Marine Geology 382 (2016) 151–161

Contents lists available at ScienceDirect

Marine Geology

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

Sediment sorting and focusing in the eastern equatorial Pacific

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ARTICLE INFO

Article history:
Received 28 August 2015
Received in revised form 21 September 2016
Accepted 26 September 2016
Available online 28 September 2016

Keywords:
Grain size
Sediment focusing
Sorting coefficient
Particle sorting
Eastern equatorial Pacific

ABSTRACT

The interpretation of sedimentary records in terms of glacial-interglacial changes in particle flux in the eastern equatorial Pacific (EEP) has been controversial. Here, we analyze disaggregated inorganic grain size (DIGS) distributions of three marine sediment cores from this region, focusing on the last 21 ka, to investigate evidence of sediment redistribution on the sea floor. Grain size sorting coefficients show that sediments in the EEP are moderately to well sorted, indicating sediment reworking in this region due to bottom currents. Furthermore, a systematic correlation between focusing factors and sorting coefficients at two sites shows that more focused sediments are also better sorted. We conclude that grain size based sedimentary records are consistent with the ^{230}Th-based evidence of lateral sediment redistribution on the sea floor in the EEP.

1. Introduction

The eastern equatorial Pacific (EEP) has been an area of interest for present and past biogeochemical studies because of its elevated primary productivity due to upwelling of nutrient rich subsurface waters. Considerable efforts have been made to reconstruct paleoproductivity in the EEP, the connection of this region to higher latitudes, and its link to climate variability on glacial-interglacial and millennial time scales (e.g., Calvo et al., 2011, Costa et al., 2016, Dubois et al., 2011, 2014, Hayes et al., 2011, Kienast et al., 2006, Lea et al., 2006, Loubere et al., 2004, Lyle et al., 2002, Patarroyo and Martínez, 2015, Pena et al., 2008, Pichat et al., 2004, Robinson et al., 2009, Winckler et al., 2016 and references therein). Several biological (Loubere, 2000) and geochemical proxies (Averty and Paytan, 2004) have been developed for reconstructing past changes in productivity and vertical flux. These proxies usually quantify changes in the burial flux of a biogenic component, which is then used to estimate vertical flux and paleoproductivity (Murray and Leinen, 1993; Murray et al., 2012; Paytan et al., 1996). However, the interpretation of sedimentary records in this region has been controversial.

Traditionally, the burial flux of a component is quantified as mass accumulation rate (MAR) based on linear sedimentation rate, dry bulk density and the concentration of the component of interest (DeMaster, 1981; Curry and Lohmann, 1986). The uncertainties associated with this method can be high, especially since it does not discriminate between vertical flux from the overlying water column (the variable of interest) and lateral flux from sediment redistribution on the sea floor due to bottom currents. The newer and increasingly used approach for estimating burial flux is based on the constant flux tracer ^{230}Th and is considered to provide more accurate estimates of vertical flux. Thorium-230 is produced uniformly in the water column by the decay of uranium-234 (^{234}U) at a known constant rate of 0.0267 dpm m^{-3} yr^{-1}. Thorium is highly insoluble in seawater and has a high affinity for particles, resulting in prompt removal from the water column as it adsorbs to settling particles (Bacon and Anderson, 1982; Francois et al., 2004; Henderson and Anderson, 2003). Based on the particle-reactive behavior of ^{230}Th, Bacon (1984) proposed that the flux of scavenged ^{230}Th to the sea floor is equivalent to its production from ^{234}U decay in the overlying water column. Therefore, the accumulation rate within a sediment horizon can be estimated by normalizing the known production rate of ^{230}Th to the concentration of ^{230}Th in the same horizon.

