delta^{13}\text{C}$ gradient within dysoxic basins such as those along the California margin (Fig. 5). The only apparent exception is *B. tenuata* in Santa Barbara Basin. Additionally, there can be temporal changes in the isotopic composition of photosynthate carbon oxidized in the sediments that would alter the isotopic composition of pore waters. This may explain the fact that the measured and estimated values of pore water values differs in the Santa Barbara Basin. The estimate pore water $\delta^{13}\text{C}$ gradient is expected to reflect a more time-averaged record of carbon oxidized within the sediments. Hence, separate measurements or constraints must be made on the isotopic composition of marine organic carbon.

7. Response of benthic foraminiferal $\delta^{13}\text{C}$ to increased carbon oxidation rates

The oxidation of organic carbon in the sediments preferentially adds ^{12}C to the pore waters, increasing the $\delta^{13}\text{C}$ gradient below the sediment/water interface. In laminated sediments where the flux of CO_2 is controlled by diffusion, the rate of carbon oxidation increases the $\delta^{13}\text{C}$ difference between the epifaunal and infaunal species ($\Delta\delta^{13}\text{C}$) (Fig. 6). Benthic foraminifera that incorporate the pore water isotopic composition into their calcite can therefore be used to reconstruct a history of carbon oxidation changes within a basin (Stott et al., 2000, Berelson and Stott, 2003). The results from the present study indicate this methodology can be extended to other basins that differ in sediment properties and particularly where

Table 2

Predicted depths of test calcification according to comparison of benthic foraminiferal $\delta^{13}\text{C}$ with the $\delta^{13}\text{C}$ of pore water TCO_2 along the northeastern Pacific margin

	<i>B. argentea</i> predicted depth (mm)	<i>B. subadvena</i> predicted depth (mm)	<i>B. tenuata</i> predicted depth (mm)
Santa Barbara Basin	1	2	None
Santa Monica Basin	0	2	6
Soledad Basin	None	4	6
Matzatlan margin	0	2	5
San Blas Basin	1	3	5
Average	0.5	2.4	5.5

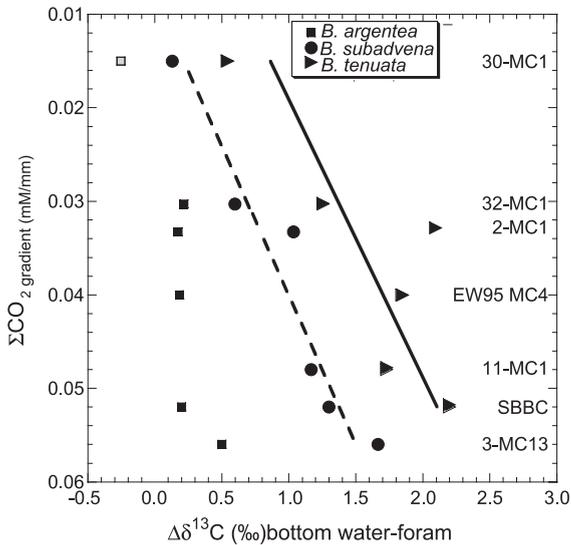


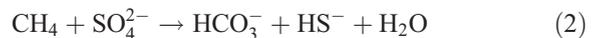
Fig. 6. The difference between foraminiferal and bottom water $\delta^{13}\text{C}$ ($\Delta\delta^{13}\text{C}$) at sites of varying ΣCO_2 gradients. The ΣCO_2 gradients were calculated by regression of the data shown in Fig. 2. *Bolivina argentea* (squares), *Bolivina subadvena* (circles, dashed regression line) and *Buliminella tenuata* (triangles, solid regression line) show an increased offset from bottom water with increased carbon oxidation. The offset from bottom water for *B. argentea* s.l. is close to zero at all sites except 30 MC1. The $\Delta\delta^{13}\text{C}$ increases as the ΣCO_2 gradient increases. The high $\Delta\delta^{13}\text{C}$ values for 2-MC1 suggest that the ΣCO_2 gradient in Santa Monica Basin measured in 2001 was lower than predicted by the foraminiferal offset and lower than values measured in 1995 (EW95 MC4) (see text).

