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Abstract

Revision of central Mediterranean paleoclimate archives containing tephra layers indicates that three widely dispersed tephra layers occur during Bronze Age. They are: Agnano Mt Spina from Campi Flegrei (ca. 4.4 cal ka BP), Avellino from Somma-Vesuvius (ca. 3.9 cal ka BP) and FL from Etna (ca. 3.3 cal ka BP). Stratigraphical correlations of selected archives using these tephra layers indicates that some records have severe chronological biases, posing important limitations for the use of these archives in defining paleoclimate conditions during Bronze Age. Regardless the temporal mismatches, Agnano Mt Spina tephra seems to occur at the beginning of a centennial scale period of climatic deterioration, whereas Avellino tephra, occurring during a wetter period, seems to mark the end of this event. The dry event bracked by the two tephra seems to be correlated with the so-called “4.2 event”. Instead, FL tephra from Etna, seems to herald a new climatic deterioration at ca. 3.3-3.2 cal ka BP. Although the general frame is still incomplete, these three tephra layers appear to play a fundamental role in synchronizing archives, and can lead to the definition of a detailed paleoclimatic framework of the Bronze Age in the central Mediterranean.

Keywords	explosive eruptions, southern Italian volcanoes, tephrostratigraphy, Bronze Age, palaeoclimate

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File Name [File Type]

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Reply_letter-final.docx [Response to Reviewers]

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UNIVERSITÀ DI PISA
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Pisa 18/12/2017

Dear Editor and Guest editor,

Please you will find the revised manuscript "Tephrostratigraphy of paleoclimatic archives in the central Mediterranean during the Bronze age" to the special issue "'Distal Effects of Volcanic Eruptions on Pre-Industrial Societies'". Consider me as corresponding author (zanchetta@dst.unipi.it)

Sincerely

Prof. Giovanni Zanchetta

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Dear Editor,

We thank both reviewers for their comments and criticisms, which we have tried to include in our revised version. However, we are not able to insert all of them, and a detailed discussion on the matter is in the following rebuttal letter. Along the manuscript, the changes are marked in red. In this letter our comments are in italic.

Comments from the reviewers:
-Reviewer 1

-Palaeoclimatic studies of terrestrial and marine archives in the Mediterranean have been enhanced during the last years by modern advances in tephra studies. The synchronization of sedimentary records through the use of widespread tephras, i.e. isochron horizons, is, in fact, one of the main objectives in scientific papers dealing with climate change. The attention towards the recognition and characterization of cryptotephras in the last decade, moreover, has allowed to perform high- and ultrahigh- resolution analyses sometimes at centennial scale. Hence, based on these general considerations, I approached the paper by Zanchetta et al. with scientific curiosity also because the investigated period is of great interest for all those researchers working for example on possible relations between volcanism and cultural changes.

Please note that we are not dealing with volcanism and cultural changes

-However, by the last page I felt unsatisfied for a number of reasons. Firstly, reading was difficult due to the bad English form, a number of spelling mistakes and missing parts (e.g. the caption of figure 5; Shkodra instead of Skutary in figure 5 and more..) throughout the text.

Yes, we agree, special issue with deadline often force to be on hurry. We have done our best to improve the text in the new version following the suggestions of both reviewers.

-Secondly, I was not able to find any original data, which would justify its publication in this journal. It did not seem a review either since the few records presented were discussed superficially with no consistent and substantial conclusions.

The manuscript is clearly a review as stated in many part of the text. The criteria of selection of the records are specified along the text.
Beside Zanchetta et al. 2011 (The Holocene) there are no papers (as far as we know) before the present one which attempt regional correlation, trying also to advance some conclusions about the climatostratigraphic significance of the discussed tephras. Zanchetta et al., 2011 needs in fact to be updated as we have done here. Therefore, the observation is specious and we reject this point.

-The attempt made by the authors to synchronize lacustrine, marine and cave successions was worthy but the investigated tephras do not occur in all the presented marine and continental records, hence I've the impression we are dealing with a correlation process rather than a synchronization one. The synchronization process relies on a new age model derived from the correlated records. This approach allows to verify if the palaeoclimatic events can be considered synchronous or not. Moreover, the different resolutions of the records hinder reliable results (and the authors themselves admit this limit in the "Methodology and Terminology" section).

Indeed, we do not state that we "synchronize archives", even if we use this word (and we specify the sense). Indeed in the introduction we stated:

"In this paper, we review selected archives from the Central Mediterranean (Fig. 1) containing tephra layers and yielding highly resolved paleoclimatic records with the aim of providing a reference scheme for placing at regional scale and in a coherent framework, climatic, cultural and eruption activity during the Bronze Age."

No synchronization activity is performed (and we see why in reply to ref#2). Moreover, we state in the methodology section that we use the data as they are, in way the limit of the chronology of many succession become clear and the need of tephra evident. To avoid further confusion we have deleted the term also in the title.

Probably the ref#1 was too superficial about the fact that there are no enough tephras to attempt an independent chronology for most of the discussed records. Moreover, the selected records are what we have. There is no limitation in that: it is the material available. Indeed, as stated by the ref#1 the record containing all the tephras are very few (basically at this stage just one in Shkodra record!). We think this kind of paper can push researchers to look in better details in their record for cryptotephras and give more importance to tephrostratigraphic studies. This is a point, for sure ref#1 agrees with. The process of a final synchronization is a further step but not achievable at this stage.

-From a more strictly tephrostratigraphic point of view, there's no additional data with respect to what is already published about the AP, Avellino, AMS and FL- related tephras.

That is puzzlingly and once again is specious. The ref#1 keeps on forgetting the values of reviews and the aim of our paper (where we stated that we are publishing new data?). Note that our paper deals only marginally with AP eruptions.

-On the contrary, their lithological and chemical features are excessively summarized both in the text and in the figures and sometimes even lacking as in the case of AP data in the TAS diagram.

We have improved this part also considering the note of ref#2. However, there is a complete set of references, and this paper is not a review of the chemical characteristic of all tephra layers, but just of the layers, which are most widespread. APs have been inserted in the TAS even if of marginal interested in this paper. In our discussion (which is quite clear for instance, for Ref#2) the main topic is the chronological values and the "climatostratigraphic position" of the discussed tephra layers.

-Moreover, the ageing of the younger APs deposits resulting from published tephra studies (e.g. in the Salerno Bay) presents some important chronological issues which should be taken into consideration and discussed in the text.

We thank for the suggestions but, again, our intention is no to discuss all the documented tephra layers recovered in all the records but just the most widespread and potentially useful for correlating very distant archives with paleoclimatic values. Once again, this comment is not pertinent. For quite obvious reason we are mostly dealing with Avellino tephra, for which a good chronology is well presented. And we deliberately avoid eruptions with very poor dispersion and *poor chronological constrains. This is not the target of our paper and it is very clearly written along the manuscript.*

-In reference to the AMS marker tephra, I think it is very hard to chemically distinguish it from Astroni deposits as already stated in some papers by the same authors. They have usually referred, in fact, to the Astroni-AMS group. The distinctive recognition of AMS and Astroni tephras reported in Margaritelli et al (2016) and cited by Zanchetta et al. in the text, was possible due to the occurrence in the C5 record of Astroni3 deposits which are the only ones (for that period of flegrean activity) to be characterized by a bimodal composition, hence easily distinguishable. Otherwise, all the other Astroni deposits have a very homogeneous trachy-phonolitic composition which is common to the AMS products. Up to now, the Astroni3 composition has been recognised only in the Gaeta Bay hence appearing to have just a "local" relevance in terms of marker isochron.