Export fluxes calculated using the traditional MAR and the ^{230}Th normalization method sometimes give divergent results, particularly in the equatorial Pacific (e.g., Anderson and Winckler, 2005; Averty and Paytan, 2004; Broecker, 2008; Francois et al., 2007; Kienast et al., 2007; Loubere et al., 2004; Lyle et al., 2005, 2007; Marcantonio et al., 2001; Paytan et al., 1996; Singh et al., 2011). Traditional MARs suggest large export fluxes (e.g., organic matter) and by inference higher primary productivity during the glacial period compared to the Holocene (Broecker, 2008; Lyle et al., 2002; Paytan et al., 1996). However, estimates based on ^{230}Th normalization show significantly

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http://dx.doi.org/10.1016/j.margeo.2016.09.016
0025-3227/

lower export flux (by 20–40 %) and little to no change in glacial and interglacial trends in the equatorial Pacific (Anderson et al., 2008; Higgins et al., 2002; Loubere et al., 2004; Marcantonio et al., 2001). The inconsistencies between these two methods have given rise to the "focusing debate" (Broecker, 2008; Francois et al., 2004, 2007; Lyle et al., 2005, 2007).

Studies supporting ^{230}Th normalization suggest that traditional MARs are influenced by lateral sediment redistribution that occurs in the deep Pacific Ocean, possibly in a systematic climate related fashion. Suman and Bacon (1989) quantified syndepositional sediment redistribution using the inventory of excess ^{230}Th in the sediment and introduced the "focusing factor". Calculation of the focusing factor (Ψ) is based on the assumption that the inventory of excess ^{230}Th in the sediment is equal to its production rate in the water column by uranium decay. If there is no syndepositional sediment redistribution on the sea floor, the ratio between inventory and production is equal to 1 ($\Psi = 1$). The inventory of excess ^{230}Th in the sediment will change if there is addition (focusing, $\Psi > 1$) or removal (winnowing, $\Psi < 1$) of sediment on the sea floor (Francois et al., 2004; Suman and Bacon, 1989). In the EEP, focusing factors as high as 10.5 have been observed (Singh et al., 2011) for glacial age sediments.

Studies challenging ^{230}Th normalization argue that sedimentary evidence does not support widespread sediment redistribution in the equatorial Pacific (Broecker, 2008; Lyle et al., 2005, 2007). These studies suggest that the observed high inventory of ^{230}Th in the sediment is due to boundary scavenging of dissolved ^{230}Th in the water column from areas of low particle flux, such as gyres, to areas of high particle flux, such as the equatorial upwelling region. Francois et al. (2007), however, argued that the low residence time of dissolved ^{230}Th ($<$ 4–40 yrs) and suspended particulates (5–10 yrs) inherently limits the lateral transport of both dissolved ^{230}Th and ^{230}Th attached to suspended particles. Hayes et al. (2013) found a uniform distribution of dissolved ^{230}Th despite spatial gradients in particle flux in the North Pacific Ocean. In the highly productive upwelling region off North West Africa, Hayes et al. (2015) constrained boundary scavenging of ^{230}Th to 40±10 % of its water column production. Siddall et al. (2008) used an ocean circulation model to further argue against the studies by Lyle et al. (2007) and Broecker (2008) and showed that boundary scavenging does not fully explain the high excess ^{230}Th accumulation observed in the Panama Basin. Similarly, Singh et al. (2013) found that the transport of dissolved ^{230}Th from the Peru Basin into the Panama Basin is relatively small and only contributes 15–30 % of the total dissolved ^{230}Th found within the water column of the Panama Basin itself. The lateral export of dissolved ^{230}Th between these two basins could only produce focusing factors of 1.3 and cannot explain the high focusing factors found at some sites in Panama Basin (Kienast et al., 2007; Singh et al., 2011).

