The Late Holocene tephra record of the central Mediterranean Sea: Mapping occurrences and new potential isochrons for the 4.4–2.0 ka time interval

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ABSTRACT: Five cores from the southern Tyrrhenian and Ionian seas were studied for their tephra and cryptotephra content in the 4.4–2.0 ka time interval. The chronological framework for each core was obtained by accelerator mass spectrometry 14C dating, the occurrence of distinct marker tephra and stratigraphic correlation with adjacent records. Tephrochronology allowed us to correlate the analyzed deposits with tephra markers associated with Somma-Vesuvius (79 AD), Ischia Island (Cretaio), Mt Etna (FG, FL and FS) and Campi Flegrei (Astroni-Agnano Monte Spina) events. For the first time in the marine setting, a large single glass data set is provided for the Late Holocene Etna marker beds including the FS tephra (ca. 4.3 ka). Moreover, unknown deposits from Lipari (ca. 2.2–2.0 ka) and Vulcano (3.6–3.3 ka) are also recognized at more distal sites than previously reported. These results contribute to improve the high-resolution tephrostratigraphic framework of the central Mediterranean Sea. They also provide new insights into the chemical composition and dispersal pattern of tephras that can be used as inter-archive tools for regional and ‘local’ stratigraphic correlations and for addressing paleoclimate research.

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KEYWORDS: central Mediterranean; cryptotephra; isochronous marker; Italian volcanism; tephra.

Introduction

The need for high-resolution, robust chronostratigraphic records, mainly for paleoclimate research, has resulted in numerous tephra and cryptotephra studies over the last decade (e.g. Abbott et al., 2018). This is particularly true for the central Mediterranean, a key area for tephrochronology due to the occurrence of active volcanoes during the Quaternary and the availability of long and continuous marine and continental archives (e.g. Keller et al., 1978; Paternè et al., 1988, 2008; Calanchi et al., 1998; Siani et al., 2004; Wulf et al., 2004; Munno and Petrosino, 2007; Sulpizio et al., 2010; Insinga et al., 2014; Matthews et al., 2015; Giacchi et al., 2017). To date, in the marine setting, tephra and cryptotephra have been analyzed in ca. 129 sediment cores (198 in the whole Mediterranean) (Alberico et al., 2017). As a result, more refined tephrostratigraphic frameworks for the Late Quaternary are now available from shelf to basin. They include mostly major tephra markers related to high-energy volcanic events (e.g. Wulf et al., 2008; Zanchetta et al., 2011; Bronk Ramsey et al., 2015; Tomlinson et al., 2015) and, to a lesser extent, deposits from moderately explosive eruptions (Sacchi et al., 2009; Lirer et al., 2013; Crocitti et al., 2018; Di Donato et al., 2019). These studies have relied heavily on recent advancements in the methods and technology of sampling systems, that allow for the recovery of undisturbed sediment cores with the possibility of retrieving tephra and cryptotephra deposited in recent centuries even in the few centimeters of the sub-sea floor (e.g. Jalali et al., 2018; Margaritelli et al., 2016). Improved results in terms of tephra correlation have also been derived from high-precision characterization of glass composition at proximal sites. A large database compiled in recent years for Somma-Vesuvius and Campi Flegrei volcanoes (Santacroce et al., 2008; Smith et al., 2011; Tomlinson et al., 2012), for example, has provided a significant contribution to the recognition of distal tephra and associated source vents. Conversely, for other eruptive centers, such as the Aeolian Islands and Mt Etna, chemistry from single glass shards is available only for major markers (Albert et al., 2012, 2013, 2017). As a result, a number of distal deposits, found in both the Tyrrhenian and the Ionian seas and related to moderately explosive eruptions, are still uncorrelated (e.g. Paternè et al., 1988; Di Donato et al., 2019).

In this study we present a tephrostratigraphic framework for the 4.4–2.0 ka time interval of the central Mediterranean underpinned by the analysis of five marine cores. Our results are integrated with the Weather and Water Database (WDB)-Paleo, which records paleoproxy metadata from the extensive marine core network (Alberico et al., 2017). The main outcomes of this work include the detection of tephra with ‘local’ correlation potential and the definition of robust isochrons for high-resolution stratigraphy.
Data set and analytical methods

Gravity cores

The tephra and cryptotephra analyzed in this work were sampled from cores located in the southern Tyrrhenian and Ionian Seas (Fig. 1). They were collected between 1994 and 2012 in the framework of several research projects on board the Research Vessel (RV) *Urania* of the Italian Research Council (cores C14, C1, AP1,1, UM42BC) and the RV *Pelagia* (core CP10BC). Details are reported in Table 1.

Southern Tyrrhenian Sea

Gravity core C14 was recovered during the GMS98-01 cruise dedicated to the geological mapping of continental and marine areas (CARG project, 1997–2004). A 5.22-m-long succession was retrieved from the western sector of Naples Bay at a depth of 186.5 m below sea level (bsl) and it is composed of silt deposits with volcaniclastic turbidites and interbedded primary tephra layers. The stratigraphic record sampled at the C14 site spans the last ca. 9 ka (Petrosino et al., 2018).

Gravity core MSK-12 C1 (hereafter C1) was acquired during the MARISK_12 cruise along the eastern Tyrrhenian margin. The 4.50-m-long record is located offshore Capo Vaticano at a depth of 604 m below the sea floor (bsf) and it is mostly composed of silt and interbedded primary tephra deposited during the last 17 ka (our unpublished data).

Ionian Sea

Gravity core AP1.1 (hereafter AP1) was sampled in the northern Ionian Sea during Sin-Sap 98 cruise. The 3.20-m-long succession is located at 811 m bsl and characterized by silt deposits which include sapropels S1, S3 and S5 (D’Antonio et al., 2016).

