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Ecological tolerances of Miocene larger benthic foraminifera from Indonesia

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ABSTRACT

To provide a comprehensive palaeoenvironmental reconstruction based on larger benthic foraminifera (LBF), a quantitative analysis of their assemblage composition is needed. Besides microfacies analysis which includes environmental preferences of foraminiferal taxa, statistical analyses should also be employed. Therefore, detrended correspondence analysis and cluster analysis were performed on relative abundance data of identified LBF assemblages deposited in mixed carbonate-siliciclastic (MCS) systems and blue-water (BW) settings. Studied MCS system localities include ten sections from the central part of the Kutai Basin in East Kalimantan, ranging from late Burdigalian to Serravallian age. The BW samples were collected from eleven sections of the Bulu Formation on Central Java, dated as Serravallian. Results from detrended correspondence analysis reveal significant differences between these two environmental settings. Cluster analysis produced five clusters of samples; clusters 1 and 2 comprise dominantly MCS samples, clusters 3 and 4 with dominance of BW samples, and cluster 5 showing a mixed composition with both MCS and BW samples. The results of cluster analysis were afterwards subjected to indicator species analysis resulting in the interpretation that generated three groups among LBF taxa: typical assemblage indicators, regularly occurring taxa and rare taxa. By interpreting the results of detrended correspondence analysis, cluster analysis and indicator species analysis, along with environmental preferences of identified LBF taxa, a palaeoenvironmental model is proposed for the distribution of LBF in Miocene MCS systems and adjacent BW settings of Indonesia.

1. Introduction

Southeast Asia hosts the most diverse marine ecosystems in the world (Bellwood et al., 2005; Hoeksema, 2007). The origin of this biodiversity hotspot (Renema et al., 2008) is still unresolved, as well as the precise timing and associated environmental conditions. The biodiversity hotspot first occurred at latest during the Early Miocene (Renema et al., 2008), but diversified coral faunas have been reported from the early Late Oligocene (McMonagle et al., 2011). In order to understand the environmental conditions associated with the ecological processes leading to this high biodiversity, a more comprehensive understanding of the fossil record is needed.

Tropical shallow marine ecosystems comprise diverse depositional systems, amid them mixed carbonate-siliciclastic (MCS) environments developed in turbid waters (Mount, 1984; Wilson, 2005; Brandano et al., 2010; Morsilli et al., 2011), and carbonates deposited in nutrient-poor, high water transparency environments ('blue-water' (BW); Wilson, 2012). Mixed carbonate-siliciclastic systems were considered to be inhospitable for carbonate producers (Friedman, 1988), at least compared to the BW systems. However, in recent years fossil MCS systems have received an increased interest, with studies revealing high species/genus/taxon richness in these turbid settings, including corals (Wilson and Rosen, 1998; Brandano et al., 2010; Morsilli et al., 2011; Santodomingo et al., 2015), larger benthic foraminifera (LBF) (Kumar and Saraswati, 1997; Novak and Renema, 2015), algae (Bassi and Nebelsick, 2010; Rösler et al., 2015) and bryozoans (Di Martino and Taylor, 2014). Among these fossil groups, LBF are most frequently present in MCS deposits due to their high tolerance for these challenging environments, their abundant occurrences and high preservation potential (Renema and Troelstra, 2001; Renema, 2006b; Lokier et al., 2009; Novak et al., 2013).

The distribution of LBF is controlled by environmental factors such as light levels, hydrodynamic energy, water temperature, salinity, food availability and substrate type (Hottinger, 1983; Hohenegger, 1994; Renema and Troelstra, 2001; Renema, 2006a,b). Therefore, the assemblage composition of LBF provides important insights into the effects of the environmental change on shallow marine ecosystems. Most of the current understanding of ecological tolerances of LBF is based on analogues with the modern fauna. Many studies are available that describe the distribution of LBF in modern shallow marine environments (e.g., Hallock, 1984; Reiss and Hottinger, 1984; Hohenegger, 1994; Hohenegger et al., 1999; Renema and Troelstra, 2001; Renema,

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2006a,b; Baker et al., 2009). However, a substantial part of the modern fauna has post-Middle Miocene origins (Renema et al., 2008). Furthermore, for the Middle Miocene and older LBF faunas, e.g. characterised by large involute nummulitids often with lateral chamberlets (e.g., *Spiroclypeus)*, or large orbitoidal forms also with lateral chamberlets (e.g., lepidocyclinids, miogypsinids), there are no modern analogues.

One of the pioneer studies dealing with environmental parameters of Miocene foraminifera examined cores collected from four Philippine wells (Hallock and Glenn, 1986). By testing the depositional model based on key ecological observations of modern foraminifera, including algal symbiosis, size, shape, water salinity, substrate and water turbulence, the authors distinguish three major groups of foraminifera and five major facies types (Larger Foraminifera Wackestone, Coral Boundstone, Red Algal-Larger Foraminiferal Packstone, Small Foraminiferal Grainstone and Packstone, Additional Facies). In another study, Kumar and Saraswati (1997) analysed the response of larger foraminifera to mixed carbonate-siliciclastic environments of Oligocene-Miocene sediments from the Gulf of Kutch, India. While focusing on microfacies analysis and reconstruction of depositional environment, the authors also examined the different susceptibility of larger foraminifera to clastic influx in the environment. In their study *Miogypsina* showed the highest tolerance to terrigenous input, while *Spiroclypeus* and *Sorites* preferred relatively clear BW environments. One of the most detailed studies of marine shallow water biota deposited in mixed carbonate volcanoclastic/siliciclastic systems focused on Miocene sediments from Java and east Borneo and included LBF, coralline algae and corals (Lokier et al., 2009). The influence of siliciclastic/volcanoclastic influx on shallow water carbonate producers was quantifiably assessed by analysing the taxa quantity, sediment type and grain size. The most tolerant groups to clastic influx were LBF and coralline algae. The platy corals were dependent on the grain size of the sediment and were restricted to facies in which clay was the dominant component in the matrix. All of above mentioned studies provide important and valuable information regarding LBF in the Miocene depositional environments. However, the comprehensive distribution model for LBF dwelling in fossil MCS systems of Miocene is still lacking.