We agree with the ref#1. Then, it is unclear what the ref#1 wants to demonstrated. In the text we have written:

"However ambiguities can exist in distinguish these tephra layers from others occurring during the same period, due to the actual difficult to find significant differences on major element composition or to lacking details in the available database. A good case is the Agnano Mt Spina tephra. The identification of this eruption on very distal setting may poses some difficulties on the basis of major elements alone (Smith et al., 2011), since it is the highest in intensity and magnitude occurring in a period of activity lasting ca. 1000 years punctuated by numerous explosive events. The general composition of all these products is similar, and usually they are not easily distinguishable on the basis of major elements or petrography (Turney et al., 2008; Sulpizio et al., 2010b; Smith et al., 2011), especially if they are not recognized in stratigraphic succession (e.g. like at Lago Grande di Monticchio, Wulf et al., 2004, 2008; or at Lake Skhodra, Sulpizio et al., 2010b). To this end, the new geochemical database reported by Smith et al., (2011) allows a better discrimination between some products of different eruptions, which was not really possible in the past (e.g. Margaritelli et al., 2016)."

We wrote exactly what the ref#1 mentions. However, we appreciate the observation about Astroni 3 and we have inserted a sentence in the text.

-In conclusion, I think that the paper in the actual form does not satisfy the journal's standards. I suggest that the authors improve this paper with a more accurate dataset, discussion and editing and submit a new version.

We think that the ref#1 misunderstood the aim of the manuscript and most of the comments were born by a wrong and specious reading of the manuscript. However, some points have been considered worth of interest and we thank for these suggestions, and we included them in the new version of the manuscript.

-Reviewer 2

The manuscript of Zanchetta et al. deals with the interesting topic of defining a coherent chronological and paleoclimatic framework for the Bronze Age of the Central Mediterranean area via tephra correlation and synchronization.

As a review study, the author present an exhaustive synthesis of the knowledge about three important tephra bracketing the Bronze Age period (Agnao Monte Spina; Avellino and Etna FL) and of the general climatic context from both high-resolution records, not containing the tephra layers, and, more importantly from lesser records which contain one or more of the three considered tephra.

From this synopsis the authors highlight some heavy chronological discrepancies between records revealed by the fluctuations of the tephra on time-scale up to 20% of the best age of the tephra. On the other hand, regardless of the chronology, the same records reveal a quite coherent framework of the climatostratigraphic positions of tephra which can be used as potential marker of some important climatic events, as e.g. the so-called 4.2 event.

Generally speaking, I find that this kind of review paper provide a great service for people operating in archaeology and paleoclimatology, or better for who intend to address the interplay between ancient human societies and climatic change.

I have little to disagree here. Below are appended some main suggestions, while I annotated directly on a pdf the minor ones.

We have virtually included all the observation on the annotated pdf. In particular, we have changed figures as requested.

Fig. 3: in addition to the field of Avellino, you here correctly show also the composition of the AP eruption to highlight how these differ from Avellino tephra. It should be useful for the readers that have no so much acquaintance with the Campi Flegrei tephrostratigraphy, to add also a figure with the composition of AMS and some of the main tephra which have a similar age and chemical composition.

Yes, this partially overlaps the request of ref#1 and we have improved the figure including the data of the APs and those of the Campi Flegrei activity.

Fig. 5: This is a very informative figure, but a bit hard to read and appreciate in its whole importance. I suggest to be a bit more brave and also present another figure (Fig. 6) with the same records synchronized along the tephra. I'm aware that the change of the chronologies might be a bit dangerous and arbitrary, but this would make the definition of the climatostratigraphic position much more clear and immediate, and would allow to appreciate the coherence of the records (if any) resulting from the synchronization along the tephra.

Yes, this would be important and probably will find the favour of ref#1 as well. However, ref #1 already notes the main point: most of the selected records did not contain contemporaneously the three tephra layers. Moreover, some of the age models are based on radiocarbon dating with clear problems of selection of material (i.e. bulk organic matter in lacustrine setting) and to find the original data set is not obvious (depth-series instead of time-series). This, at this stage frustrate the possibility to have a real complete synchronization between archives. These tephras, however, can have important stratigraphic and chronological point of control and improve the age model. Because this point is important, we have added some sentences along the text. We absolutely agree that this is a work in progress.

We hope to have clarified all the requests of the two reviewers

Sincerely

For the authors

Gianni Zanchetta

Tephrostratigraphy of paleoclimatic archives in the central Mediterranean during the Bronze Age

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Abstract

Revision of central Mediterranean paleoclimate archives containing tephra layers indicates that three widely dispersed tephra layers occur during Bronze Age. They are: Agnano Mt Spina from Campi Flegrei (ca. 4.4 cal ka BP), Avellino from Somma-Vesuvius (ca. 3.9 cal ka BP) and FL from Etna (ca. 3.3 cal ka BP). Stratigraphical correlations of selected archives using these tephra layers indicates that some records have severe chronological biases, posing important limitations for the use of these archives in defining paleoclimate conditions during Bronze Age. Regardless the temporal mismatches, Agnano Mt Spina tephra seems to occur at the beginning of a centennial scale period of climatic deterioration, whereas Avellino tephra, occurring during a wetter period, seems to mark the end of this event. The dry event bracked by the two tephra seems to be correlated with the so-called "4.2 event". Instead, FL tephra from Etna, seems to herald a new climatic deterioration at ca. 3.3-3.2 cal ka BP. Although the general frame is still incomplete, these three tephra layers appear to play a fundamental role in synchronizing archives, and can lead to the definition of a detailed paleoclimatic framework of the Bronze Age in the central Mediterranean.

Keywords: explosive eruptions, southern Italian volcanoes, tephrostratigraphy, Bronze Age, palaeoclimate.

1. Introduction

The Bronze Age of the Mediterranean region and of the Fertile Crescent is an interesting period, for investigating and understanding resilience and responses of complex societies to different kinds of environmental stresses, including climate change, tsunami and Earthquakes, for which different and contrasting hypotheses has been hitherto formulated (e.g. Nur and Cline, 2000; Drake 2012). In recent literature, the climate, and particularly the significant reduction in precipitation, has been invoked as the triggering cause for Bronze Age civilization crisis over Near East, Eastern Mediterranean and Aegean worlds (e.g. Kaniewski et al., 2010, 2012; Schneider and Adalı, 2014). In the Middle East and Egypt the most impacting climatic event has been identified with the so-called 4.2 ka event, which has been related, for instance, to the "collapse" of the Akkadian civilizations (Weiss et al., 1993, 2015) and to the decline of the Egyptian Old Kingdom (e.g. Welc and Marks 2014). Similarly, the Late Bronze Age collapse or crisis (Weiss, 1982), is an additional example of a complex process, in which climatic change has been invoked as fueling trigger of collapse by a growing number of evidences (Kaniewski et al., 2010, 2012).