Box core UM42BC (hereafter UM42) was recovered in the western Ionian Sea at a depth of 1375 m bsl during the oceanographic cruise Urania 18. It is 35.5 cm long and...
| Core   | Location          | Depth below sea level (m) | Length (m) | Age control along the record | Tephra-event (source) | Type/lithology                                      | Composition                          | Age on proximal | Age in marine setting |
|--------|-------------------|---------------------------|------------|------------------------------|----------------------|----------------------------------------------------|--------------------------------------|-----------------|-----------------------|
| C14    | 14°113.0° E 40°44'47"N | 186.5                     | 5.22       | Stratigraphic relationship with other cores | C14/89-Pompeii + Cretaio (SV + I) | Visible tephra/Light and light gray micropumice, dark scoria, lithics (some leucite bearing), loose crystals of feldspar and clinopyroxene. | Phonolite (population a) + Trachyphonolite (population b) | 79 AD/1st century AD(1) | 3 ± 42 AD for Cretaio(2) |
| CI     | 15°48.236° E 38°44.573°N | 604                       | 4.5        | 14C and stratigraphic relationship with other cores | C1/56-Pompeii (SV) | Cryptotephra/Light and light gray vesiculated micropumice, leucite-bearing lithics, loose crystals of feldspar and biotite | Phonolite | 79 AD | – |
|        |                   |                           |            |                              | C1/82-FL (Et) | Cryptotephra/Dark to iron-gray porphyritic scoriaeous fragments, loose crystals and reddish lava lithic fragments | Benmoreite |                    |                        |
|        |                   |                           |            |                              | C1/85–? (Vulc) + FL (Et) | Cryptotephra/Dark dense scoria and grayish pumice. Dark honey glass shards with blocky morphology also occur. Loose crystals of olivine, pyroxene and brown mica. | Mugearite (population a) + Tephriphonolite (SHO) (population b) | 3361 ± 76 cal a BP (FL)(3) |                    |
|        |                   |                           |            |                              | C1/87-FL (Et) | Cryptotephra/Dark porphyritic scoria and grayish pumice. Loose crystals of feldspar and clinopyroxene | Benmoreite-trachyte |                    |                        |
|        |                   |                           |            |                              | C1/90-FL (Et) | Cryptotephra/Dark gray porphyritic scoria | Benmoreite | 3625 ± 96 cal a BP (this study) |                        |
| SAPGACP1.1 | 19°06.78°E 39°12.99°N | 810                       | 3.2        | 14C datings, sedimentation rates | AP1/13*-FS + AAMS (Et + CF) | Cryptotephra/Dark grey dense scoria and rare pale grey pumice. | Benmoreite (population a) + Trachyphonolite (population b) | 4.36 ± 0.092 cal ka or 4.46–4.1 cal ka or 5(1) | 4420 ± 60 cal a BP(2); 4237 ± 44 cal a BP (this study) |
| UM42BC | 17°51.75°E 34°57.23°N | 1375                      | 0.355      | 14C datings, sedimentation rates | UM42/7*-FG (Et) | Visible tephra/Brown to yellowish vesiculated glass fragments with feldspar crystals and minor honey dense aphyric glass fragments. Dark brown and grayish | Mugearite to benmoreite | 380 BC to 120 AD (II 22 to historical age)(6) | ~2.2 cal ka or (this study) |

(Continued)
**Table 1.** (Continued)

| Core | Location | Depth below sea level (m) | Length (m) | Age control along the record | Age on proximal setting | Type of tephra-event (source) | Composition | Tephra-event (source) |
|------|----------|---------------------------|------------|-----------------------------|-------------------------|-------------------------------|-------------|----------------------|
| CP10BC | 34°32’70”N | 1501 | 3.35 | 13C datings, sedimentation rates | 1.97 cal ka BP for Cryptotephra/Dark Mugearite–tephriphonolite | 680–740 AD | brown poikilitic scoria, reddish lithics and loose crystals. Loose crystals of feldspar and platy glass shards. | CP10BC#14 |

**Sampling and selection of materials**

Two visible tephras and four cryptotephras were sampled and analyzed (Table 1). Where applicable (e.g., relatively thick deposits) or where required for specific purposes (e.g., ultra-high-resolution stratigraphic studies), a number of subsamples were taken from the same deposit. All samples were labeled according to the identifying core code/name and depth (cm) below the sea floor.

Sediment samples were disaggregated in distilled water and wet sieved at 63, 90, 125 and 250 µm to remove the fine-grained fraction. The sieved material was cleaned with an ultrasonic probe and dried at 60°C. A magnetic separator was used for scoria-rich samples. Subsequently, lithology was described using an optical microscope and fresh glass fragments were picked from selected samples for major-element characterization. As a criterion for the identification of cryptotephra, we selected those deposits where the juvenile fraction (mainly glass fragments) exceeded 50% of the bulk sediment.

Visible tephras were found in cores C14 (89–74 cm bsf) and UM42 (7.4–6.7 cm bsf). The selected sample in core C14 (C14/89) includes the 89–87 cm bsf interval characterized by prevailing volcanic materials (Table 1). Sample UM42/7 was picked from the 6.7–7.1 cm bsf interval where scoria fragments represent 90% of the deposit (Table 1; Supporting Information Fig. S1).

In core CP10, the analyzed cryptotephra was recognized initially through elemental composition of the bulk sediments (Wu et al., 2016, 2017). It was between 7 and 6.5 cm bsf (sample CP10/7) (Fig. S1).

In cores AP1 and C1, cryptotephras were identified by inspection of washed sediments (>63 µm fraction) used for foraminifera analysis. The deposit investigated in core AP1 occurs between 13 and 12 cm bsf (sample AP1/13), whereas in core C1, two cryptotephras are dispersed between 56 and 52 cm bsf (sample C1/56) and within the 90–80 cm bsf interval. The latter was subsampled at 1–2 cm steps to observe possible changes in lithology and the juvenile fraction content. Four subsamples (C1/82, C1/85, C1/87 and C1/90) were selected for chemical characterization.

