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The marine isotope stage 1–5 cryptotephra record of Tenaghi Philippon, Greece: Towards a detailed tephrostratigraphic framework for the Eastern Mediterranean region

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A B S T R A C T

The iconic climate archive of Tenaghi Philippon (TP), NE Greece, allows the study of short-term palaeoclimatic and environmental change throughout the past 1.3 Ma. To provide high-quality age control for detailed palaeoclimate reconstructions based on the TP archive, (crypto)tephra studies of a peat core 'TP-2005' have been carried out for the 0–130 ka interval. The results show that the TP basin is ideally positioned to receive tephra fall from both the Italian and Aegean Arc volcanic provinces. Two visible tephra layers, the Santorini Cape Riva/Y-2 (*c.* 22 ka) and the Campanian Ignimbrite (CI)/Y-5 (*c.* 39.8 ka) tephras, and six primary cryptotephra layers, namely the early Holocene E1 tephra from the Aeolian Islands (*c.* 8.3 ka), the Campanian Y-3 (*c.* 29 ka) and X-6 tephras (*c.* 109.5 ka), as well as counterpart tephras TM-18-1d (*c.* 40.4 ka), TM-23-11 (*c.* 92.4 ka) and TM-33-1a (*c.* 116.7 ka) from the Lago Grande di Monticchio sequence (southern Italy), were identified along with repeatedly redeposited Y-2 and CI tephra material. Bayesian modelling of the ages of seven of the primary tephra layers, 60 radiocarbon measurements and 20 palynological control points have been applied to markedly improve the chronology of the TP archive. This revised chronology constrains the age of tephra TM-18-1d to 40.90–41.66 cal ka BP (95.4% range). Several tephra layers identified in the TP record form important isochrons for correlating this archive with other terrestrial (e.g., Lago Grande di Monticchio, Sulmona Basin and

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Lake Ohrid) and marine (e.g., Adriatic Sea core PRAD 1-2 and Aegean Sea core LC21) palaeoclimate records in the Mediterranean region.

1. Introduction

In light of current anthropogenic climate change, detailed temporal-spatial reconstructions of past natural climate variability are required. This holds true particularly for the climatically highly sensitive Eastern Mediterranean region, which is currently experiencing increased frequency and intensity of droughts and heat waves (e.g., Giorgi and Lionello, 2008; IPCC, 2014). Past short-term climate change as evidenced in marine cores from the North Atlantic (e.g., Shackleton et al., 2000) and ice cores from Greenland (e.g., NGRIP members, 2004) is also registered in Mediterranean palaeoclimate archives. However, the exact age relationships of climate signals recorded in these archives have remained difficult to decipher due to a lack of precise age control. Long key records from this region include the annually laminated archive from Lago Grande di Monticchio (e.g., Allen et al., 1999; Brauer et al., 2007; Martin-Puertas et al., 2014), the Sulmona and Fucino Basins in Italy (e.g., Giaccio et al., 2012, 2017b; Regattieri et al., 2017), and Lake Ohrid (e.g., Sadori et al., 2016; Wagner et al., 2017), Lake Prespa (e.g., Damaschke et al., 2013; Panagiotopoulos et al., 2014) and the Tenaghi Philippon peatland (e.g., Pross et al., 2015; Tzedakis et al., 2006) in the Balkan Peninsula. In addition, precise correlation of terrestrial records with marine records from the Adriatic, Ionian and Aegean Seas is notoriously difficult due to dating uncertainties stemming from unknown or regionally variable radiocarbon reservoir ages (e.g., Rohling, 1994; Siani et al., 2001). Precise land-sea correlations can, however, be obtained through using event markers such as volcanic ash (tephra) layers that are preserved in the respective sedimentary archives. Tephras from explosive eruptions are deposited synchronously, often over wide geographic areas, and provide independent chronological markers in geological archives when well dated (e.g., Thorarinsson, 1944; Lowe, 2011). The Eastern Mediterranean region is ideally suited for a tephrochronological approach due to (i) the frequent activity of high-explosive, volcanoes in central and southern Italy, the Aegean Arc (Greece), central and eastern Anatolia (Turkey), and the East Carpathians (Romania) during the Quaternary (Fig. 1a); (ii) distinctive glass chemical compositions of tephras derived from different volcanic sources that enable unambiguous identification; and (iii) wide tephra dispersal plumes transported by prevailing westerly, but also minor northerly and southerly, winds, leading to the stratigraphical layering of tephras derived from different source regions (e.g., Druitt et al., 1995; Federman and Carey, 1980; Keller et al., 1978; Narcisi and Vezzoli, 1999).