However, some evidences of climatic changes could be questionable and, after careful scrutiny of the relative chronologies of climate change could not be so straightforwardly linked to social upheaval (Finné et al., 2011; Rosen and Rivera-Collazo, 2012; Zanchetta et al., 2013).

Also in the Central Mediterranean there is a growing number of evidences of climatic changes occurring from the Neolithic to the Bronze Age (Drysdale et al., 2006; Piva et al., 2008; Di Rita and Magri 2009; Magny et al., 2009; Regattieri et al., 2014; Zanchetta et al., 2014; Margaritelli et al., 2016), and some periods of climate deterioration have been invoked as responsible of civilization crises, like for the end of the Terramare culture in central-northern Italy (Cremaschi et al., 2016).

To complicate the picture, during the middle-to-late Holocene the Mediterranean landscapes experienced significant transformations, related to the definitive stabilization of the sea-level (Vacchi et al., 2014; Fontana et al., 2017), to coastal progradation (Anthony et al., 2014), fluvial avulsion and diversion (Bini et al., 2015; Sarti et al., 2015) and urbanization (Mozzi et al., 2018; Bini et al., 2018ab), and, more in general, to the progressive impact of human activities in shaping the Earth surface (e.g. Zanchetta et al., 2013; Borrelli et al., 2014; Fyfe et al., 2015).

One of the main concerns in correlating climatic events and archeological evidences, and then to asses relations of cause and effect, is that most of the best chronologically constrained and continuous paleoclimatic records are located far away from archaeological sites (off-site). This implies that correlation with archaeological stratigraphy is not always a simple task (Zanchetta et al., 2013; Izdebski et al. 2016).

Attempts have been made to use proxies directly collected from archeological sites, but their resolution and quality is often not fully satisfying (e.g. Colonese et al., 2007; 2010; Riehl, 2008; Masi et al., 2013,2014). In addition, perfect correlation between archeological and palaeoclimatic records is rarely attained, for unavoidable concerns related to proxy recovery (e.g. bioturbations), sedimentary continuity and to poor achievable temporal resolution or stratigraphic control. In many cases however, dating and age models defeats, leading to scarce age control, are the main limitation to proper correlation of environmental conditions and archeological evidences (e.g. Telford et al., 2004; Zanchetta et al., 2011).

Explosive eruptions with large dispersion of pyroclastic material supply a fundamental tool for firm correlation and synchronization between in-site and off-site archives (e.g. Giaccio et al., 2008; Lowe D.L., 2011; Lowe J. et al., 2012; Tamburrino et al., 2012; Zanchetta et al., 2008; Giaccio et al., 2017; Zanchetta et al., 2018), so overcoming all the limitations inherent to the chronological correlations.

In particular, due to the widespread presence of both ancient cultures and explosive volcanoes, the Central Mediterranean is a key area for studies aimed to synchronize climatic and archaeological archives by means of tephrostratigraphy (e.g. Sevink et al., 2011; Di Vito et al., 2013; Pelle et al., 2013; Giaccio et al., 2008; Zanchetta et al., 2011). In this paper, we review selected archives from the Central Mediterranean (Fig. 1) containing tephra layers and yielding highly resolved paleoclimatic records with the aim of providing a reference scheme for placing at regional scale and in a coherent framework, climatic, cultural and eruption activity during the Bronze Age.

2. Methodology and terminology

We are aware that boundaries of archeological periods are, by definition, temporally diachronous, but as reference for the Bronze Age in the central Mediterranean, we consider the period comprised between ca. 4200 and ca. 2900 cal yr BP (Bietti Sestieri, 2010). To better characterize the investigated period, in the description and analyses of paleorecords we extend this chronological range from ca. 2000 to ca. 6000 cal yr BP. Paleoclimatic archives were selected on the basis of the presence of chemically-fingerprinted tephra layers (at least for the major elements), and with a temporal resolution able to resolve at least centennial climatic events. We are aware that correlation of published records using tephra layers can highlight the presence of differences between individual chronologies on the order of centuries or even millennia (e.g. Zanchetta et al., 2011, 2012a, 2016ab), however all the records are plotted with their original age model. We are also aware that the correlation of some tephra layers is not always straightforward and that margins of ambiguity can be present in absence of a complete set of accurate and precise chemical data (i.e. major and trace elements, mineral associations, e.g. Lowe et al., 2007; Albert et al., 2015; Smith et al., 2011). We usually accept the proposed correlations, if not differently stated. The term synchronization along the text follow the usage proposed by Govin et al. (2015), and for instance, applied by Zanchetta et al. (2016b).

3. Main Bronze age eruptions in the Central Mediterranean: characteristics and chronologies

Several volcanic sources were active during the Holocene over southern Italy (Fig. 1). During the Holocene and particularly during the Bronze Age, large-dispersion tephra layers originated mostly from the Campanian plains. For the Somma-Vesuvius volcano seven explosive eruptions are well documented, (Santacroce et al., 2008). The Plinian eruption of Avellino (Fig. 2) is by far the largest (Rolandi et al., 1993; Sulpizio et al., 2010a), followed by a succession of at least six explosive eruptions (AP-1 to AP-6, Andronico and Cioni, 2002; Di Vito et al., 2013). For Campi Flegrei at least 28 explosive eruption of different magnitude are documented (Di Vito et al., 1999). The most widespread eruption of Campi Flegrei during this period is the eruption of Agnano Mt. Spina (de Vita et al., 1999). Also Ischia is active with some low magnitude explosive eruptions (de Vita et al., 2010, 2013). During the Holocene, also Etna shows important and frequent explosive activity (Coltelli et al., 2000; Branca and Del Carlo, 2004) with at least one explosive volcanic event, which leads to tephra dispersion over a wide area (e.g. Wagner et al., 2008; Sulpizio et al., 2014): the FL layer. Aeolian Islands (Albert et al., 2012; Caron et al., 2012). Finally, Pantelleria (Speranza et al., 2010; Scaillet et al., 2011; Magny et al., 2011) was active too, even if there are no evidences for explosive eruptions with large dispersion during the Bronze Age.

The Monticchio volcanic maar-lake (Fig. 1), located downwind of most of the southern Italian volcanoes, is usually considered one of the best registration of the southern Italy explosive volcanic activity in distal setting during the last 130 ka (Wulf et al., 2004, 2008, 2012). For the period comprised between ca. 6000 and ca. 3000 yr BP, Wulf et al. (2008) reported at least eleven tephra layers with variable thickness (from 0.1 to 31 mm) embedded within the lake sediments. Among the identified tephra layers, five were correlated to Campi Flegrei, five to Somma-Vesuvius, and one to Ischia.

Figure 2 summarizes the main tephra layers with regional distribution occurred during the Holocene, with highlighted the considered Bronze Age period. Table 1 shows the most widespread tephra markers in the central Mediterranean during the Bronze Age, and the best ages estimate for these layers.