**Major element analysis**

Juvenile fragments (pumice, scoria and glass shards) of samples selected from each deposit were mounted on epoxy resin and suitably polished for microprobe analyses performed on a JEOL JSM 5310 scanning electron microscope (15 kV, ZAF Correction Routine) equipped with an energy-dispersive spectrometer at DiSTAR (University of Naples “Federico II”). Operating conditions were 15 kV primary beam voltage, 50–100-nA filament current, 50-s acquisition time and variable spot size. Correction for matrix effects was performed using INCA version 4.08 software that used the XPP correction routine, based on a Phi-Ro-Zeta approach. Primary calibration was performed using international mineral and glass standards. Details on the standards used are given in Morabito et al. (2014). Precision and accuracy were assessed using the rhyolitic Lipari obsidian ID3506 and basaltic Laki 1783 AD tephras (Kuehn et al., 2011) as secondary standards and the
respective analytical values are reported in Supporting Information Table S1 along with analyses of individual glass fragments extracted from the studied deposits. Total oxide sums ≥93% were deemed acceptable given that magmatic dissolved volatile components may reach >5% in evolved trachytes and rhyolites (e.g., Pearce et al., 1999). Correlation of the analyzed tephras with proximal deposits or equivalents from different sites was based on a comparison of the new data with published scanning electron microscopy/energy-dispersive spectrometry (SEM-EDS) and wavelength-dispersive spectrometry (WDS) data where available. The criteria used to infer the primary origin of the studied deposits are described in Insinga et al. (2014).

\(^{14}C\) AMS dating

Radiocarbon dating was performed by accelerator mass spectrometry (AMS) on planktonic foraminifera collected from five samples in stratigraphic association with the analyzed tephras. Measurements were performed at the Poznań Radioisotope Laboratory, at the J. G. van de Graaff laboratory (Utrecht University) and at INFN-Labec of Florence following procedures described in Goslar et al. (2004), Van Der Borg et al. (1997) and Lubritto et al. (2018). All \(^{14}C\) dates were converted into calendar ages using the Marine13 calibration curve (Reimer et al., 2013) implemented in the program OxCal 4.3 (Bronk Ramsey, 2009) with no regional reservoir correction (i.e. \(\Delta R = 0\)), which is valid for the modern Mediterranean (Siani et al., 2000).

The WDB-Paleo database

The WDB-Paleo database includes data on about 6000 cores recovered from the Mediterranean Sea (Alberico et al., 2017). It hosts metadata concerning paleoclimatic proxies, stratigraphic and chronological data (planktonic and benthic foraminifera, pollen, calcareous nanoplankton, magnetic susceptibility, oxygen stable isotope, AMS \(^{14}C\) dating and tephras) published in ca. 200 scientific publications with associated reference information (authors, journal, book, year, title). Quantitative proxy data from all cores acquired in the frame of a number of Italian research projects were also integrated along with metadata on tephra from continental archives of central–southern Italy used in this work. A new entity hosting geochemical data has been implemented with data obtained here as shown in the logical model reported in Fig. 2.

Results

Composition and sources of tephra

Lithological features of tephras (C14/89, UM42/7) and cryptotephras (C1/56, C1/80–90, AP1/13, CP1/07) are reported in Table 1. According to the total alkali–silica (TAS; Le Maitre, 2005) diagram and serial affinity (sodic to ultrapotassic), the analyzed samples are classified as basaltic trachyandesite, trachyphonolite and rhyolite, and from tephrphonolite to phonolite (Fig. 3a–c; Table 2). Tephra with Na-alkaline affinity occur in all cores except C14 (Fig. 3c). Two geochemical populations characterize tephra C14/89 (phono-lite + trachyphonolite), and cryptotephra C1/85 (tephripho-nolite-litite + mugearite), CP1/07 (rhyolite + mugearite) and AP1/13 (trachyphonolite + benmoreite) (Fig. 3). The overall chemical features of the analysed samples match well those of the Italian volcanic products and, in detail, with Mt Etna, Aeolian Arc s.l., Somma-Vesuvius, Ischia Island and Campi Flegrei deposits (Fig. 3a,b; Table 1). These correlations are consistent with the location of the core sites, downwind and in the proximity of source vents.

Mt Etna related tephra

Deposits with Na-alkaline affinity (Fig. 3c) can be classified as mugearites, benmoreites and trachytes in the TAS diagram (Fig. 3a,b). These compositions are typical of the intermediate–evolved products erupted by Mt Etna volcano during the late Pleistocene–Holocene (Peccerillo, 2005) (Fig. 3a,b; Table 2). The analyzed tephras generally consist of fine ash, which displays a crystalline groundmass of juvenile materials with rare interstitial glass. Microlites are represented by clinopyroxene, plagioclase and opaques (Fig. 4a,b).