the ΣCO_2 gradients are different. We also note that the pore water isotopic gradient estimated using the *B. argentea* s.l.–*Bolivina subadvena* s.l. isotopic difference ($\Delta\delta^{13}\text{C}$) gives similar results between two sampling periods in the Santa Barbara Basin (core SBBC, Stott et al., 2002, and 3-MC13, this study). Similarly, in the Santa Monica Basin, the $\Delta\delta^{13}\text{C}$ values using *B. argentea* s.l. and *Buliminella tenuata* from the present study are similar to measurements made several years ago (Stott et al., 2000, Stott et al., 2002). At the same time, however, the pore water ΣCO_2 gradient in this basin and the isotopic gradient is different between sample periods of 1995 and 2001 (Fig. 6). The ΣCO_2 gradient was 0.04 mM/mm in the 1995 (EW95 MC4, Stott et al., 2000) core compared to 0.032 mM/mm observed in 2-MC1. Because seasonal and interannual variations in marine productivity affect the rain of carbon and therefore the amount of carbon oxidation within the sediments, these differences are not unex-

pected. The similarity of the foraminiferal $\delta^{13}\text{C}$ measurements between the sampling periods implies that benthic foraminifera probably live and calcify long enough to integrate a time-averaged estimate of the $\delta^{13}\text{C}$ values within the pore waters. The $\Delta\delta^{13}\text{C}$ values of *B. argentea* s.l.–*B. tenuata* measured in 2-MC1 are close to those measured from samples collected in 1995 (Fig. 6). This may mean that the ΣCO_2 gradient measured during the 2001 cruise is not representative of conditions that have existed predominantly in this basin during recent years.

8. Influence of CH_4 oxidation on pore water ΣCO_2 and $\delta^{13}\text{C}$

There is methane present within the pore waters of most of the sites investigated in the present study. Currently, the concentration of methane near the sediment water interface (0–70 cm) does not exceed 50 μM and the methane gradient trends toward 0 μM at the sediment–water interface at all sites we investigated (Sansone et al., in press). These gradients reflect a flux of methane of between 0.2 and 5 $\mu\text{mol C/m}^2$ day. Perhaps some methane oxidation occurs near the sediment–water interface. The flux of methane through the sediments is small compared to that of ΣCO_2 (850–4600 $\mu\text{M C/m}^2$ day, Sansone et al., in press). As the methane diffuses upward through the sediments, it can add ^{12}C to the pore waters through anaerobic reactions such as:



Because the $\delta^{13}\text{C}$ of methane is so much lower than that of photosynthetic marine carbon (–57 to –73‰, Kvenvolden, 1995), the oxidation of methane and its addition to the dissolved CO_2 pool could be an important influence on the $\delta^{13}\text{C}$ values recorded by benthic foraminifera inhabiting the sediments. However, because the flux of methane is much smaller than that of ΣCO_2 , even if all available methane is oxidized, it has no discernible influence on pore water $\delta^{13}\text{C}_{\Sigma\text{CO}_2}$ (Table 3).

In a previous study Stott et al. (2002) used a diffusion-reaction model to estimate the isotopic composition of carbon added to pore waters to produce the observed $\delta^{13}\text{C}_{\text{DIC}}$ profile in the Santa

Table 3
Influence of methane oxidation on pore water TCO₂ and δ¹³C

Site	Depth (cm)	Pore water δ ¹³ C (‰)		
		Calculated if available CH ₄ oxidized	Calculated if only C _{org} oxidized	Observed
Santa Barbara	1	−3.68	−3.66	−3.67
Basin	39	−17.68	−17.62	No data
Soledad	1.5	−5.39	−5.13	−4.04
Basin	46.5	−18.81	−18.76	−18.73
Magdalena	1	−0.92	−0.92	−2.2
Basin	46.5	−19.89	−19.88	−19.89