The Tenaghi Philippon (TP) peatland in NE Greece is situated in an ideal geographical position to record eruptions of Eastern Mediterranean volcanoes (Fig. 1), and has a long history of palaeoclimatic and environmental research that extends back to coring campaigns during the 1960s (van der Wiel and Wijmstra, 1987a, 1987b; Wijmstra, 1969; Wijmstra and Smit, 1976; see review of Pross et al., 2015, and references therein). The millennial-scale-resolution pollen records generated from these early TP cores for the last *c.* 1.35 Ma revealed strong similarities with deep-sea oxygen isotope records (e.g., Tzedakis et al., 2006; van der Wiel and Wijmstra, 1987b; Wijmstra and Groenhart, 1983; Wijmstra and Young, 1992).

Because the core material recovered through the drilling efforts from the 1960s has long since deteriorated and also suffered from partially limited core recovery, the potential of the TP archive for the analysis of short-term climate and ecosystem variability has long remained untapped. Therefore, two new long cores (TP-2005 and TP-2009) were drilled in 2005 and 2009 (Pross et al., 2007, 2015). The excellent core recovery achieved during these later drilling campaigns allows high-resolution (i.e., decadal to centennial) analyses (e.g., Fletcher et al., 2013; Milner et al., 2012, 2013, 2016; Müller et al., 2011; Pross et al., 2009).

A full, state-of-the-art tephrostratigraphic record for the TP sediment sequence, (crypto)tephra analysis has been conducted on the upper 34 m of the TP-2005 core, encompassing the time interval of the last *c.* 130 ka (Marine Isotope Stages [MIS] 1 to 5/6). This core interval has been selected because it spans the last full glacial-interglacial cycle and reveals pronounced millennial-scale climate variability similar to those reported from other high-resolution, tephra-dated Eastern Mediterranean palaeoclimate archives. Hence, it offers the potential for distal correlation of palaeoclimate signals in this region using common tephra isochrons (see Section 6.4).

In this study, we present major and trace element geochemical data for visible and non-visible (crypto)tephras from the 1–34 m depth interval of the TP-2005 core. Where the new data are combined with previously published tephra data (e.g., Müller et al., 2011, Albert et al., 2015, Pross et al., 2015: see details in Section 3), the results allow refined correlation of individual tephra layers to their respective volcanic sources. Published ages for the assigned tephra eruptions, together with radiocarbon dates and palynological control points from the TP archive, lead to an improved age model for the TP sequence, while refinement of the tephra record allows more secure correlations with other high-resolution palaeoclimate archives. Our results therefore provide additional critical anchor points to underpin the distal tephrostratigraphical framework of the Eastern Mediterranean region.

2. Regional setting

The TP site is situated in the Philippi peatland within the southeastern part of the Drama Basin in NE Greece (Fig. 1b). The Drama Basin (40–200 m a.s.l.; Fig. 1) formed as a low-elevation graben structure resulting from post-orogenic, arc-parallel extension that started in the late early or middle Miocene (Christanis, 1983; see Pross et al., 2015, for a discussion of its geological evolution). The basin is bordered by the Phalakron Range (2232 m a.s.l.) to the north, the Menikion Range (1956 m a.s.l.) to the west, the Pangaeon Range (1956 m a.s.l.) to the south, and the Lekanis Mountains (1150 m a.s.l.) to the east; to the southeast, the Symvolon Hills (477 m a.s.l.) separate the basin from the northern Aegean Sea. Today, several streams that discharge into the Angitis River and onward into the Strymon River drain the Drama Basin.

The Philippi peatland harbours nearly 200 m of limnotelmatic sediments, which make it the thickest known peat-dominated succession in the world (Christanis, 1987). A shallow unconfined aquifer exists at ~1–1.5 m below the surface in the central part of the basin (Georgakopoulos et al., 2001). Between 1931 and 1944, the Philippi peatland was drained for intensive agricultural cultivation, which has caused severe disturbances at the peat surface