Figure 3a shows the Total Alkali SiO_2 diagram (TAS, Le Bas et al., 1986) for the products of the three eruptions of Table 1. It is quite apparent that these three eruptions can be easily discriminated based on the TAS diagram. However ambiguities can exist in distinguish these tephra layers from others occurring during the same period, due to the actual difficult to find significant differences on major element composition or to lacking details in the available database. A good case is the Agnano Mt Spina tephra. The identification of this eruption on very distal setting may poses some difficulties on the basis of major elements alone (Smith et al., 2011), since it is the highest in intensity and magnitude occurring in a period of activity lasting ca. 1000 years punctuated by numerous explosive events. The general composition of all these products is similar, and usually they are not easily distinguishable on the basis of major elements or petrography (Turney et al., 2008; Sulpizio et al., 2010b; Smith et al., 2011), especially if they are not recognized in stratigraphic succession (e.g. like at Lago Grande di Monticchio, Wulf et al., 2004, 2008; or at Lake Shkodra, Sulpizio et al., 2010b). To this end, the new geochemical database reported by Smith et al., (2011) allows a better discrimination between some products of different eruptions, which was not really possible in the past (e.g. Margaritelli et al., 2016). It is interesting the fact that Margaritelli et al. (2016), in the Gulf of Gaeta (Core SW104-C5, table 1) have been able to identify the Astroni 3 tephra, which is the only tephra layer in that period showing a peculiar bimodal chemistry (Smith et al., 2011). This peculiarity supported the correlation of the lower tephra layer with Agnano Mt. Spina.

The less evolved products of the Avellino eruption also show some chemical overlaps with the successive AP 1-6 explosive eruptions (Santacroce et al., 2008 and references therein). These overlaps need to be considered with care in distal settings, when different product dispersal may leave some margin of ambiguity (Sulpizio et al., 2008; 2010b; Roeser et al., 2012; Zanchetta et al., 2012ab). When the whole set of chemical composition of Avellino eruption is available, the overlap is relatively minor (for example see Fig. 3b) and mistakes are easily avoidable. In controversial cases, additional chronological, mineralogical and stratigraphic information are necessary for a more secure attribution (Wulf et al., 2004; Magny et al., 2007; Sulpizio et al., 2008).

The etnean eruption FL was defined on proximal deposits by Coltelli et al., (2000), but no glass shards chemistry was reported in this fundamental work on Etna tephrostratigraphy. The first proposed correlation of a distal tephra with FL was suggested by Sadori and Narcisi (2001) for a volcanic layer found in the Pergusa Lake. The sediment containing it was directly radiocarbon dated at ca. 3.3 cal ka BP (Table 1). This first identification then became archetypal for the definition and correlation of FL in distal archives (Wagner et al., 2008; Sulpizio et al., 2010b; Vogel et al., 2010), because of the very poor chemical data available from the proximal area. The stratigraphy and chemistry of the tephra layer preserved in Pergusa have since then revisited coupled with high-resolution paleoclimatic records (Zanchetta et al., 2007; Sadori et al., 2008, 2013).

From a chronological point of view, the best constrained eruption of this interval is the Avellino tephra, dated at ca. 3.9 cal ka BP (Table 1), as the result of an important number of radiocarbon dating (Santacroce et al., 2008; Passariello et al., 2009; Sevink et al., 2011; Zanchetta et al. 2011). Agnano Mt. Spina age is ca. 4.4-4.5 cal ka BP (Passariello et al., 2010; Smith et al., 2011, Table 1); and interpolate ages from marine cores yielded 4420±58 cal yr BP (Lirer et al., 2013), which in absence of further chronological data would be considered the best age available. However, Agnano Mt Spina chronology needs to be significantly improved before it can be used as a fundamental anchoring chronological point. For FL, the radiocarbon age obtained by Sadori and Narcisi (2001) in the Pergusa Lake (3171-3359; Table 1) can be affected by different degrees of hardwater and reservoir effects, but is close to the age obtained by Coltelli et al. (2000) on charcoals (3334-3448; Table 1, the two ages overlap at 2σ level). Both ages have been used as chronological tie points for paleoclimatic records (Wagner et al., 2008; Zanchetta et al., 2012a; Sadori et al., 2013), but likely, or probably more than the case of Agnano Mt. Spina, the chronology of this layer needs to be significantly improved.

Other tephra layers can be potentially of interest to improve the tephrostratigraphy of the Bronze Age. For instance, in some records the presence of the AP eruptions is also reported (e.g. Magny et al., 2007; Wulf et al., 2008; Insinga et al., 2008). For these eruptions, the chronology is not particularly robust (Andronico and Cioni, 2002; Santacroce et al., 2008; Passariello et al., 2009, 2010), and the correct attribution to a specific one of the AP1-6 group is not always straightforward basing on chemistry. For instance, the tephra found at Lake Isnik (Turkey) and initially correlated to AP3 (Roeser et al., 2012), is more likely corresponding to the less evolved composition of Avellino, also considering the very limited dispersion of AP3 eruption compared to the Plinian character of Avellino. Moreover, this alternative correlation seems to be coherent with the finding of Avellino tephra in the Sea of Marmara (Çağatay et al., 2015).

4. Climatostratigraphic position of tephra layers

Figure 4 shows some examples of paleoclimatic records from the central Mediterranean based on robust radiometric chronologies but not containing the tephra layers. Although these records do not pretend to be exhaustive for the whole considered area, they can be useful as general reference for climatic and environmental conditions during the period of interest. In particular, the alkenone sea surface temperature (SST) record of the marine core ODP-976 (Martrat et al., 2014, Fig. 1) shows a long cooling trend from ca. 6 to 2 cal ka BP, with two short spikes indicating more marked cooling centered at ca. 5.7 and 5.1 cal ka BP, and an interval of evident cooling between 2.1 and 2.8 cal ka BP (Fig. 4). Paleohydrological records from Renella and Corchia caves (Regattieri et al., 2014; Zanchetta et al., 2014,2016b) show some similarities with the marine record, even if differences are also apparent. The Corchia Mean Anomaly Index (a statistical combination of stable isotope and trace element data from the same stalagmite, Regattieri et al., 2014) indicates two phases of wetter climate conditions, coincident with SST cooling in ODP976 at ca. 5.7 and 5.1 cal ka BP, separated by drier events (Zanchetta et al., 2014). At Renella Cave, the $\delta^{18}O$ record shows a very prominent drier period centered at ca. 4 cal ka BP and lasting ca. 500 yr, even if in the details it can be considered as two separate interval with a recovery of wetter condition in the middle (Magny et al., 2009). This event is less pronounced at Corchia, and not evident in the SST from ODP 976. This phase of drier conditions, which occurred at the very beginning of the Bronze Age, is apparent in others records from the central Mediterranean (Magri and Parra, 2002; Di Rita and Magri, 2009), but in others records it is not so obvious. Zanchetta et al. (2011, 2016b) observed that the 4.2 event is not so evident in some archives where proxies are typical indicators of winter conditions suggesting that this event may have been characterized by strong and long aridity during the warmer part of the year.

Figura 5 shows the selected paleorecords containing all or some of the discussed tephra layers. Only Shkodra Lake $\delta^{18}O$ record (Zanchetta et al., 2012a) contains all the three tephra layers. This makes it particularly interesting for our discussion. In Figure 5 the shadowed bars indicated the range of ages reported in Table 1 for the discussed tephra layers, whereas thinner and darker lines indicate the stratigraphic position of the same tephra layers. It is apparent that in some records the age for Avellino is too old (Monticchio, Brauer et al., 2007; and Accesa, Magny et al., 2007), a fact already noted (e.g. Sevink et al., 2011; Zanchetta et al., 2012ab, 2016b). Also, the age of Agnano Mt. Spina appears overstimated in the records from core MD90-917, Lake Monticchio and Lake Accesa. Due to these discrepancies, these records have to be considered with caution when drawing a precise and accurate paleoclimatic reconstruction of the Bronze Age interval and a careful revision of their age model for this interval is necessary.

