Marine Micropaleontology 128 (2016) 14–27

Contents lists available at ScienceDirect

Marine Micropaleontology

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

Research paper

Constraining foraminiferal calcification depths in the western Pacific warm pool

Nadine Rippert [a,*], Dirk Nürnberg [b], Jacek Raddatz [b,c], Edith Maier [a], Ed Hathorne [b], Jelle Bijma [a], Ralf Tiedemann [a]

[a] Alfred-Wegener-Institut Helmholtz Zentrum für Polar- und Meeresforschung, Postfach 12 01 61, 27515 Bremerhaven, Germany
[b] GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1–3, 24148 Kiel, Germany
[c] Goethe University Frankfurt, Institute of Geosciences, Altenhöferallee 1, 60438 Frankfurt am Main, Germany

ARTICLE INFO

Article history:
Received 9 February 2016
Received in revised form 5 August 2016
Accepted 31 August 2016
Available online 3 September 2016

Keywords:
Living planktonic foraminifera
Apparent calcification depth
Western equatorial Pacific
Stable oxygen and carbon isotopes
Mg/Ca analyses
Foraminiferal vital effects

ABSTRACT

Insight into past changes of upper ocean stratification, circulation, and nutrient signatures rely on our knowledge of the apparent calcification depth (ACD) and ecology of planktonic foraminifera, which serve as archives for paleoceanographic relevant geochemical signals. The ACD of different species varies strongly between ocean basins, but also regionally. We constrained foraminiferal ACDs in the Western Pacific Warm Pool (Manihiki Plateau) by comparing stable oxygen and carbon isotopes ($\delta^{18}O_{calite}$, $\delta^{13}C_{calcite}$) as well as Mg/Ca ratios from living planktonic foraminifera to *in-situ* physical and chemical water mass properties (temperature, salinity, $\delta^{18}O_{seawater}$, $\delta^{13}C_{DIC}$). Our analyses point to *Globigerinoides ruber* as the shallowest dweller, followed by *Globigerinoides sacculifer*, *Neogloboquadrina dutertrei*, *Pulleniatina obliquiloculata* and *Globorotaloides hexagonus* inhabiting increasing greater depths. These findings are consistent with other ocean basins; however, absolute ACDs differ from other studies. The uppermost mixed-layer species *G. ruber* and *G. sacculifer* denote mean calcification depths of ~95 m and ~120 m, respectively. These Western Pacific ACDs are much deeper than in most other studies and most likely relate to the thick surface mixed layer and the deep chlorophyll maximum in this region. Our results indicate that *N. dutertrei* appears to be influenced by mixing waters from the Pacific equatorial divergence, while *P. obliquiloculata* with an ACD of ~160 m is more suitable for thermocline reconstructions. ACDs of *G. hexagonus* reveal a deep calcification depth of ~450 m in oxygen-depleted, but nutrient-rich water masses, consistent to other studies. As the $\delta^{13}C$ of *G. hexagonus* is in near-equilibrium with ambient seawater, we suggest this species is suitable for tracing nutrient conditions in equatorial water masses originating in extra-topical regions.

1. Introduction

Geochemical signals of planktonic foraminifera shells (=tests) are frequently used for paleoceanographic studies as they well reflect past environmental conditions (e.g., Shackleton, 1974; Ravelo and Fairbanks, 1992; Nürnberg, 1995; Nürnberg et al., 1996; Bemis et al., 1998; Elderfield and Ganssen, 2000; Lea et al., 2000). Many species, however, are known to migrate through the water column during their life cycle and thus, their geochemical signals most likely provide an integrated signal across both the entire water depth range and the entire ontogenetic (calcification) cycle of the species (e.g., Hemleben and Bijma, 1994). Hence, the foraminiferal habitat depths determined by these geochemical signals are best described by the term Apparent Calcification Depth (ACD). It should be noted that the shell weight and therefore the chemical signature of the shell as a whole is mainly determined by the chemical composition of the last few chambers.

Approaches using planktonic foraminifers as biotic carriers of geochemical signals generally emphasize the importance of the knowledge of foraminiferal ACDs. Since the first plankton tow studies of Bé (1959, 1962), efforts were launched to most reliably define the foraminiferal depth habitat (Thunell and Honjo, 1981; Fairbanks et al., 1982; Thunell et al., 1983). With the development of geochemical analysis on foraminiferal tests, it was further possible to assess foraminiferal ACD (Emiliani, 1955; Shackleton, 1974; Nürnberg, 1995; Faul et al., 2000; King and Howard, 2005; Regenberg et al., 2009; Steph et al., 2009; Wilke et al., 2009; Birch et al., 2013; Wejnert et al., 2013) These studies reveal significant regional intraspecific differences in the ACD (Faul et al., 2000; Steph et al., 2009). The species *Globigerinoides ruber*, for example, is often referred to as a “surface dweller”, i.e. living within the upper 30 m of the water column (Hemleben et al., 1989; Faul et al., 2000; Steph et al., 2009; Birch et al., 2013). However, in cases of high sea surface temperatures (SST) and a deep chlorophyll maximum (DCM), it has been shown to descend to and calcify in deeper waters (Fairbanks et al., 1982; Wejnert et al., 2013). Contrary, the ACDs of *Neogloboquadrina dutertrei* scatter within the 40–200 m water depth range (Hemleben et

