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Chronostratigraphy of uplifted Quaternary hemipelagic deposits from the Dodecanese island of Rhodes (Greece)

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ABSTRACT

An integrated magneto-biostratigraphic study, based on calcareous nannofossils and foraminifers, together with the radiometric dating of a volcaniclastic layer found in several outcrops, was carried out on the hemipelagic deposits of the *Lindos Bay Formation* (LBF) at six localities on the island of Rhodes (Greece). Our highly refined chronostratigraphic framework indicates that the lower and upper lithostratigraphic boundaries of the LBF are diachronous. Associated with the $^{40}Ar/^{39}Ar$ age determination of 1.85 ± 0.08 Ma for the volcaniclastic layer, our data show that among the investigated outcrops, the Lindos Bay type locality section provides the longest record (1.1 Ma) of the LBF. Hemipelagic deposition occurred continuously from the late Gelasian (~1.9 Ma) to the late Calabrian (~0.8 Ma), i.e., from Chrons C2n (Olduvai) to C1r.1r (Matuyama) and from nannofossil Zones CNPL7 to CNPL10. This long record, together with the hemipelagic nature of the deposits, make the Lindos Bay type locality section a unique element in the eastern Mediterranean region, allowing future comparisons with other early Quaternary deep-sea sections available in the central and western Mediterranean regions.

Introduction

In the central Mediterranean, the subduction of the Ionian crust beneath Eurasia has contributed to the uplift of Quaternary hemipelagic sedimentary sequences now exposed onshore along the Calabrian and Hellenic fore-arcs (e.g., Lourens et al., 1996; Papanikolaou et al., 2011). Located at coastlines and on islands of the Ionian Sea, these sequences have been of immense assistance for our understanding of the tectonic and climatic evolution of the Mediterranean (e.g., Massari et al., 2002). Some of them, in particular in Calabria and Sicily, now formally serve as global stratotype sections and points (GSSPs) for the Quaternary system (e.g., Gibbard et al., 2010; Cita et al., 2012). In the Aegean Sea, some uplifted Quaternary marine sedimentary successions occur in Crete (Tortorici et al., 2010), Karpathos (Barrier et al., 1979) and Kos (Drinia et al., 2010) but none of these exhibit hemipelagic facies comparable to those available from the Ionian Sea. On the Dodecanese island of Rhodes (Greece) in the easternmost part of the Hellenic fore-arc, however, such deep-water deposits outcrop onshore. Although their chronostratigraphy is still a matter of debate (Titschack et al., 2013; see below), these deposits are well exposed, easily accessible, very fossiliferous and have the potential to be amenable for future comparisons with sequences available in the central and western Mediterranean regions.

The tectonic and sedimentary evolution of Rhodes has been investigated for several decades because of its significance for reconstructing the geodynamic history of the Hellenic sedimentary fore-arc (Meulenkamp et al., 1972; Pirazzoli et al., 1989; Duermeijer et al., 2000; Ten Veen and Kleinspehn, 2002). Since the Pleistocene, Rhodes was affected by tectonics controlled by major N 70° trending sinistral strike-slip faults, anticlockwise rotation and important vertical motions (e.g., Benda et al., 1977; Flemming and Woodworth, 1988; Hanken et al., 1996; Cornée et al., 2006a; van

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Hinsbergen et al., 2007; Ten Veen et al., 2009). Such vertical motions have contributed to the uplift of Pleistocene deep-sea sedimentary sequences, now cropping out on the eastern coast of the island (Fig. 1). These deposits rest upon a deformed and deeply eroded, mainly calcareous Mesozoic basement (Mutti et al., 1970; Lekkas et al., 2001). The multiple faulting of this basement has generated a series of steep horsts and grabens that later conditioned the nature and distribution of the Pleistocene deposits (Hanken et al., 1996). Within the separate grabens, sedimentary facies changes are common. Despite recent advances relying on a range of approaches including bio-, magneto-stratigraphy and/or radioisotope dating (Thomsen et al., 2001; Cornée et al., 2006a, 2006b; Titschack et al., 2013), correlations between separated infillings are difficult to establish and the chronostratigraphy of these marine deposits is consequently still poorly understood.

The Pleistocene marine deposits of Rhodes have been shown to record a major, tectonically controlled transgressive–regressive cycle (Hanken et al., 1996; Kovacs and Spjeldnaes, 1999; Cornée et al., 2006a; Titschack et al., 2013), which reached bathyal depths during maximum transgression (Moissette and Spjeldnaes, 1995; Hanken et al., 1996). This promoted the deposition of the hemipelagic clays of the so-called *Lindos Bay Formation*, which crop out in numerous localities along the eastern coast of Rhodes. Because of their hemipelagic nature and the preservation, in particular, of calcareous nannofossils and planktonic foraminifera (Frydas, 1994; Beckman, 1995; Thomsen et al., 2001; Cornée et al., 2006a, 2006b), these uplifted deposits constitute a key target for identifying bio-events that can be used to correlate between sections of the island and estimate their age and timing of deposition.

The present study aims to resolve the chronostratigraphy of these deposits. On the basis of biostratigraphic analyses (calcareous nannofossils and foraminifers) combined with magnetostratigraphy and $^{40}Ar/^{39}Ar$ dating of a volcaniclastic tuff, we generate firm chronological constraints for the *Lindos Bay Formation* type locality section. Comparisons with new and previously published stratigraphic data from other isolated sections distributed along the eastern coast of Rhodes (e.g., Thomsen et al., 2001; Cornée et al., 2006a, 2006b; Titschack et al., 2013) allow us to better document the sedimentary evolution of Rhodes. Such a previously poorly known hemipelagic succession exposed on land is finally elevated to a level where it can serve as a useful archive for reconstructing the tectonic, environmental and climatic changes that occurred in the Mediterranean region during the Pleistocene.