In core C1, the Etnean cryptotephra is dispersed in a relatively thick interval (ca. 10 cm) and it is characterized by a variable ratio between the content of juvenile fragments over the lithic and bioclastic fraction (Supporting Information Fig. S1). No evidence of reworking has been observed. The content of the juvenile fraction in the selected samples ranges from 70...
to 90% (C1/87 and C1/85) with respect to the biotic component in all the sieved fractions. Grayish pumice fragments occur with the ubiquitous dark scoria in sample C1/85. Glasses extracted from samples C1/90, C1/87 and C1/82 have a benmoreitic composition with some points also falling in the trachytic and tephriphonolitic field. In contrast, an almost homogeneous mugearitic glass (a), along with minor tephriphonolitic glass (b) characterize sample C1/85 (Fig. 4b).
### Table 2. Single glass chemistry for the studied tephra.

| Core          | Sample | CP10/7a | CP10/7b | AP1/13a | AP1/13b | C14/89a | C14/89b |
|---------------|--------|---------|---------|---------|---------|---------|---------|
|               | cm bsf | 6.5–7   | 12–13   | 88–89   |         |         |         |
| **SiO₂**      | 53.91  | 54.04   | 52.20   | 52.71   | 51.57   | 51.92   | 75.29   | 75.91   |
| **TiO₂**      | 1.78   | 2.06    | 1.76    | 1.65    | 1.76    | 1.98    | 0.00    | 0.00    |
| **Al₂O₃**     | 16.08  | 15.81   | 16.02   | 16.67   | 17.00   | 17.26   | 13.67   | 13.14   |
| **FeO**       | 8.79   | 8.24    | 8.84    | 8.71    | 8.30    | 9.50    | 9.04    | 1.41    |
| **MnO**       | 0.27   | 0.39    | 0.22    | 0.33    | 0.04    | 0.27    | 0.12    | 0.00    |
| **MgO**       | 2.42   | 2.56    | 3.31    | 2.96    | 2.58    | 3.49    | 3.59    | 0.00    |
| **CaO**       | 3.52   | 4.07    | 6.48    | 6.84    | 7.01    | 7.75    | 7.29    | 0.76    |
| **Na₂O**      | 5.34   | 5.12    | 4.67    | 5.18    | 4.70    | 4.81    | 4.71    | 2.87    |
| **K₂O**       | 5.78   | 5.53    | 4.31    | 3.23    | 2.99    | 2.44    | 2.27    | 4.01    |
| **P₂O₅**      | 1.27   | 1.21    | 1.08    | 1.60    | 0.70    | 0.87    | 0.97    | 1.18    |
| **Cl**        | 0.42   | 0.48    | 0.41    | 0.31    | 0.28    | 0.30    | 0.34    | 0.30    |
| **Original total** | 97.59  | 99.83   | 97.69   | 98.23   | 96.40   | 97.38   | 95.88   | 95.31   |

| Core          | Sample | UM42/BC | UM42/7 |
|---------------|--------|---------|--------|
|               | cm bsf | 6.7–7   |        |
| **SiO₂**      | 59.58  | 52.87   | 55.86  |
| **TiO₂**      | 1.26   | 1.17    | 1.40   |
| **Al₂O₃**     | 17.50  | 17.04   | 17.98  |
| **FeO**       | 5.25   | 9.24    | 6.40   |
| **MnO**       | 0.10   | 0.15    | 0.41   |
| **MgO**       | 1.38   | 3.56    | 2.41   |
| **CaO**       | 2.64   | 7.43    | 4.92   |
| **Na₂O**      | 6.70   | 4.45    | 5.84   |
| **K₂O**       | 4.58   | 2.52    | 3.56   |
| **P₂O₅**      | 0.50   | 0.11    | 0.87   |
| **Cl**        | 0.52   | 0.43    | 0.34   |
| **Original total** | 98.59  | 95.71   | 97.35  |

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### Table 2. (Continued)

| Core    | Sample | cm bsf | MgO | CaO | Na2O | K2O | P2O5 | Cl | Original total |
|---------|--------|--------|-----|-----|------|-----|------|----|----------------|
| Core UM42BC | Sample UM42/7 | cm bsf | 6.7 | 7.1 | 6.7 | 7.1 | 6.7 | 7.1 | 6.7 | 7.1 | 6.7 | 7.1 | 6.7 | 7.1 |
| SiO2     | 56.04  | 51.21  | 57.36 | 57.26 | 57.00 | 56.43 | 56.37 | 56.55 | 57.02 | 56.51 | 57.14 |
| TiO2     | 1.97   | 1.75   | 1.86 | 1.96 | 2.00 | 1.99 | 2.01 | 2.00 | 1.99 | 2.00 | 1.99 |
| Al2O3    | 16.91  | 16.91  | 16.91 | 16.91 | 16.91 | 16.91 | 16.91 | 16.91 | 16.91 | 16.91 | 16.91 |
| FeO      | 5.53   | 5.53   | 5.53 | 5.53 | 5.53 | 5.53 | 5.53 | 5.53 | 5.53 | 5.53 | 5.53 |
| MgO      | 4.22   | 4.22   | 4.22 | 4.22 | 4.22 | 4.22 | 4.22 | 4.22 | 4.22 | 4.22 | 4.22 |
| CaO      | 6.39   | 6.39   | 6.39 | 6.39 | 6.39 | 6.39 | 6.39 | 6.39 | 6.39 | 6.39 | 6.39 |
| Na2O     | 4.58   | 4.58   | 4.58 | 4.58 | 4.58 | 4.58 | 4.58 | 4.58 | 4.58 | 4.58 | 4.58 |
| K2O      | 3.26   | 3.26   | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 |
| P2O5     | 0.90   | 0.90   | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 |
| Cl       | 0.15   | 0.15   | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| Original total | 96.82 | 96.82 | 96.82 | 96.82 | 96.82 | 96.82 | 96.82 | 96.82 | 96.82 | 96.82 | 96.82 |
Table 2.

| Sample cm bsf | C1/82 | C1/56 |
|---------------|-------|-------|
| SiO₂          | 54.70 | 54.96 |
| TiO₂          | 0.36  | 0.41  |
| Al₂O₃         | 17.3  | 17.9  |
| FeO           | 7.6   | 9.0   |
| MnO           | 0.02  | 0.03  |
| MgO           | 1.92  | 2.26  |
| CaO           | 3.48  | 4.04  |
| Na₂O          | 6.33  | 4.04  |
| K₂O           | 4.32  | 5.55  |
| P₂O₅          | 1.23  | 1.52  |
| Cl            | 0.10  | 0.10  |
| Original total| 100.46| 100.46|

All the analyses recalculated free water to 100. The original totals have been also reported.