Barbara Basin. Those calculations indicated the carbon being added to pore waters had a δ¹³C value of −17‰, similar to that of marine photosynthate carbon, which in this basin is typically around −19‰ to −20‰ (Stott et al., 2002). When a similar model is applied to data from the present study, we estimate a value of −19‰ for carbon added to the pore waters. For the Santa Monica and Soledad Basins, the closest match between the modeled pore water profile and the observed δ¹³C values requires a carbon isotopic source of −21‰, again similar to that of phytoplankton. In each of the basins studied, we find no evidence that methane is affecting the pore water isotopic gradient at the study sites. The results of this diffusion-reaction model calculation indicate the pore water isotopic values in these environments result from the addition of marine photosynthate carbon alone.

At other sites along the eastern Pacific margin, however, where there are comparatively higher rates of methane flux and methane oxidation within the pore waters, pore water isotopic values can be significantly different from those measured in this study (i.e. Torres et al., 2003; Rathburn et al., 2003). Somewhat surprisingly, benthic foraminifera inhabiting these methane-rich environments do not exhibit calcite δ¹³C values that are indicative of the depleted pore water values (Torres et al., 2003). These results seem to imply that benthic foraminifera are particular about the conditions within which they secrete calcite. Apparently, the infaunal species restrict calcification to times when the flux and oxidation of methane in the sediments is reduced (Torres et al., 2003; see also discussion by Rathburn et al., 2003). Hence, it remains unclear whether or not fossil

infaunal benthic foraminifera can be used to reconstruct histories of methane release and oxidation within the sediments.

9. A history of changing carbon oxidation along the northeast pacific margin

The pore water δ¹³C gradient is a proxy for the pore water ΣCO₂ gradient, which, as we have discussed, is controlled by the rate of carbon oxidation occurring near the sea floor. At the study sites, we investigated the carbon being added to the pore has an isotopic composition similar to photosynthate carbon. Methane-derived carbon is not being added to the pore waters at the present time in appreciable amounts. Berelson and Stott (2003) established a relationship between the difference in δ¹³C (Δδ¹³C) of benthic foraminifera, i.e. the pore water δ¹³C gradient, and carbon oxidation in Santa Monica Basin. Where benthic foraminiferal calcite reflects the δ¹³C of ambient pore water ΣCO₂, such as in Santa Monica Basin, long records of carbon oxidation can be reconstructed using down samples of fossil foraminifera.

Extending the benthic isotope record in Santa Monica Basin demonstrates a spatial and temporal change in carbon oxidation over the past 500 years (Berelson and Stott, 2003). The DOE 26 core was collected from the center of the basin and is laminated through the past 400 years. The EW95 MC4 core is from the slope and is laminated beginning in the 1940s. The values and trends of Δδ¹³C of *Bolivina argentea* s.l.–*Buliminella tenuata* is similar in both sites where the cores are laminated (Fig. 7). This implies that both sites are recording similar changes in carbon oxidation through time. Over the last three centuries, there has been a progressive increase in the pore water gradient, concurrent with an expansion of the zone of laminated sediments outward from the center of the basin as documented by Christensen et al. (1994). The Δδ¹³C record from the last century in the basin records a decrease in carbon oxidation between 1900 and 1920 AD that was followed by an increase through the late 1970s. Since the late 1970s, the rate of carbon oxidation has declined and the laminated zone began to retreat (Stott et al., 2000).

