Journal of Marine Systems xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Marine Systems

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

Planktonic foraminiferal abnormalities in coastal and open marine eastern Mediterranean environments: A natural stress monitoring approach in recent and early Holocene marine systems

Antonarakou A.[a,*], Kontakiotis G.[a], Zarkogiannis S.[a], Mortyn P.G.[b,c], Drinia H.[a], Koskeridou E.[a], Anastasakis G.[a]

[a] Faculty of Geology & Geoenvironment, School of Earth Sciences, Department of Historical Geology-Paleontology, National & Kapodistrian University of Athens, Panepistimiopolis, Zografou 15784, Greece
[b] Institute of Environmental Science and Technology (ICTA), Universitat Autçnoma de Barcelona (UAB), Edifici Z - Carrer de les Columnes, Bellaterra 08193, Spain
[c] Department of Geography, Universitat Autçnoma de Barcelona (UAB), Spain

ARTICLE INFO

Keywords:
Natural stress
Marine ecosystem monitoring
Twin planktonic bio-indicators
Salinity
Eutrophication
Eastern Mediterranean hydrodynamics

ABSTRACT

Marine environmental status can be assessed through the study of bio-indicator species. Here, we monitor natural environmental stress by the occurrence of morphologically abnormal planktonic foraminiferal specimens from a suite of surface sediments in the eastern Mediterranean Sea. We also compare Scanning Electron Microscopy (SEM) abnormality observations from sapropel S1-derived sediments in the Aegean, Libyan and Levantine basins, since they provide a direct record of a natural stress experiment that took place over past time scales. At initial sapropel deposition levels, we observe increased growth asymmetry in *Globigerinoides ruber* twinned and twisted individuals, possibly associated with eutrophication and anoxia. In modern material, a range of malformations and aberrant morphologies from slight deformity with smaller or overdeveloped chambers to more severe deformity with abnormally protruding or misplaced chambers, distorted spirals, and double tests is also observed, as a result of the hypersaline, oligotrophic and oxygen-depleted nature of the Mediterranean Sea water column. Overall, we highlight the current use of the relative abundance of abnormal tests as a bio-indicator for monitoring natural stress, especially the occurrence of twin specimens as indicative of high-salinity stress conditions, and further illustrate the necessity to map both their spatial and temporal distribution for accurate paleoenvironmental reconstructions. Such an approach presents the advantage to rapidly provide information over wide spatial and temporal scales, extending our ability to monitor a wide variety of environments (from coastal to the open-sea). However, further investigations should extend this approach to test the robustness of our findings in a number of similar oceanic settings.

1. Introduction

Open marine and coastal ecosystems are increasingly impacted globally by a series of threats that include climate change (Danovaro et al., 2001, 2004; Overland et al., 2010; Hoegh-Guldberg and Bruno, 2010), pollution by heavy metals (Le Cadre and Debenay, 2006; Frontalini and Coccioni, 2008, 2011; Caruso et al., 2011; Aloulou et al., 2012; Melis and Covelli, 2013; Cosentino et al., 2013), wide salinity fluctuations (Stouff et al., 1999a, 1999b; Debenay et al., 2001; Ballent and Carignano, 2008; Nigam et al., 2008), water acidification (Geslin et al., 2002; Le Cadre et al., 2003; Wall-Palmer et al., 2011; Haynert and Schönfeld, 2014), change of nutrient status (Diaz and Rosenberg, 2008; Rossignol et al., 2011), oxygen depletion (Debenay et al., 2009; Luciani et al., 2010; Geslin et al., 2014), habitat loss and degradation (Dobson et al., 2006), hydrodynamic damages (Stouff et al., 1999b; Geslin et al., 2000), and/or excessive human activities (Matthiessen and Law, 2002; Lotze et al., 2005; D'Alessandro et al., 2016). These stressors can have synergistic effects on marine ecosystems (Griffen et al., 2016), especially in semi-enclosed basins surrounded by high population density, tourism flow and maritime activities (Danovaro, 2003). Although recent large advances in the field of simulation and quantification of the majority of the above-mentioned causes have been made through laboratory experiments and field investigations (Le Cadre et al., 2003; Le Cadre and Debenay, 2006; Nigam et al., 2008; Geslin et al., 2014;