Table 2. (Continued)

| Sample cm bsf | C1/56 |
|---------------|-------|
| SiO₂          | 54.51 |
| TiO₂          | 0.39  |
| Al₂O₃         | 17.7  |
| FeO           | 7.6   |
| MnO           | 0.02  |
| MgO           | 1.92  |
| CaO           | 3.48  |
| Na₂O          | 6.33  |
| K₂O           | 4.32  |
| P₂O₅          | 1.23  |
| Cl            | 0.10  |
| Original total| 100.53|

Tephra AP1/13 has a benmoreitic-mugearitic composition (a) and is associated with a minor trachyphonolitic glass (b).

Tephra UM42/7 is the only visible layer among the Etnean products. The deposit is well preserved and includes a fresh juvenile fraction exceeding 85% of the whole lithic and biotic content. The juvenile materials are represented by aphyric and microite-bearing glass shards (Fig. 4c) and a minor component of porphyritic scoriae (Table 1). A larger compositional variability characterizes this deposit, which has a mugearitic, benmoreitic and trachytic composition. Trachytic points with SiO₂ concentration up to ca. 60 wt% are observed in aphyric glasses.

Tephra CP10/7 is characterized by a mugearitic population (a) with two glass fragments falling in the tephriphonolite field.

### Aeolian Arc related tephra

Glass shards of cryptotephra CP10/7 appear light in color and characterized by a plagioclase rich mineralogy under optical observation. They have a rholitic composition (b) with a high-K calc-alkaline (HKCA) affinity typical of Lipari deposits erupted during the Late Pleistocene–Holocene (Fig. 3d; Table 2). Cryptotephra C1/85b is a tephphonolite with shoshonitic (SHO) affinity (Fig. 3d; Table 2). Glasses are dark yellow and display a blocky morphology. Major element composition is fairly homogeneous: SiO₂ values range from 56.3 to 57.6 wt%, FeOtot from 5.8 to 6.3 wt%, CaO from 3.4 to 4.2 wt% and TiO₂ from 0.46 to 0.87 wt%. Volcanic products with such chemical composition have been erupted both by Stromboli and by Vulcano during the Holocene (Fig. 3b).

### Somma-Vesuvius, Ischia and Campi Flegrei related tephra

Tephra C14/89 is 15 cm thick and formed by a medium-grained ash lying on a sharp erosive basal contact. Towards the top of the deposit, laminated structures containing biotite and lithics can be observed and the glass fraction decreases significantly over the lithic, crystal and biotic portion. Chemically, a phonolitic composition (a) coexists with a trachyphonolitic one (b) (Fig. 3a); both are very homogeneous in terms of major oxide concentration (Table 2). The phonolitic shards are characterized by average SiO₂ values of ca. 54.7 wt%, Al₂O₃ of ca. 20.5 wt%, Na₂O of ca. 4.7 wt%, K₂O of 9.7 wt% and FeOtot of ca. 4.01 wt%. The trachyphonitic glass shards display average SiO₂ values of 62 wt%, CaO of ca. 4.7 wt%, Na₂O/K₂O = 0.85. According to these chemical features, the phonolitic and trachyphonolitic populations of tephra C14/89 can be related to the highly and mildly silica-undersaturated potassic series of rocks (Fig. 3a,b) erupted by Somma-Vesuvius and Ischia volcanoes, respectively, during the Holocene (e.g. Conticelli et al., 2010).

Cryptotephra C1/56 is a fine ash consisting of mostly light gray micromere. Leucite-bearing scoria and lithic fragments, obsidian, blocky glass shards and loose crystals also occur (Table 1). The glass fragments have a phonolitic composition (Fig. 3a; Table 2) with SiO₂ values ranging from 54.8 to 56.2 wt%, Al₂O₃ from 20 to 22.74 wt%, Na₂O from 5 to 7.37 wt% and CaO from 2.6 to 5.6 wt%. Lithological features (e.g. occurrence of leucite) and composition suggest a correlation of C1/56 with Somma–Vesuvius deposits.

The minor trachyphonolitic component (b) occurring in cryptotephra AP1/13 is characterized by an average SiO₂ value of 61.5 wt%, Al₂O₃ of ca. 18.46 wt% and K₂O/Na₂O = 1.77. These analyzed points display mildly
silica-undersaturated potassic compositions typical of Campi Flegrei products.

Age of tephra

AMS 14C dates from cores C1, AP1, UM42 and CP10 are reported in Table 3. They are consistent with the stratigraphic position of the picked samples. Cryptotephra occurring in core C1 from 80 to 90 cm bsf is chronologically constrained by an age of 3625 ± 96 cal aBP obtained from a 2 cm-thick sample immediately below the deposit. Tephra UM42/7 occurs ~1 cm below sample DD01317 located at (on average) 5.65 cm bsf and dated at 1797 ± 56 cal aBP. Because cosmogenic nuclide measurements indicate negligible loss of material from the core top (our unpublished data), the mean sedimentation rate (SR) for the stratigraphic interval can be estimated at ca. 3 cm ka⁻¹. Extrapolating this SR down in the section for the very first

Table 3. Summary of AMS 14C dates on planktonic foraminifera extracted from core samples.