In this study, we use disaggregated inorganic grain size (DIGS) measurements of EEP downcore sediments as an independent approach to investigate sea floor sediment dynamics over time. The DIGS distribution is a function of the physical processes affecting sediment transport and deposition, and records information about the environmental conditions under which the sediment was deposited (Folk and Ward, 1957; Kranck, 1975; Kranck and Milligan, 1985; Kranck et al., 1996a; Middleton, 1976). Grain size parameters such as mean size, sorting coefficient, and skewness are therefore used to gain insight into processes affecting the sediment prior to final deposition (Blott and Pye, 2001; Flemming, 2007; Folk and Ward, 1957). A particle with a given settling velocity (which is related to its grain size) gets deposited when the current shear stress is below its critical deposition stress. Sediment grains are hydrodynamically size sorted according to particle settling velocity and shear stress (Kranck and Milligan, 1985; McCave et al., 1995). During transport, particles with a larger settling velocity are deposited on the seabed while grains with smaller settling velocity are kept in suspension and are transported further downstream (McCave et al., 1995; McCave and Hall, 2006). Thus, under the influence of bottom currents, an originally unsorted hemipelagic sediment becomes sorted according to settling velocity (grain size), and will display a mode in its DIGS distribution (Fig. 1). Sediments that have undergone multiple resuspension and settling events, therefore, display a narrow, well sorted DIGS distribution (McCave et al., 1995; McCave and Hall, 2006; Kranck et al., 1996a,b).

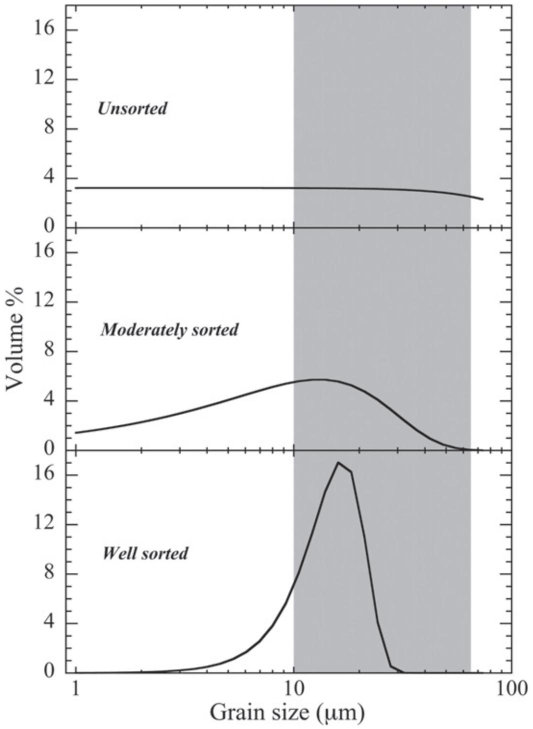

Fig. 1. Idealized DIGS distributions of an unsorted hemipelagic sediment, a moderately sorted, and a well sorted sediment on semi-log axes. The shaded area represents the sortable silt (10–63 μm) size range. The distribution of unsorted sediment (top panel) approximately follows the hemipelagic sediment observed by Rea and Hovan (1995). The distributions of moderately sorted (middle panel) and well sorted (bottom panel) sediment are similar to the size distribution of sediment from the Nova Scotian Rise at moderate and fast current velocity, respectively (McCave et al., 1995). Note that the well sorted sediment shows a narrower spread in its size distribution.

McCave et al. (1995) showed that in the deep sea, bottom current hydrodynamics mostly affect quartz grains in the sortable silt size range (10–63 μm) because of the tendency of material finer than 10 μm to behave cohesively, and because of the inability of average deep sea currents to move materials coarser than 63 μm (Ledbetter, 1986; McCave et al., 1995; McCave and Hall, 2006). Sediments in the sortable silt range are likely to be broken up and respond as single particles within the high shear region near the seabed. A high degree of sorting indicates that sediments have undergone lateral transport on the sea floor, so a positive correlation should exist between focusing factors and the degree of sediment sorting.

2. Methods

2.1. Core material and study area

Three cores from the EEP were studied for this project (Fig. 2, Table 1). ME0005A-27JC (hereafter referred to as ME-27) was recovered from 2203 m water depth on the southern side of the Carnegie Ridge, which forms the southern boundary of the Panama basin. Core TR163-19 (hereafter referred to as TR-19) was recovered