* Corresponding author.
E-mail addresses: aantonar@geol.uoa.gr (A. Antonarakou), gkontak@geol.uoa.gr (G. Kontakiotis), graham.mortyn@uab.es (P.G. Mortyn), cntrinia@geol.uoa.gr (H. Drinia), ekosker@geol.uoa.gr (E. Koskeridou), anastasakis@geol.uoa.gr (G. Anastasakis).

https://doi.org/10.1016/j.jmarsys.2018.02.004
Received 19 July 2017; Received in revised form 26 January 2018; Accepted 6 February 2018
0924-7963/

Haynert and Schönfeld, 2014), their combined and synergistic impacts are still not fully understandable. Therefore, improved knowledge on the consequences of the effects of multiple stressors on marine biodiversity and ecosystem functioning is urgently required, motivating the needs of the recently enacted Marine Strategy Framework Directive (Cardoso et al., 2010).

Such environmental stressors, caused by natural or human causes, can be assessed directly from physical and chemical parameters or indirectly by the study of environmental bio-indicators (Borja et al., 2000; Antonarakou et al., 2007; Drinia et al., 2007; Barras et al., 2014; Coccioni et al., 2016). In this respect, marine microzooplankton, such as foraminifera, offer the most valuable oceanographic tool for environmental monitoring and are increasingly used in studies for the assessment of environmental quality (e.g. Bergamin et al., 2009; Schönfeld et al., 2012; Naeher et al., 2012; Barras et al., 2014; Capotondi et al., 2015). Calcite shells of planktonic foraminifera are preserved in a wide range of marine sediments, leaving a highly representative record of population changes through time (Kucera, 2007), and they reveal a close relationship between their morphology and environmental parameters (Renaud and Schmidt, 2003; Schmidt et al., 2004a, 2004b; Caromel et al., 2014). These protists host a potentially large number of cryptic- or morpho-species (Aurahs et al., 2009; Kontakiotis et al., 2017), which could be used as novel candidates for marine ecosystem biomonitoring. Furthermore, evidence of stress exposure can be directly observed from this fossil record. In spite of several works dealing with benthic foraminifera as environmental bio-indicators, morphological abnormalities of planktonic foraminifera are less studied this way (Gerstel et al., 1986; Coccioni and Luciani, 2006; Keller and Abramovich, 2009) and such data are largely missing from the literature (including the possible connection between the mode of deformation and environmental properties), especially during the late Quaternary. It has been suggested that in stressed and/or polluted environments, these protists may react to changes in environmental parameters through a series of changes not only in abundance and species richness, but also by developing morphological abnormalities, related to the shape, size or disposition of one or more chambers of the test. For instance, under extremely stressful conditions the ability of planktonic foraminifera to constrain the shape of their shells is limited, leading to aberrant morphologies (Caron et al., 1987), possibly due to the decreased capacity of chaperones to facilitate the conformation of structurally relevant enzymes (Debat et al., 2006; Takahashi et al., 2010). Moreover, several aspects of morphology, such as the continuity of growth regularity (fluctuating asymmetry) are influenced by environmental stress (Furlow et al., 1997; Leung et al., 2000; Weinkauf et al., 2013).

Foraminiferal test abnormalities are frequently observed in naturally stressed marine environments (possibly induced by a deviation from optimum chemical and physical conditions), as well as in environments affected by anthropogenic pollution. These range from the development of oxygen-depleted conditions in the water column (Luciani et al., 2010), sometimes combined with nutrient injections into the photic layer in response to monsoon activity (Rossignol et al., 2011), to extremely stressful conditions (e.g. rapid and extreme climate/sea-level fluctuations, increased terrigenous input and intense volcanism; Coccioni and Luciani, 2006; Omaña et al., 2012).