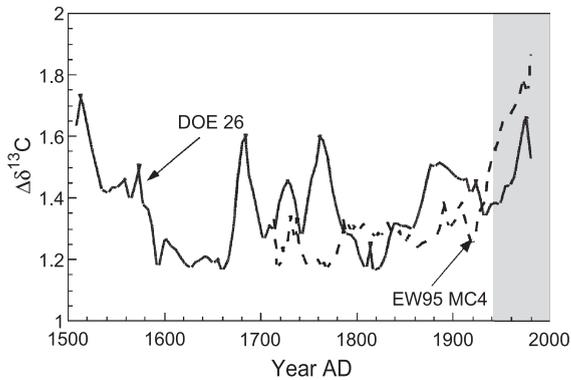


Fig. 7. $\Delta\delta^{13}\text{C}$ values using the difference between *Bolivina argentea* and *Buliminella tenuata* $\delta^{13}\text{C}$ values from Santa Monica Basin center (DOE26) and slope (EW95 MC4) cores. *Bolivina argentea* is used to estimate bottom water values. The shaded section indicates where the cores are simultaneously laminated (data from Berelson and Stott, 2003).

The addition of a second extended *Buliminella tenuata* record from Santa Monica Basin using CALMEX multicore NH01-2-MC1 confirms the longer trends observed in the DOE 26 data (Fig. 8). These cores were collected from the deep southern section of the basin plain, within the zone of laminated sediments (Christensen et al., 1994). While the spatial and temporal correlation between the EW95 MC4 and DOE 26 sites is visible only during the last century, the *B. tenuata* $\delta^{13}\text{C}$ data from NH01-2-MC1 extends the record of concurrent changes in carbon oxidation in different areas of Santa Monica Basin through the last 500 years. The geochemical relationship between epifaunal and in-faunal benthic foraminifera and ambient pore water can potentially be used to establish century-scale reconstructions of carbon oxidation for regional correlation.

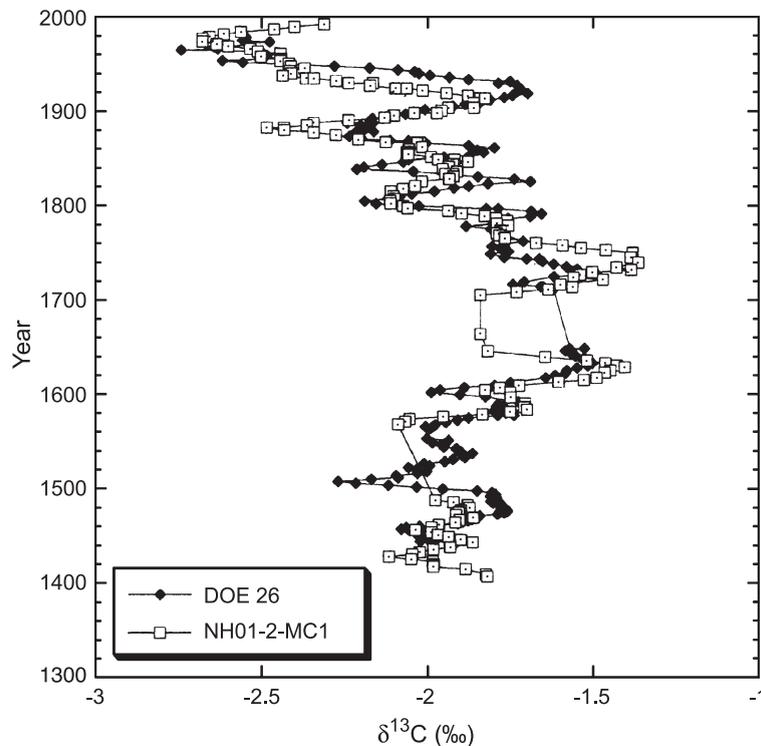


Fig. 8. The comparison of two *Buliminella tenuata* $\delta^{13}\text{C}$ records from the Santa Monica Basin (cores DOE26 and NH01-2-MC1). Both cores were collected from the center of the basin and record similar $\delta^{13}\text{C}$ values and trends over time. However, core NH01-2-MC1 has two large turbidites within the core. In order to compare the two down-core records on a similar age scale, the turbidite sediments were subtracted assuming they represented instantaneous deposition and that no time was lost by subtracting them from the core.