| Core  | Sample | Lab no. | Sample type | Sampling depth from top of core (cm) | Depth of tephra from top of core (cm) | Radiocarbon age (a BP) | Calibrated age (cal aBP) |
|-------|--------|---------|-------------|-------------------------------------|--------------------------------------|------------------------|--------------------------|
| C1    | C1/90  | F4084   | Mixed planktonic foraminifera | 90–92                                | 80–90                                | 3702 ± 71              | 3625 ± 96                |
| AP1   | GG0123 | Poz-82785 | G. ruber     | 7–13                                | 6.5–7                                | 2260 ± 49              | 2176 ± 56                |
| AP1   | GG0130 | Poz-82765 | G. ruber     | 14–15                               | 8.5–9                                | 4570 ± 31              | 4477 ± 53                |
| UM42  | D001317| Poz-8625  | G. ruber     | 5.4–5.9                              | 6.7–7                                | 2202 ± 41              | 2197 ± 56                |
| CP10BC#25 + #26 | Poz-55177 | G. ruber and G. sacculifer  | 6.5–6.5                              | 8.9–9.5                              | 1890 ± 44              | 1880 ± 44                |
| CP10BC#37 + #38 | Poz-74801 | G. ruber and G. sacculifer  | 9–9.5                                | 9–9.5                                | 3075 ± 60              | 3075 ± 60                |

*From Wu et al. (2016).
few centimeters, we infer an age of ~2.2 cal ka for tephra UM42/7. The OxCal U_Sequence function (Bronk Ramsey, 2008) was used to obtain a linear interpolated age for cryptotephra AP1/13 and CP10/7 constrained above and below by two radiocarbon ages (Table 3). This procedure yielded an age of 4237 ± 44 cal a BP for AP1/13 and of 2187 ± 37 cal a BP for UM42/7. The estimated SRs for the stratigraphic intervals containing the two cryptotephra are ca. 3 and 2.5 cm ka⁻¹, respectively.

Discussion

Proximal counterparts and marine equivalents

The tephrostratigraphic results and AMS ¹⁴C ages are discussed for the studied deposits grouped according to their source vent. Most of the tephras and cryptotephra are correlated with age-dated volcanic events on land and/or with marine correlatives in the central Mediterranean. Cross-correlations reveal the occurrence of two main marker tephras, whereas other deposits have been recognized for the first time in the marine setting (Fig. 5).

Somma-Vesuvius, Ischia and Campi Flegrei

The phonolitic composition of C14/89a and C1/56 indicates Somma-Vesuvius as the source volcano and Pompeii 79 AD (Sigurdsson et al., 1985) as the source eruption (Figs 3 and 6). This event is widely recognized in areas adjacent to the C14 core site in the Pozzuoli Bay (Sacchi et al., 2014) and to the C1 core site offshore Capo Vaticano (Cosentino et al., 2017) (Fig. 1). The lithology of tephra C14/89 in core C14 is distinctive of Pompeii deposits in the Naples and Pozzuoli bays. Sedimentological features include a significant thickness, an erosive bottom surface and parallel laminations, which suggest possible syneruptive reworking (Sacchi et al., 2005; Insinga et al., 2008). The correlation of cryptotephra C1/56 with Pompeii products is supported by its stratigraphic position in the C1 record above tephra unit C1/90-82 (ca. 3.6 cal ka BP; Table 1). According to the FeOtot versus CaO diagram (Fig. 6a), a continuous compositional variation trend from 79 AD gray to white pumice is observed in C1/56, whereas other distal equivalents display a single and/or two-fold clusters. This includes C14/89a glass shards which display the gray pumice composition, and cryptotephra ND14_Q/79 from the southern Adriatic that is characterized by the white pumice chemistry (Figs 1, 6).

The Ischia glass population of tephra C14/89b matches well with Cretaio deposits (Orsi et al., 1992) (Fig. 3a), widely dispersed offshore of the island (De Alteriis et al., 2010). A number of radiocarbon datings from terrestrial and marine setting locate this event between 85 BC and 423 AD (Table S2). However, this large interval can be reasonably limited to the 1st century AD according to stratigraphic evidence from the marine settings, i.e. the amalgamation of Cretaio and Pompeii deposits observed in Pozzuoli Bay (Sacchi et al., 2014) and in the southern Tyrrhenian (CET1 core site; Morabito et al., 2014) (Figs 3 and 6).

The Campi Flegrei cryptotephra AP1/13b (4237 ± 44 cal a BP) can be correlated with the intense activity that occurred during the Late Holocene and produced mostly trachyphonolitic
products. Their homogeneous composition in terms of major elements makes discrimination very difficult (Smith et al., 2011). This is particularly true for the Agnano Mt Spina and Astroni eruptions (AAMS group) reported between ca. 4.4 and 4.6 cal ka BP and between ca. 4.1 and 4.3 cal ka BP at proximal sites, respectively (Smith et al., 2011). In the marine setting, robust ages of $4166 \pm 114$ cal a BP for Astroni tephra and $4422 \pm 58$ cal a BP for Agnano Mt Spina tephra are provided by radiocarbon dating.
dating and age–depth modeling (Siani et al., 2004; Lirer et al., 2013) (Table S2). Distal products of the AAMS group may occur either as multiple layers or amalgamated within one or more horizons (Siani et al., 2004; Crocki et al., 2018). Although a discrimination criterion based on major element chemistry has been proposed (Margaritelli et al., 2016), the very low amount of glass shards found in the deposit hampers any robust statistical analysis and hence we prefer to maintain a generic attribution of AP1/13b to the AAMS group.

**Lipari**

Two HKCA rhyolitic glass shards occur in CP10/7b dated at 2187 ± 37 cal a BP. Distal cryptotephra with such a rhyolitic composition and a similar age have been found in cores KET80-03 (Paterne et al., 1988) and TEA C6 (Di Donato et al., 2019) in the southern Tyrrenian Sea and in the Gulf of Taranto, respectively (Fig. 5). In detail, a main Lipari rhyolitic population occurs at the top of core KET and it coexists with Aeolian tephrphonolites (Fig. 3a) dated at ca. 1.7 ka based on sapropel chronology and isotope stratigraphy. In core TEA C6, cryptotephra C6/122 occurs immediately below the 79 AD tephra (C6/119) and it includes HKCA rhyolites with few reworked Pompeii micropumice (Fig. 3a) dated at 1.97 cal ka BP according to an age–depth model age constrained by tephrorchronology and AMS 14C dates. The proximal–distal correlation of this widespread deposit is hampered by the chronostratigraphy because no volcanic event is reported on the island at ca. 2 ka (e.g. Forni et al., 2013).