In the present study, we investigate morphological abnormalities of recent planktonic foraminiferal tests from a suite of modern core-top samples, spanning strong gradient of several environmental factors (temperature, salinity, dissolved oxygen, productivity, and carbonate saturation state) in coastal (Aegean Sea) and open marine (Levantine Sea) settings of the eastern Mediterranean Sea, to address the possible origins, as well as their potential application in paleoenvironmental reconstructions. Following the recent findings of Weinkauf et al. (2014), Coccioni et al. (2016) and Kopaevich and Gorbachik (2017), where morphological changes in the fossil assemblage occurred during the onset of sapropel S5 and oceanic anoxic event 2 (OAE2, Bonarelli Event) respectively, we compare the occurrence in the present samples (percentages and characters) with abnormal specimens from sapropel S1 (~6–10 kyr BP; Mercone et al., 2000; Kontakiotis, 2016; Drinia et al., 2016) sediments from the eastern Mediterranean. Corresponding to older time periods where natural stressful conditions were prevailing (e.g. the mid-Cretaceous anoxic oceanic events; Venturati, 2007; Venturati and Baudin, 2007; Coccioni et al., 2016; Kopaevich and Gorbachik, 2017, late Maastrichtian Crisis; Abramovich and Keller, 2002; Keller et al., 2007; Omaña et al., 2012, the K-T boundary; Coccioni and Luciani, 2006, the period preceding, during and just after the Messinian Salinity Crisis (MSC); Sgarrella et al., 1997; Drinia et al., 2007, 2008; Kontakiotis et al., 2016b; Karakitsios et al., 2017a, 2017b; Agiadi et al., 2017, and the late Pliocene; Wade and Olsson, 2009), the deposition of sapropel layers provides a direct record of natural stress but could not be simulated during laboratory experiments. We take advantage of this natural experiment, combining biotic and abiotic forcing, to assess the morphological reaction of planktonic foraminifera to environmental stress, by discussing the significance of our observations with respect to the possible environmental stressor(s) (e.g. salinity, primary productivity, temperature, oxygen availability, carbonate saturation and hydrodynamics; some of these undoubtedly linked) which occurred during the last 10 ky in the eastern Mediterranean Sea. In both the modern oligotrophic and early Holocene eutrophic anoxic conditions of the Mediterranean water column, we particularly highlight here the "twinning" character that represents a particular survival strategy generally associated with diverse stressful environments (Boltovskoy, 1982; Ballent and Carignano, 2008). Especially in the hypersaline eastern Mediterranean basin, we highlight the dominant role of salinity in such biotic stress response. We extensively explore this parameter and present for the first time its influence on the twinning effect, since it appears for the first time to be the key-factor for the observed planktonic foraminiferal abnormalities related to stressful environments (in contrast to the productivity and oxygen depletion factors which are referred to for all Cretaceous oceanic anoxic events and Cenozoic sapropels). Therefore, this work adds a new perspective on the application of the occurrence of the planktonic foraminiferal twinning effect as a tool for marine ecosystem biomonitoring, and this might provide helpful insights on assessing the marine environmental status and on the paleoecological basis for better understanding the modern eastern Mediterranean Sea.

1.1. Geo-environmental setting: the Aegean coastal and Levantine open marine environment

The eastern Mediterranean Sea, which encompasses the Aegean, Libyan and the Levantine Seas (Fig. 1), is ideal for addressing forcing mechanisms of both (sub)tropical climate variability and environmental bio-monitoring, due to its intermediate position between the higher-latitude (i.e. North Atlantic-influenced) and lower-latitude (i.e. monsoonally influenced) climate systems (Zervakis et al., 2004; Marino et al., 2009; Rohling et al., 2009), and its large sea surface temperature (SST), salinity (SSS) and productivity fluctuations (Lykousis et al., 2002; D'Ortenzio and Ribera d'Alcalà, 2009). Overall, the warm and dry conditions in these sub-basins result in intensive evaporation that exceeds precipitation and river runoff. However, the study basins have significantly different hydrographic characteristics, controlled by the exchange of water masses with the Levantine and Black Seas and by the climate contrasts between more humid conditions in the north and semiarid conditions in the south (Lykousis et al., 2002). The north-eastern extension, the marginal basin of the Aegean Sea, is generally characterized by particularly complex hydrography, geography and topography (Theocharis et al., 1993). In the north, it communicates with the Black Sea through the Dardanelles Strait, and in the south with the Ionian/Libyan and Levantine basins through the western and eastern straits of the Cretan Arc respectively (Poulos, 2009) (Fig. 1). The surface water mass in the Aegean forms a counter-clockwise gyre,