Lithostratigraphic and chronostratigraphic background

Previous stratigraphic studies of the marine Pleistocene deposits of Rhodes have been conducted by Keraudren (1970), Mutti et al. (1970), Meulenkamp et al. (1972), Løvlie et al. (1989), Frydas (1994), Hanken et al. (1996), Nelson et al. (2001), Thomsen et al. (2001), Nielsen et al. (2006), Cornée et al. (2006a; 2006b) and Titschack et al. (2013). After Hanken et al. (1996), several lithostratigraphic schemes were proposed (Fig. 2) in which the marine deposits recording the major, tectonically-controlled Pleistocene transgressive–regressive cycle has been qualified as the *Rhodes Synthem* (Titschack et al., 2013). Below the *Rhodes Synthem*, the *Kritika Formation* (~180 m thickness) is composed of brackish to shallow marine siliciclastic deposits considered either as Piacenzian-Gelasian (Sissingh, 1972; Benda et al., 1977; Moissette et al., 2016) or Calabrian (Thomsen et al., 2001; Rasmussen et al., 2005). Within the *Rhodes Synthem*, the *Kolymbia Formation* (4–20 m thickness) is composed of lower offshore (~30–120 m paleo-water depth; Steinthorsdottir et al., 2006) bioclastic limestones, which have been

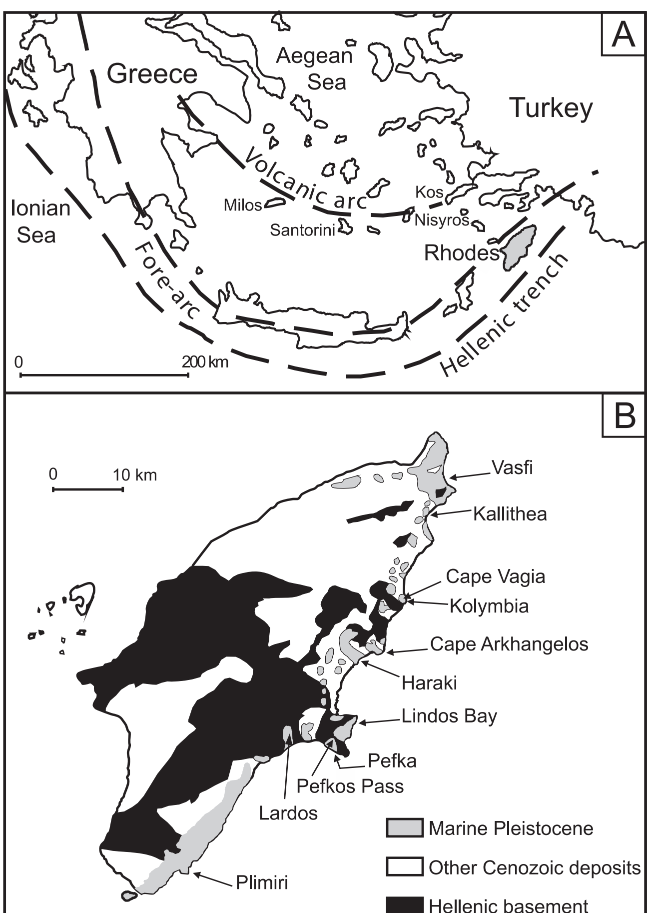

Figure 1. (A) Location map and geodynamic context of the island of Rhodes in the eastern Mediterranean (modified from Meulenkamp et al., 1972) and (B) simplified geological map of Rhodes (modified from Mutti et al., 1970), with location of the sections/outcrops of the *Lindos Bay Formation* studied or mentioned in this paper.

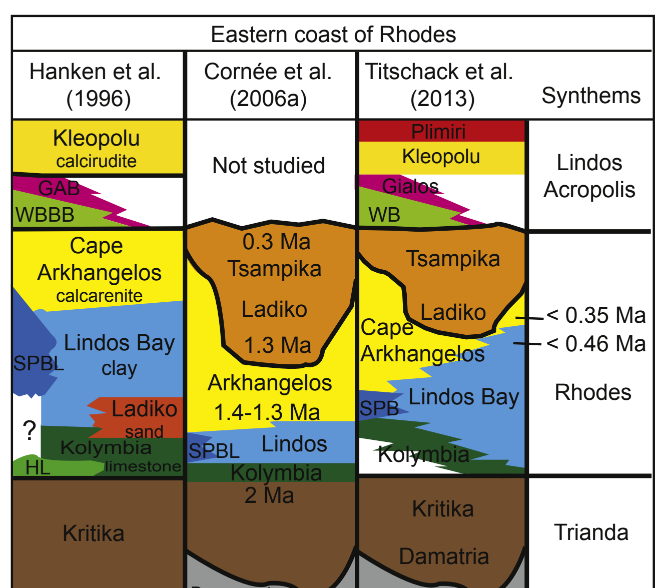

Figure 2. Comparison of lithostratigraphic schemes for the Pliocene and Pleistocene deposits of the eastern coast of Rhodes with associated published temporal landmarks. HL = Haraki Limestone, SPBL = Saint Paul's Bay Limestone, WBBB = Windmill Bay Boulder Bed, GAB = Gialos Algal Biolithite, SPB = Saint Paul's Bay, WB = Windmill Bay.