The combination of a long-term record of benthic carbon oxidation in low oxygen environments and records of organic carbon burial provides a reconstructed history of carbon rain. Previous work (Berelson and Stott, 2003) in Santa Monica Basin demonstrated that a change in carbon rain and benthic carbon oxidation could account for the change in oxygen levels within the basin and affect the presence or absence of a bioturbating community. In other words, it is not necessary to call upon changes in circulation and basin ventilation to explain the patterns of laminated and bioturbated sedimentation observed in down core sequences such as those from the Pleistocene of Santa Barbara Basin (Behl and Kennett, 1996).

10. Summary

The depth distribution patterns and $\delta^{13}\text{C}$ of three benthic foraminifera, *Bolivina argentea* s.l., *Bolivina subadvena* s.l. and *Buliminella tenuata*, reflect the specific sedimentary microenvironments in which they live. *Bolivina argentea* s.l. inhabits the upper millimeter of the sediment column, *B. subadvena* s.l. is most abundant at depths of 1–3 mm, and *B. tenuata* prefers a slightly deeper habitat at 4–6 mm. In most instances, these three species record unique but uniform $\delta^{13}\text{C}$ values, suggestive of a narrow range of depths for test calcification with little variation from site to site. The foraminiferal $\delta^{13}\text{C}$ values are similar to the $\delta^{13}\text{C}$ of pore water ΣCO_2 at the sediment depth horizon of species maximum abundance. *Bolivina argentea* s.l. records $\delta^{13}\text{C}$ values that are similar to the $\delta^{13}\text{C}$ of pore water ΣCO_2 at an average of 0.5 mm sediment depth, coincident with its epifaunal habitat. *Bolivina subadvena* s.l. $\delta^{13}\text{C}$ is representative of pore water at an average of 2.4 mm sediment depth, which agrees with its observed living maximum abundance. *Buliminella tenuata* reflects pore water isotopic composition at an average of 5.5 mm, similar to the sediment depth at which most living individuals are found.

This study extends to additional environments the previously observed relationship between the $\delta^{13}\text{C}$ of infaunal benthic foraminifera and pore water ΣCO_2 gradients. The consistent microhabitat preferences and relationships between the $\delta^{13}\text{C}$ of benthic foraminifera and pore water ΣCO_2 are recognized at four

different locations along the northeastern Pacific margin each varying in carbon accumulation and carbon oxidation rate: Santa Barbara Basin, Soledad Basin, the Mazatlan margin and San Blas Basin. There is a positive correlation between the $\Delta\delta^{13}\text{C}$ of species pairs and the pore water ΣCO_2 gradient. The $\delta^{13}\text{C}$ of each species becomes increasingly offset from that of bottom water as carbon flux increases. At the current rate of methane flux and methane oxidation observed at these sites, there is no discernible influence on the isotopic values of benthic foraminifera in Santa Barbara Basin, Soledad Basin or the Magdalena margin.

Evaluating the relationship between benthic foraminiferal habitat and the isotopic signature of infaunal species in relation to varying pore water geochemical gradients has demonstrated a potential for using fossil records to reconstruct longer regional-scale patterns of benthic carbon oxidation changes.

Acknowledgements

The authors wish to express thanks and appreciation to the crew of the R/V New Horizon for their assistance in this study. Drs. Joan Bernhard, Kevin Cannariato, Robert Douglas and Donn Gorsline provided valuable assistance and advice throughout the project. Appreciation is also extended to Elena Nilsen, Paola Gomez, Oscar Gonzalez-Yajimovich and Andrew Graham for their help during the research cruise. Miguel Rincon conducted the isotopic measurements in Stott's laboratory with great skill and patience. The authors wish to express thanks to Paul Aharon, Daniel McCorkle and an anonymous reviewer for their thoughtful and helpful comments and suggestions. The work was supported from a grant from the National Science Foundation, Marine Geology Division, NSF-OCE-0002250.