However, some important considerations can be done, if we focus on the climatostratigraphic position of these tephra layers instead on their relative ages. Interestingly, Agnano Mt. Spina tephra at Shkodra is at the beginning of a drying trend which culminates at ca. 4 ka, as shown by $\delta^{18}O$ (Zanchetta et al., 2012a) and pollen record (Sadori et al., 2015). This trend is similar to what observed in the core SW104-C5 (Margaritelli et al., 2016). In the lake level record from Accesa, the tephra is within a marked period of lowstand. Thus, in all these records, the Agnano Mt. Spina tephra seems to mark the very beginning of a drying phase. On the contrary, in all the considered records the Avellino eruption seems to be placed in a period of substantial recover of wetter conditions (Fig. 5). This is in agreement with the analysis of vegetation macroremains buried by the Avellino eruption (Monica Stanzione, personal communication) in the central-northern part of the Campania Plain, which revealed a rich vegetation cover indicating wet conditions. Similarly, isotopic composition of pedogenic carbonate collected in the volcanic soils of Campanian Plain, indicates that Avellino occurred in a wetter period (Zanchetta et al., 2000), even if the low resolution of the data does not allow to clarify the temporal extension of this phase. So, the Avellino and Agnano Mt. Spina seems to bracket a climatic deterioration, which could be correlated with the so called 4.2 event (Weiss, 2015; Zanchetta et al., 2012ab, 2016b).

As discussed in the previous section, the chronology of FL is not very robust; however, it is interesting to note that in core Co1262 from the Lake Ohrid (Wagner et al., 2012) the FL is placed at the beginning of a decrease in the Total Organic Carbon and Ca content (Fig. 5). This trend indicates a period of declining of primary productivity, related to cooling. At lake Shokra FL is similarly placed at the beginning of increase of $\delta^{18}O$, suggesting a progression toward drier conditions. Therefore, it appears that FL tephra marks a phase of climatic deterioration, dated at ca. 3.4-3.2 cal ka BP. Some evidences can be inferred also from Monticchio, with a concomitant decrease in Mesic forest, and from lake level oscillations at Accesa, (admitting that chronology during this interval is correct), as well as from some oscillations observable at core SW104-C5 (Margaritelli et al., 2016). However, pollen data from SW104-C5 did not show any significant event at this time. Differently, even if the arboreal pollen from Pergusa (Fig. 5) does not show particular changes, Sadori et al. (2013) highlighted that the olive expansion occurring soon after the FL tephra cannot be ascribed only to human impact, even if this could be the more obvious interpretation. Increased temperature and decreased precipitation might have in fact favored the growing of the thermophilous and less moisture demanding olive trees. A change in forest biomass is also found at Shkodra (Sadori et al., 2015) with arboreal pollen influx decreasing soon after FL. Interestingly, SST from core ODP 976 shows a decrease (Fig. 3) at this time, confirming the presence of a short event of climatic deterioration.

5. Conclusion

Revision of paleoclimate archives containing tephra layers within the central Mediterranean indicate that three main tephra layers are widely dispersed during Bronze Age. The physical correlation of these archives using tephra layers suggests that some of them have severe chronological biases, which poses important limitation for their use in precisely defining the paleoclimate conditions during the Bronze Age. However, some general consideration can be drawn analyzing the "climatostratigraphic position" of these tephra layers in different archives. Agnano Mt. Spina tephra seems to occur at the beginning of a period of climatic deterioration, whereas Avellino tephra seems to be placed just at the end of this event, during a wetter period. The two tephra layers appear to constrain a dry event, which would be correlated with the so-called 4.2 event. FL eruption, from Etna, seems to herald a new climatic deterioration at ca. 3.4-3.2 cal ka BP. However, and despite fundamental improvement achieved in the last years, the climatic framework for the central Mediterranean Bronze Age is still far to be complete. To this end, tephra layers will play a fundamental role in synchronizing archives, helping to define detailed lead and lag between archives and proxies. However, there are still few Holocene records where a sufficient number of tephra layers are available to build a robust synchronization process and this represent a target for future researches.

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Figure and Table captions

Figure 1. Reference map of the sites and records quoted in text. Corchia Cave (CC26 record, Regattieri et al., 2014); Renella Cave (LR4 record, Drysdale et al., 2006; Zanchetta et al., 2016b); Lake Shkodra (core SK13; Sulpizio et al., 2010b; Zanchetta et al., 2012a); Lake Ohrid (core Co1262; Wagner et al., 2012); Gulf of Gaeta (core SW104-C5, Margaritelli et al., 2016); ODP-976 (Martrat et al., 2015); Pergusa Lake (Core PG2; Sadori et al., 2013); Monticchio Lake (Pollen from Brauer et al., 2007); Core MD90-917 (Siani et al., 2001, 2004).

Figure 2. Scheme of the main tephra layers widely dispersed in the central Mediterranean (modified and updated from Zanchetta et al., 2011).