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* Corresponding author.
E-mail address: Nadine.Rippert@awi.de (N. Rippert).

http://dx.doi.org/10.1016/j.marmicro.2016.08.004
0377-8398/

al., 1989; Dekens et al., 2002; Steph et al., 2009; Faul et al., 2000; Nürnberg et al., 2015). Particularly, during strong upwelling the ACD can shoal from within the thermocline to distinctly shallower waters (Loubere, 2001). As the studies are scattered over the world oceans, reliable estimations of the ACDs of planktonic foraminifera in a specific area remains a challenge, which is further hampered by logistical difficulties.

The Western Pacific Warm Pool (WPWP) is the largest warm water area on Earth with SSTs consistently higher than 28 °C (Fig. 1a) (Yan et al., 1992). The WPWP deep thermocline (~175–300 m in the center of the WPWP; Andreasen and Ravelo, 1997) allows for a large heat capacity, making it the major source of heat and moisture transfer from low to high latitudes. In contrast, in the eastern equatorial Pacific (EEP) the thermocline reaches depths as shallow as 30 m (Locarnini et al., 2013). This asymmetric behaviour is also clearly seen in the zonal nitrate section (Fig. 1b), which points towards overall oligotrophic conditions in the WPWP and contrasting with fertile conditions in the EEP. Fluctuations in size and temperature of the WPWP are important drivers for the El Niño–Southern Oscillation (ENSO), the Asian monsoon system and, through atmospheric teleconnections, the global climate system (Sagawa et al., 2012). Despite the importance of the WPWP in the climate system, only little information about foraminiferal ACDs are available. To-date, the limited number of studies from the WPWP have concentrated on reconstructing upper ocean conditions with known ACDs from different regions (e.g., Wara et al., 2005; Russon et al., 2010) or focused on foraminiferal assemblages from the center of the WPWP near New Guinea (Kawahata et al., 2002; Yamasaki et al., 2008), or on plankton tows and surface sediments from the central equatorial Pacific (Watkins et al., 1996; Lynch-Stieglitz et al., 2015).

Our multinet study from the Manihiki Plateau attempts for the first time to define the modern ACDs of selected planktonic foraminifera at the south-eastern margin of the WPWP. Five modern planktonic foraminiferal species are studied: *G. ruber* (white), *Globigerinoides sacculifer*, *N. dutertrei*, *Pulleniatina obliquiloculata* and *Globorotaloides hexagonus*. We measured stable oxygen and carbon isotopes ($\delta^{18}O_{calcite}$, $\delta^{13}C_{calcite}$) as well as Mg/Ca ratios on the foraminiferal calcite and compared these data to in-situ physical and chemical seawater characteristics (temperature, salinity, $\delta^{18}O_{seawater}$, dissolved inorganic carbon $\delta^{13}C_{DIC}$). By doing so, we were able to better constrain species-specific ACD in an area with the thickest and warmest mixed layer on Earth and to determine the species-specific carbon-isotope disequilibrium. By doing so, we developed a great understanding of regional foraminiferal ACDs in the WPWP. We were then able to define to what extent the geochemical measurements deviate from predictions based on empirical relationships. Our study can be used to inform on what species to use for upper ocean water mass reconstructions of WPWP internal dynamics.

1.1. Foraminiferal ecological preferences and hydrographic setting

The abundance of planktonic foraminiferal species is strongly affected by environmental parameters such as, the thermal structure of the water column, salinity, and food supply (e.g., Bijma et al., 1990; Watkins et al., 1996; King and Howard, 2003; Žarić et al., 2005). Culture experiments and surface-sediment samples indicate temperature as one of the major environmental parameters affecting the foraminiferal biogeographic distribution (Bé and Tolderlund, 1971; Bijma et al., 1990; Morey et al., 2005). Even though most planktonic foraminifera