Appendix A. List of benthic foraminiferal taxa

Bolivina argentea s.l. Cushman = *Bolivina argentea* Walton, 1955 (p. 1001, pl. 101, Figs. 26–27) = *Bolivina argentea* var. *monicana* Zalusky 1959.

Remarks. In the present study, we apply a broader species concept to include the wide range of morpho-

logic variability observed. In previous studies that focused on a limited number sample locations, other authors (e.g. Zalusky, 1959) have applied subspecies designation to distinguish among morphotypes. In our examination of specimens from a range of locations along the Pacific margin, there appears to be a continuum of morphologies that make it difficult to precisely define where the subspecies division should be drawn. Hence, we group all morphotypes that have elongate, twisted to slightly twisted tests with acute and keeled edges. The number of chambers is not considered in our identification.

Bolivina subadvena s.l. Cushman 1935 = *Bolivina subadvena* Cushman var. *sulphurensis* Cushman and Adams 1935 (p. 20, pl. 3, Figs. 8–9).

Buliminella tenuata Cushman = *Buliminella subfusiformis* Cushman var. *tenuata* Cushman 1927 (p. 149, pl. 2, Fig. 9).

References

- Altabet, M., Francois, R., Murray, D., Prell, W., 1995. Climate-related variations in denitrification in the Arabian Sea from N15/N14 ratios. *Nature* 373, 506–509.
- Behl, R.J., Kennett, J.P., 1996. Brief interstadial events in the Santa Barbara Basin, NE Pacific, during the past 60 kyr. *Nature* 379, 243–246.
- Bender, M., Martin, W., Hess, J., Sayles, F., Ball, L., Lambert, C., 1987. A wholecore squeezer for interfacial pore water sampling. *Limnol. Oceanogr.* 32, 1214–1225.
- Berelson, W.M., 1991. The flushing of two deep-sea basins, southern California borderland. *Limnol. Oceanogr.* 36, 1150–1166.
- Berelson, W.M., Stott, L.D., 2003. Productivity and organic carbon rain to the California margin seafloor: modern and paleoceanographic perspectives. *Paleoceanography* 18 (1) 1002 (1029/2001PA000672).
- Bernhard, J.M., Reimers, C.E., 1991. Benthic foraminiferal population fluctuations related to anoxia: Santa Barbara Basin. *Biogeochemistry* 15, 127–149.
- Bernhard, J.M., Sen Gupta, B.K., Borne, P.F., 1997. Benthic foraminiferal proxy to estimate dysoxic bottom-water oxygen concentrations: Santa Barbara Basin, U.S. Pacific continental margin. *J. Foraminiferal Res.* 27, 301–310.
- Bernhard, J.M., Buck, K.R., Farmer, M.A., Bowser, S.S., 2000. The Santa Barbara Basin is a symbiosis oasis. *Nature* 403, 77–80.
- Cannariato, K.G., Kennett, J.P., 1999. Climatically related millennial-scale fluctuations in strength of California margin oxygen-minimum zone during the past 60 k.y. *Geology* 27, 975–978.
- Cannariato, K.G., Kennett, J.P., Behl, R.J., 1999. Biotic response to late quaternary rapid climate switches in Santa Barbara Basin: ecological and evolutionary implications. *Geology* 27, 63–66.