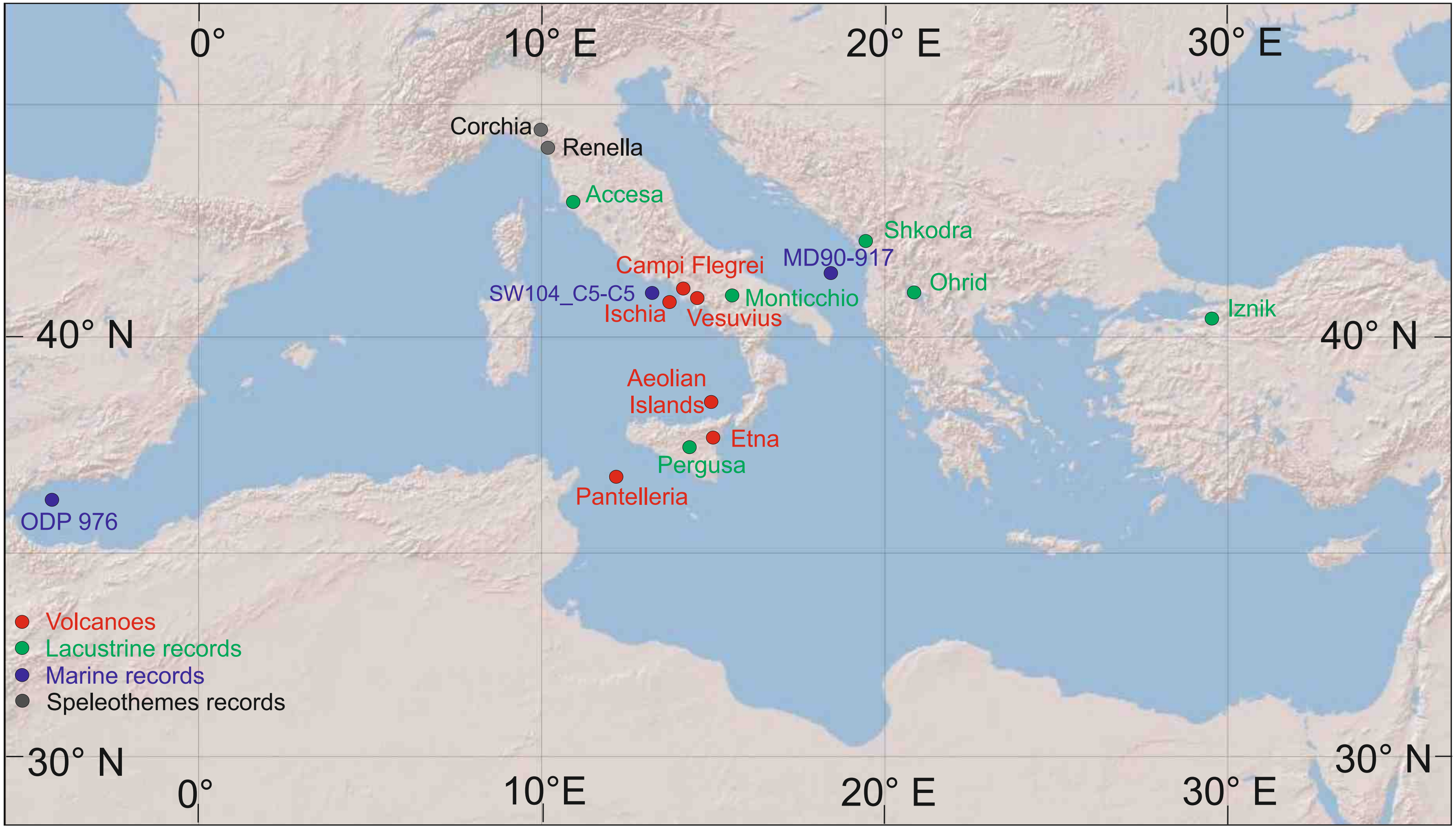
Figure 3. a) Total alkali Silica diagram (TAS, Le Bas et al., 1986) showing the chemical compositional range for the three main eruptions occurred during the Bronze Age in the central Mediterranean in comparison with AP eruptions chemical composition and Campi Flegrei volcanic activity between ca. 5.5 and 4.5 ka (data mostly from Santacroce et al., 2008; Smith et al., 2011; Sulpizio et al., 2010); b) FeO_{total} vs SiO_2 for Avellino and AP eruptions, showing the margin of chemical overlapping (data from Santacroce et al., 2008).

Figure 4. Selected paleoclimate records used for describing the general paleoclimate and palaeohydrological conditions during the Bronze Age in the central Mediterranean: SST from ODP-

976 (Martrat et al., 2014); Corchia cave Mean Anomaly Index (Regattieri et al., 2014); Renella cave $\delta^{18}O$ record (Zanchetta et al., 2016b). Corchia and Renella records are interpreted to represent amount of precipitation over the cave catchement. Shaded orange areas represent the age ranges of Agnano Mt. Spina (AMS), Avellino (AV) and FL tephra layers.

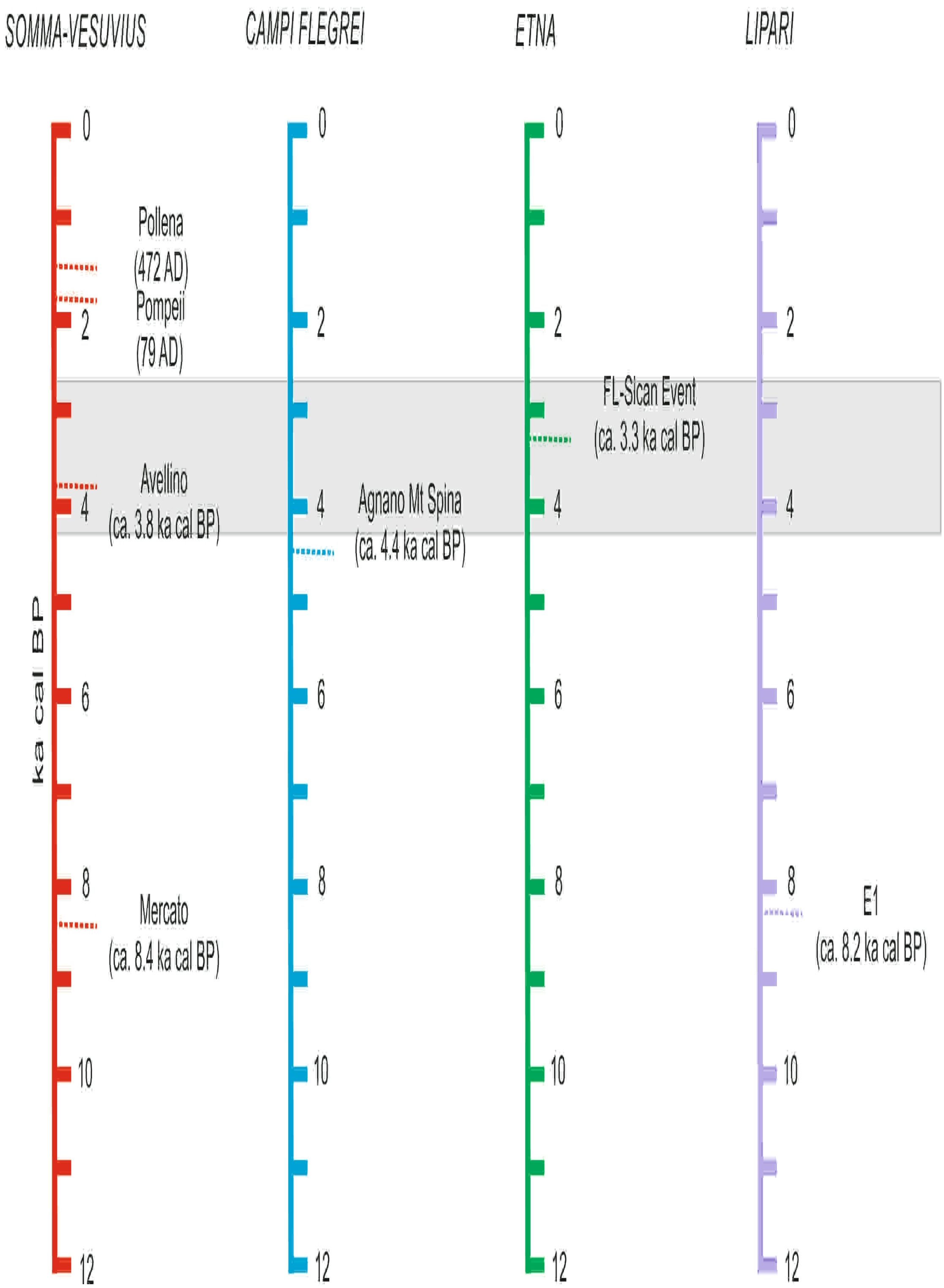
Figure 5. Selected records containing tephra layers over the central Mediterranean. From the top to the bottom: MD90-917 SST (Siani et al., 2001); MD90-917 reconstructed $\delta^{18}O$ of the sea water (Siani et al., 2014); $\delta^{18}O$ of planktonic Core SW104-C5, (Margaritelli et al., 2016); Monticchio Lake Mesic pollen (Brauer et al., 2007); Accesa lake level (Magny et al., 2007); Lake Pergusa AP pollen (Sadori and Narcisi, 2001); Orhid Total Inorganic Carbon (TOC, Wagner et al., 2012).