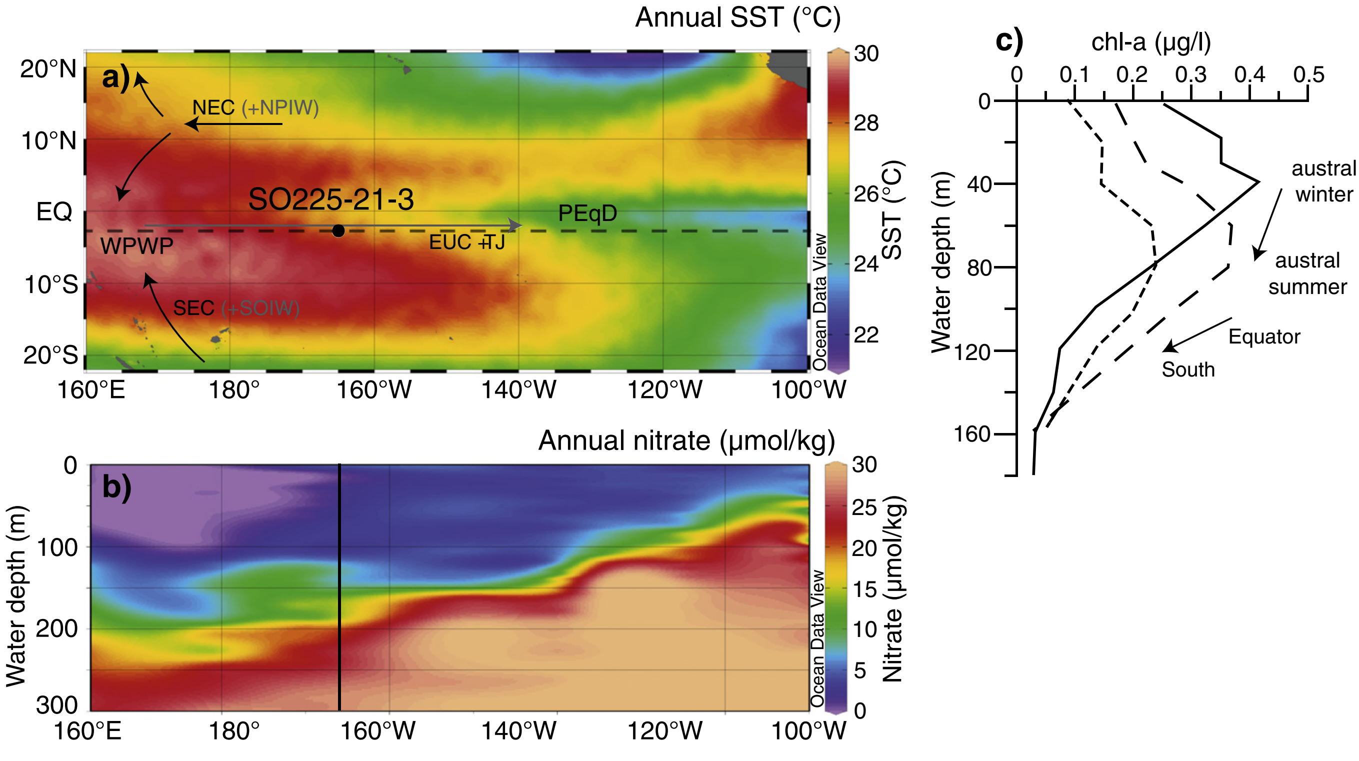

Fig. 1. Upper ocean conditions of the equatorial Pacific. (a) Annual sea-surface temperatures (SSTs) with multinet position SO225-21-3 and selected profile line shown in (b) (dashed line). WPWP denotes the Western Pacific Warm-Pool, PEqD the Pacific Equatorial Divergence. Major surface (black) and intermediate (grey) currents are indicated with arrows; NEC = North Equatorial Current fed by the NPIW = North Pacific Intermediate Waters, SEC = South Equatorial Current fed by the SOIW = Southern Ocean Intermediate Waters, and EUC + TJ = Equatorial Undercurrent and Tsuchiya Jets (after Tomczak and Godfrey, 1994; Firing et al., 1998; Rowe et al., 2000). (b) Longitudinal depth section of annual nitrate along 3 °S (see dashed line in (a)) with multinet position SO225-21-3 (black vertical line). Temperature map and section were generated with Ocean Data View (Schlitzer, 2012) using World Ocean Atlas 13 Data (a; Locarnini et al., 2013) and GLODAP bottle data (b; Key et al., 2004). (c) Chlorophyll-*a* concentration of the upper 200 m showing a seasonal and latitudinal change in the depth of the deep chlorophyll maximum. Profiles taken from *FLUPAC* cruise (black line, 0°, 164 °W, October 1994; Blain et al., 1997), *Alizé 2* cruise at 0°, 165 °W (wide stippled line, February 1991; Reverdin et al., 1991) and *Alizé 2* cruise at 2.5 °S, 168 °W (narrow stippled line, February 1991; Reverdin et al., 1991), respectively.