- Christensen, C.J., Gorsline, D.S., Hammond, D.E., Lund, S.P., 1994. Non-annual laminations and expansion of anoxic basin-floor conditions in Santa Monica Basin, California Borderland, over the past four centuries. *Mar. Geol.* 116, 399–418.
- Corliss, B.H., 1985. Microhabitats of benthic foraminifera within deep-sea sediments. *Nature* 314, 435–438.
- Corliss, B., Silva, K.A., 1993. Rapid growth of deep-sea benthic foraminifera. *Geology* 21, 991–994.
- Dickens, G.R., O’Neil, J.R., Rea, D.K., Owen, R.M., 1995. Dissociation of oceanic methane hydrate as a cause of the carbon-isotope excursion at the end of the Paleocene. *Paleoceanography* 10, 965–971.
- Ganeshram, R.S., Calvert, S.E., Pedersen, T.F., Cowie, G.L., 1999. Factors controlling the burial of organic carbon in laminated and bioturbated sediments off NW Mexico: implications for hydrocarbon preservation. *Geochim. Cosmochim. Acta* 63, 1723–1734.
- Ganeshram, R.S., Pedersen, T., Calvert, S., McNeill, G., Fontugne, M., 2000. Glacial–interglacial variability in denitrification in the world’s oceans: causes and consequences. *Paleoceanography* 15, 361–376.
- Grossman, E.L., 1987. Stable isotopes in modern benthic foraminifera: a study of vital effect. *J. Foraminiferal Res.* 17, 48–61.
- Hartnett, H.E., Keil, R.G., Hedges, J.I., Devol, A.H., 1998. Influence of oxygen exposure time on organic carbon preservation in continental margin sediments. *Nature* 391, 572–574.
- Holsten, J.C., 2003. A proxy for reconstructing histories of carbon oxidation in the northeast Pacific using the carbon isotopic composition of benthic foraminifera. M.S. Thesis. Univ. of Southern California, Los Angeles, California.
- Honjo, S., Manganini, S.J., Cole, J.J., 1982. Sedimentation of biogenic matter in the deep ocean. *Deep-Sea Res., Part 1, Oceanogr. Res. Pap.* 29, 609–625.
- Huyer, A., 1983. Coastal upwelling in the California current system. *Prog. Oceanogr.* 12, 259–284.
- Kennett, J.P., Ingram, B.L., 1995. A 20,000-year record of ocean circulation and climate change from the Santa Barbara Basin. *Nature* 377, 510–514.
- Kennett, J.P., Cannariato, K.G., Hendy, I.L., Behl, R.J., 2000. Carbon isotopic evidence for methane hydrate instability during quaternary interstadials. *Science* 288, 128–133.
- Kvenvolden, K.A., 1995. A review of the geochemistry of methane in natural gas hydrate. *Organic Geochemistry* 23, 997–1008.
- Loubere, P., Fariduddin, M., Murray, R.W., 2000. Patterns of export production in the eastern equatorial Pacific over the past 130,000 years. *Paleoceanography* 15, 361–376.
- Lynn, R.J., Simpson, J.J., 1987. The California current system: the seasonal variability of its physical characteristics. *J. Geophys. Res.* 92, 12947–12966.
- 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? *Mar. Micropaleontol.* 40, 233–258.
- McCorkle, D.C., Emerson, S.R., Quay, P.D., 1985. Stable carbon isotopes in marine pore waters. *Earth Planet. Sci. Lett.* 74, 13–26.