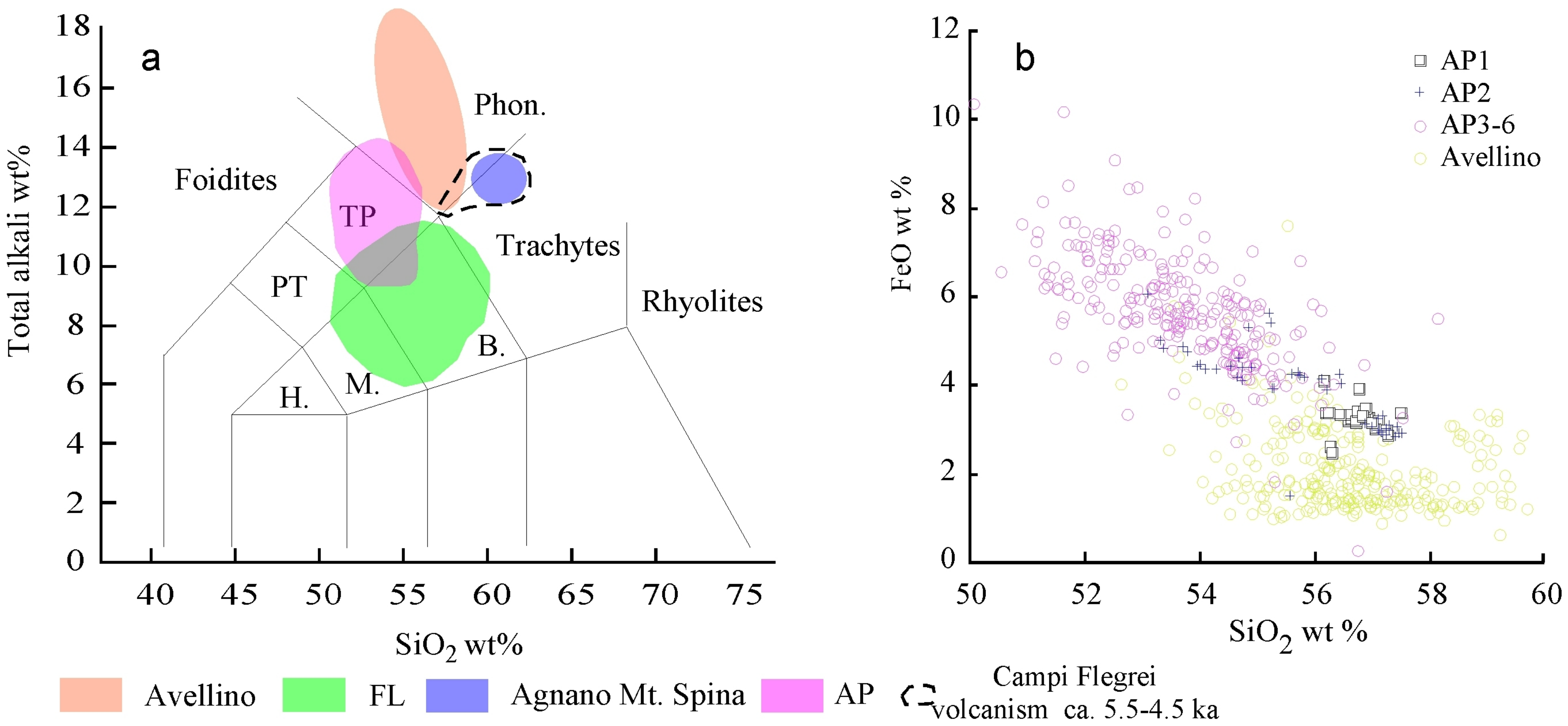
Table 1. The main tephra layers with large dispersion discussed in the text. Radiocarbon dating of 1, 2, 3, 5 are calibrated according to Reimer et al. (2015).



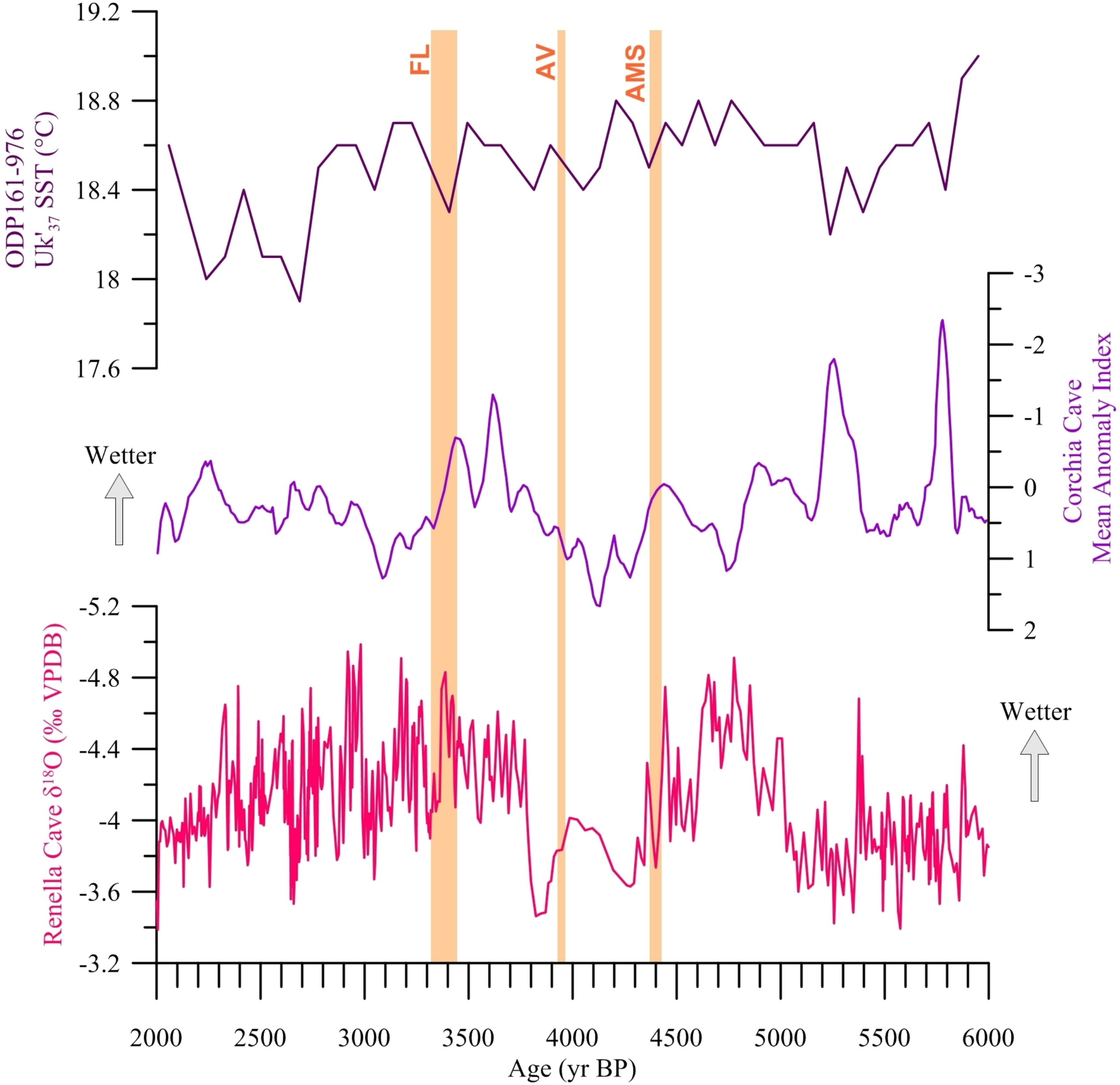
0°
10° E
20° E
30° E
Corchia
Renella
Accesa
Shkodra
MD90-917
Campi Flegrei
SW104_C5-C5
Monticchio
Ohrid
Iznik
Ischia
Vesuvius
40° N
40° N
Aeolian Islands
Etna
Pergusa
Pantelleria
ODP 976
Volcanoes
Lacustrine records
Marine records
Speleothemes records
30° N
30° N
0°
10°E
20° E
30° E