**Vulcano**

According to the TAS and binary diagrams (Figs 3, 6), we suggest a correlation of the tephrphonolitic (SHO) C1/85b with activity at Vulcano Island. This is supported by the TiO2 and Na2O concentration of Vulcano deposits, which display slightly different composition with respect to Stromboli shoshonitic products (Albert et al., 2017). Tephra TIR2000-50 in the Marsili Basin (Di Roberto et al., 2008; Albert et al., 2012) is likely to be the marine equivalent of C1/85b (Figs 5 and 6). It occurs in core TIR2000-C01 stratigraphically below the Avellino–Pompeii (AP) interplinian deposits erupted at Somma–Vesuvius with age generally reported between 2.8 and 3.6 ka (Di Roberto et al., 2008). The proximal–distal correlation of TIR2000-50 was discussed by Albert et al. (2012, 2017) but remained unresolved. Although a perfect chemical match can be observed between C1/85b and TIR2000-50 with ‘Palizzi A’ products emplaced at Vulcano at ca. 2 ka (Voltaggio et al., 1995) (Fig. 6b,c), this correlation contrasts with the age of 3625 ± 96 cal a BP obtained just below our cryptotephra. Considering older activity on the island, a possible correlation with the Tufi di Grotte dei Rossi deposits at distal sites (Fig. 6d) indicates a homogeneous mugearitic composition of FG tephra close to that of C1/85a (Figs 3, 6). Considering these observations along with the significant thickness in core C1, we infer that our cryptotephra may include the whole FL event. It was a long-lasting eruption, probably older than ca. 3.3 cal ka BP, characterized by significant chemical variability and different dispersal of products. However, further comparisons with proximal deposits and datings are required to verify this working hypothesis.

According to the age of ca. 2.2 cal ka BP, tephra UM42/7 may be regarded as the distal counterpart of tephra FG dated between 380 bc and 120 AD and ascribed to the historical 122 BC Plinian event (Coltelli et al., 1998) (Table S2). Eruptive products were dispersed mainly towards the south-east and marine findings are reported in Augusta Bay (De Martini et al., 2010; Smedile et al., 2011) and Malta Plateau (Micale et al., 2016) (see Fig. 8). Proximal and medial–distal glass data indicate a homogeneous mugearitic composition of FG tephra (Fig. 3a), whereas at the UM42 site the deposit reveals a wider chemical variability, which characterizes also other Etnean deposits at distal sites (Fig. 6d). For now, we suggest UM42/7 as the reference distal tephra of FG deposits for future correlations and further geochronological studies.

**Mt Etna**

During the last 4 ka, intense volcanism at Etna has produced a large number of tephras (Coltelli et al., 2000). Among these are regional marker beds documented on land in the ca. 4.3–2.0 ka time span and known as tephras FS, FL, FG and FF (Coltelli et al., 1998, 2000, 2005). Tephra FL and FG are reported at medial–distal sites in both marine and terrestrial settings, whereas no records have yet been documented for the other deposits outside the perivolcanic area. The attribution of distal deposits to tephras FL and FG relies mostly on their overall Etnean compositional affinity and age constraints. This is mostly due to the insufficiency of data available on these proximal deposits in terms of single glass shard chemistry. This paucity reflects the difficulties when comparing different datasets (generally bulk versus single glass analysis) to establish proximal–distal correlations and recognize the eruptive event (Insinga et al., 2014). Moreover, the microilite-rich groundmass and the rare interstitial glass, which are typical features of these Etnean deposits (Coltelli et al., 2000), make their chemical characterization a difficult task even at proximal sites. Our results are focused on more comprehensive single glass chemistry and dispersal in offshore areas and, in this context, they provide a new contribution towards a better understanding of these Late–Holocene Etnean deposits.

The benmoreitic cryptotephras AP1/13a represents the oldest Etnean deposit of this study. According to the age of 4237 ± 44 cal a BP and an Sr value of 3 cm ka−1 for the analyzed stratigraphic interval, the studied deposit can probably be correlated with the FS subplinian eruption dated at 4360 ± 92 cal a BP on land (Coltelli et al., 2000, 2005).

The compositional field shown by subsamples of cryptotephra dispersed in the interval 90–80 cm bsf in core C1 (Figs 3, 6) and the age result of 3625 ± 96 cal a BP immediately below suggest a correlation of the deposit with the FL event, a complex phreatomagmatic eruption dated on land at 3361 ± 76 cal a BP (Coltelli et al., 2000). At distal sites, the FL fall products display large chemical variability and may coexist with the AP deposits (Pepe et al., 2018; Di Donato et al., 2019) (Figs 5, 6). At Lago di Pergusa, south-east of Mt Etna (Fig. 1), where FL distal tephra was recognized for the first time and dated at ca. 3.3 cal ka BP (Sadori and Narcisi, 2001), single glass shards, instead, display a mugearitic composition close to that of C1/85a (Figs 3, 6). Considering these observations along with the significant thickness in core C1, we infer that our cryptotephra may include the whole FL event. It was a long-lasting eruption, probably older than ca. 3.3 cal ka BP, characterized by significant chemical variability and different dispersal of products. However, further comparisons with proximal deposits and datings are required to verify this working hypothesis.