- McCorkle, D.C., 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, 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 Res., Part 1, Oceanogr. Res. Pap.* 44, 983–1024.
- O'Connell, S., Ortiz, J., van Geen, A., Zheng, Y., 2001. Rapid changes in organic carbon preservation in sediments from coastal Baja California are linked to global climatic changes. *Abstr. Programs-Geol. Soc. Am.* 33, 225.
- Orozco, E.T., 1993. Analisis volumetrico de las masas de agua del Golfo de California. M.S. Thesis. Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Baja California.
- Rathburn, A.E., Corliss, B.H., Tappa, K.D., Lohmann, K.C., 1996. Comparisons of the ecology and stable isotope compositions of living (stained) benthic foraminifera from the Sulu and South China Seas. *Deep-Sea Res., Part 1, Oceanogr. Res. Pap.* 43, 1617–1646.
- Rathburn, A.E., Perez, 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. *Geochem. Geophys. Geosyst.* 4 (12) 1106 (10.1029/2003GC000595).
- Reimers, C.E., Lange, C.B., Tabak, M., Bernhard, J.M., 1990. Seasonal spillover and varve formation in the Santa Barbara Basin, California. *Limnol. Oceanogr.* 35, 1577–1585.
- Reimers, C.E., Rutenberg, K.C., Canfield, D.E., Christiansen, M.B., Martin, J.B., 1996. Porewater pH and authigenic phases formed in the uppermost sediments of the Santa Barbara Basin. *Geochim. Cosmochim. Acta* 60, 4037–4057.
- Roemmich, D., McGowan, J., 1995. Climatic warming and the decline of zooplankton in the California current. *Science* 267, 1324–1326.
- Rullkötter, J., 2000. Organic matter: the driving force for early diagenesis. In: Schulz, H.D., Zabel, M. (Eds.), *Marine Geochemistry*. Springer, Berlin, pp. 129–172.
- Sansone, F.J., Graham, A.W., Berelson, W.M., in press. Methane along the western Mexican margin. *Limnol. Oceanogr.*
- Smith, P.E., Eppley, R.W., 1982. Primary production and the anchovy population in the southern California bight: comparison of time series. *Limnol. Oceanogr.* 27, 1–17.
- Smith, K.L., Kaufmann, R.S., Baldwin, R.J., 1994. Coupling of near-bottom pelagic and benthic processes at abyssal depths in the eastern North Pacific Ocean. *Limnol. Oceanogr.* 39, 1101–1118.
- Stott, L.D., Berelson, W., Douglas, R., Gorsline, D., 2000. Increased dissolved oxygen in Pacific intermediate waters due to lower rates of carbon oxidation in sediments. *Nature* 407, 367–370.
- Stott, L.D., Bunn, T., Prokopenko, M., Mahn, C., Gieskes, J., Bernhard, J., 2002. Does the oxidation of methane leave an isotopic fingerprint in the geologic record? *Geochem. Geophys. Geosyst.* 3 (2) 10 (1029/2001GC000196).
- Thomas, D.J., Zachos, J.C., Bralower, T.J., Thomas, E., Bohaty, S., 2002. Warming the fuel for the fire: evidence for the thermal dissociation of methane hydrate during the Paleocene–Eocene thermal maximum. *Geology* 30, 1067–1070.
- Thunell, R.C., 1998. Particle fluxes in a coastal upwelling zone: sediment trap results from Santa Barbara Basin, California. *Deep-Sea Res., Part 2, Top. Stud. Oceanogr.* 45, 1863–1884.
- Thunell, R., Pride, C., Tappa, E., Muller-Karger, F., 1993. Varve formation in the Gulf of California: insights from time series sediment trap sampling and remote sensing. *Quat. Sci. Rev.* 12, 451–464.
- Torres, M.E., Mix, A.C., Kinports, K., Haley, B., Klinkhammer, G.P., McManus, J., de Angelis, M.A., 2003. Is methane venting at the seafloor recorded by $\delta^{13}\text{C}$ of benthic foraminifera shells? *Paleoceanography* 18 (3) 1062 (10.1029/2002PA00082).
- van Geen, A., Zheng, Y., Bernhard, J.M., Cannariato, K.G., Carriquiry, J., Dean, W.E., Eakins, B.W., Ortiz, J.D., Pike, J., 2003. On the preservation of laminated sediments along the western margin of North America. *Paleoceanography* 18 (4) 1098 (10.1029/2003PA000911).
- Van Mooy, B.A.S., Keil, R.G., Devol, A.H., 2002. Impact of suboxia on sinking particulate organic carbon: enhanced carbon flux and preferential degradation of amino acids via denitrification. *Geochim. Cosmochim. Acta* 66, 457–465.
- Zahn, R., Winn, K., Sarnthein, M., 1986. Benthic foraminiferal $\delta^{13}\text{C}$ and accumulation rates of organic carbon: *Uvigerina* *pergrina* group and *Cibicidoides wuellerstorfi*. *Paleoceanography* 1, 27–42.