MAIN EXPLOSIVE ERUPTIONS OCCURRED IN THE CENTRAL MEDITERRANEAN

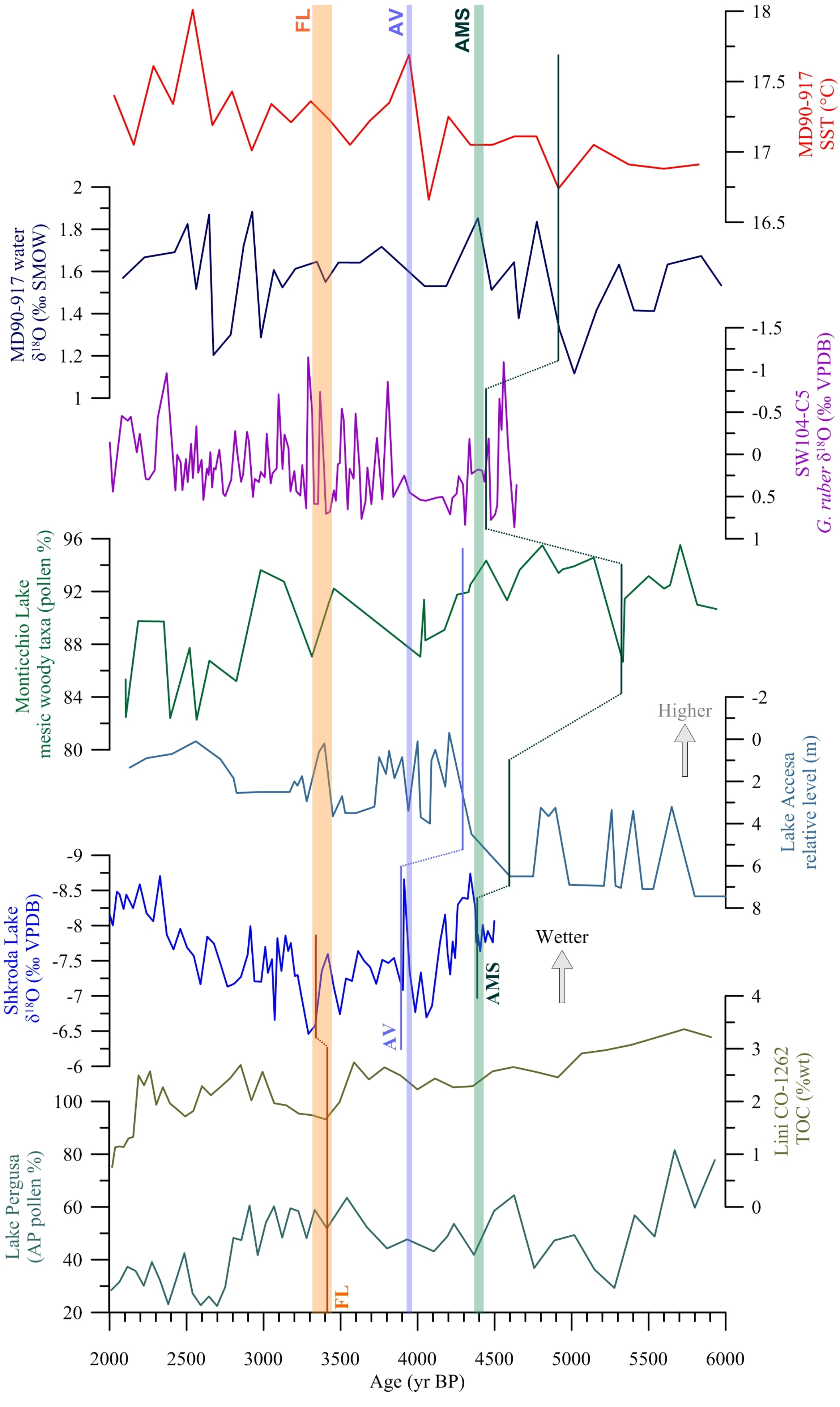




a
Total alkali wt%
SiO2 wt%
Foidites
Phon.
TP
PT
Trachytes
Rhyolites
B.
M.
H.
b
FeO wt %
SiO2 wt %
AP1
AP2
AP3-6
Avellino
Avellino
FL
Agnano Mt. Spina
AP
Campi Flegrei volcanism ca. 5.5-4.5 ka



FL
AV
AMS
ODP161-976
Uk'37 SST (°C)
19.2
18.8
18.4
18
17.6
Wetter
Corchia Cave
Mean Anomaly Index
-3
-2
-1
0
1
2
Wetter
Renella Cave δ18O (‰ VPDB)
-5.2
-4.8
-4.4
-4
-3.6
-3.2
2000
2500
3000
3500
4000
4500
5000
5500
6000
Age (yr BP)



FL
AV
AMS
MD90-917 SST (°C)
18
17.5
17
16.5
MD90-917 water δ18O (‰ SMOW)
2
1.8
1.6
1.4
1.2
1
SW104-C5 G. ruber δ18O (‰ VPDB)
-1.5
-1
-0.5
0
0.5
1
Monticchio Lake mesic woody taxa (pollen %)
96
92
88
84
80
Higher
Lake Accesa relative level (m)
-2
0
2
4
6
8
Shkroda Lake δ18O (‰ VPDB)
-9
-8.5
-8
-7.5
-7
-6.5
-6
Wetter
AMS
AV
Lini CO-1262 TOC (%wt)
4
3
2
1
0
Lake Pergusa (AP pollen %)
100
80
60
40
20
FL
2000
2500
3000
3500
4000
4500
5000
5500
6000
Age (yr BP)

Tephra name	***Volcano***	***Best estimate age (cal yr BP ±1σ)***	***Main references***
FL (or Sicani Event)	Etna	3334-3448[1] 3171-3359[2]	[1]Coltelli et al., 2000 [2]Sadori and Narcisi, 2001
Avellino	Somma-Vesuvius	3830-3880[3] 3935-3955[4] 3724-3870[5]	[3]Passariello et al., 2009 [4]Sevink et al., 2011 [5]Zanchetta et al. 2011
Agnano Mt. Spina	Campi Flegrei	4482-4625[6] 4420±58[7]	[6]Smith et al., 2011 [7]Lirer et al., 2013

Table 1

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We the authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.
We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.
We understand that the Corresponding Author is the sole contact for the Editorial process. He/She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Sincerely,

On behalf of all authors