The aims of this paper are (1) to compare LBF assemblages of turbid water MCS systems to the BW assemblages of carbonate platforms, and (2) to propose a distribution model based on combined interpretation of environmental preferences, microfacies and statistical analysis of LBF, that can serve as a tool for palaeoenvironmental reconstructions.

2. Materials and methods

2.1. Samples

In the current study investigated samples were collected from multiple sections, ranging from late Burdigalian to the Serravallian/Tortonian boundary, of East Kalimantan and Java, Indonesia (Fig. 1). Samples from Java were collected from the Bulu Formation outcrops deposited in BW environments characteristic for a carbonate platform (Sharaf et al., 2005; Lunt, 2013). The East Kalimantan sections include MCS systems of the Kutai Basin which developed in environmental settings ranging from delta front to shelf edge (Wilson, 2005; Novak et al., 2013; Santodomingo et al., 2015; Marshall et al., 2015).

Field work comprised lithological logging and sampling of each lithological unit. In lithified beds samples were collected as hand specimens, while in soft sediment bulk samples of approximately 5–7 kg per sample bag were collected. Thin sections (48 × 28 mm) were made from hand specimens for identification of LBF taxa and analysis of the assemblages. Bulk samples were washed and sieved, with the 0.5–4 mm fraction picked and analysed for LBF. Isolated specimens of LBF were identified based on their external test morphology and internal structures obtained from oriented polished thin sections. Microfacies analysis of thin sections included identification of skeletal component and lithological classification, using adopted textural schemes of Dunham (1962) and Insalaco (1998). For the purpose of statistical analysis, the same framework for facies type definitions was used in both Java and Kutai Basin sections, based on matrix type, lithology and fossil content (Table 1).

To analyse the LBF assemblage composition, washed bulk samples were split using micro-splitter until approximately 200 foraminifera specimens remained in the sample. In thin section samples LBF occurrences were counted from the whole slide surface. Identification of LBF in both sample types followed Lunt and Allan (2004) and Renema (2007 and references therein), to genus or species level. When using open nomenclature, Novak and Renema (2015) were followed for identification of *Miogypsina* and *Nephrolepidina* groups. In the current study, *Cycloclypeus* sp. 1 represents flat specimens of the *C. eidae* - *C. carpenteri* lineage (Renema et al., 2015) which cannot be identified to higher taxonomic level in the absence of oriented thin sections, while *C. annulatus* represents specimens characterized by several annular inflations of the lateral walls. Miliolid taxa are separated into Miliolidae 1, comprising forms with five-plane symmetry and Miliolidae 2, comprising forms with a three-plane symmetry.

2.2. Statistics

The relative abundance of identified LBF taxa was calculated as the percentage of the total foraminifera specimens in each sample. Only samples with at least 20 specimens were included in the analysis. The distorting impact of very abundant LBF taxa was eliminated by log-transformation of the abundance data ($y' = \log [y + 1]$). To conduct a quantitative analysis and comparison of LBF assemblages between the samples, cluster analysis, detrended correspondence analysis (DCA) and analysis of similarities (ANOSIM) were applied on the resulting LBF relative abundance matrix. The cluster analysis was performed using the group average grouping method and Bray-Curtis similarity measure. Afterwards, the outcome of cluster analysis was subjected to indicator species analysis (ISA), using the Dufrêne and Legendre (1997) method, resulting in indicator values ranging from 0 to 100 for each taxon (for more details see Renema and Troelstra, 2001). To combine the results of facies analysis with the cluster analysis, the relative occurrences of facies types in a cluster were calculated. Firstly, the abundance of each facies type was calculated per cluster, followed by calculating the absolute deviation from random expectation (i.e. percentage of samples with specific facies type in the total number of samples). In this way the facies type was characterized by both positive and negative characters. This ensured that rare facies types were also characterized in the data set. When facies type is not present in the studied cluster, the value equals -1. When calculated absolute deviation is equal to random expectation the value is 0. Therefore, when values fall between -1 and 0, the facies type has lower than expected occurrence. When values are above 0, the facies has higher than expected occurrence in the studied cluster.

The DCA was chosen for the current study because this multivariate ordination technique reveals taxonomic groupings among samples distributed across environmental gradients (Huntley, 2011). One-way ANOSIM was carried out to check the difference in the assemblage composition, using the Bray-Curtis distance measure. Cluster analysis and ISA were performed in PC-ORD v. 6.05 (McCune and Mefford, 2011), while the DCA and ANOSIM were carried out using the freeware PAST, v. 2.17c (Hammer et al., 2001).

3. Results

Studied MCS systems included three locations near the city of Bontang and seven locations in the suburbs of Samarinda; five of them from the Batu Putih outcrops and two sections near the Stadion Utama Kaltim (Fig. 1). Based on stratigraphically important LBF, the Bontang sections are inferred to be of a late Burdigalian age (Novak et al., 2013;