According to the age of ca. 2.2 cal ka BP, tephra UM42/7 may be regarded as the distal counterpart of tephra FG dated between 380 bc and 120 AD and ascribed to the historical 122 BC Plinian event (Coltelli et al., 1998) (Table S2). Eruptive products were dispersed mainly towards the south-east and marine findings are reported in Augusta Bay (De Martini et al., 2010; Smedile et al., 2011) and Malta Plateau (Micale et al., 2016) (see Fig. 8). Proximal and medial–distal glass data indicate a homogeneous mugearitic composition of FG tephra (Fig. 3a), whereas at the UM42 site the deposit reveals a wider chemical variability, which characterizes also other Etnean deposits at distal sites (Fig. 6d). For now, we suggest UM42/7 as the reference distal tephra of FG deposits for future correlations and further geochronological studies.

Considering the comparable age and the mugearitic composition (Figs 3, 6) along with the low SrS of cores CP10 and UM42 for the investigated time interval (2.5 and 3 cm ka−1, respectively), a correlation of cryptotephras CP10/7 with UM42/7 and therefore with FG tephra is likely. This inference is also supported by the dispersal direction and volume of the 122 BC tephra, which is much higher than that of the almost coeval 44 bc tephra (Coltelli et al., 2000).
Tephra occurrences in the central Mediterranean Sea during the 4.2–2.0 ka time interval

Tephra correlation and dating results from this study have been included in the WdB-Paleo database in order to draw maps showing the occurrences of marker and minor tephra and newly discovered deposits in the central Mediterranean Sea (Figs 7,8). Moreover, other major tephra, erupted during the investigated time interval but not occurring in our cores, have also been considered and mapped to provide a general overview of their distribution (Fig. 7). These are namely the Somma-Vesuvius related Avellino (3945 ± 10 cal a BP; Sevink et al., 2011) and AP1–6 (ca. 2.8–3.6 cal ka BP; Santacroce et al., 2008 and references therein) tephra, which represent important correlation tools given their significant areal distribution over southern Italy and surrounding seas (Fig. 7). If there is a general consensus on the proximal–distal correlation of the Avellino tephra across the basin, large uncertainty remains when attempting discrimination among the six AP events. This is probably due to their often overlapping chemical composition and insufficient chronological constraints, particularly concerning the AP3–6 eruptive units, commonly reported as younger than ca. 2.8 cal ka BP according to a single radiocarbon age (Table S2). However, recent results from the marine setting point to an aging of the AP3–6 cluster as suggested by age–depth models (Sacchi et al., 2009; Lirer et al., 2013) (Table S2) and the finding of these deposits in association with FL tephra at distal sites (Pepe et al., 2018; Di Donato et al., 2019). According to these considerations, an age interval of ca. 3.6–3.4 cal ka BP for the AP eruptive sequence can be regarded as a working hypothesis to be further developed.

The maps obtained from the WdB-Paleo database provide a contribution to previous studies having implications for ash dispersal hazards related to both major and minor explosive

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**Figure 7.** Occurrences of major marker tephra in the Tyrrhenian, Adriatic and Ionian seas according to the results obtained here and integrated with those of the WdB-Paleo database. A number of terrestrial sites have been also included for AP, Avellino and AAMS deposits (Crocitti et al., 2018 and references therein). The two further Avellino tephra in the Ionian Sea from the WdB-Paleo in addition to the south-east and north-west occurrences reported in Sulpizio et al. (2008, 2014) and Crocitti et al. (2018) allowed us to expand the southward dispersal of these products. Gray circles: core network investigated in this work; red full circles: study sites; colored circles: occurrence of the marker tephra in the core network; red stars: source vents; °: marine age. °° from Coltelli et al. (2000); °°° from Sevink et al. (2011); ^ from Lirer et al. (2013) for Agrano Monte Spina. ^^ from Smith et al. (2011) for Astroni. For core references see Fig. 1. [Color figure can be viewed at wileyonlinelibrary.com] [Correction added on 13th November 2019, after first online publication: Figure 7 has been replaced with new version of Figure.]
events from Italian volcanoes (e.g. Sulpizio et al., 2014; Crocitti et al., 2018).

All the new occurrences of major 79 AD, FL and the AAMS group tephra are well within their dispersal area (Fig. 7). The recent recovery of 79 AD deposits in the southern Adriatic, in particular, extends their dispersal eastward, thus providing a key correlation marker for the three marine basins (Jalali et al., 2018). Recognition of the FL tephra offshore Capo Vaticano represents its first finding in the southern Tyrrhenian. Accord-

ingly, core C1 can be regarded as the most complete marine record where this long-lasting eruption can be observed in its distal facies. Notwithstanding the small amount of glass shards, recognition of the AAMS group at the AP1 site is also of great interest, as it allows us to extend to the south-east (i.e. towards the northern Ionian Sea) the dispersal of these products, which are recorded in many Adriatic sequences.

The new finding in the Bay of Naples of Cretaio tephra allows us to expand the distribution of this deposit towards...
the east, a deposit that occurs significantly along the Campania margin, thus assuming a ‘local’ stratigraphic relevance (Fig. 8). The same can be ascribed to the uncorrelated Vulcano tephra found between the Marsili Basin and Capo Vaticano offshore. The Lipari tephra has a striking regional significance, as it occurs in all the three marine areas surrounding the Italian Peninsula and it is well age-constrained in the Taranto Bay and at the CP10 site. Finally, AP1, UM42 and CP10 represent marine records where the Late Holocene FS and FG tephras occur. These site locations agree with ash dispersal towards the east and south-east (Coltelli et al., 1998, 2005), respectively. In detail, cryptotephra AP1/13 is the first occurrence in the marine setting of FS deposits, whereas UM42 and CP10 represent the more distal findings of FG tephra, which can be definitely regarded as a regional stratigraphic marker.

Isochrons

The availability of continuous isochronous markers over wide areas of the central and western Mediterranean provides a means to verify the correlation of short- and long-term climate oscillations between terrestrial and marine systems, enabling us to better understand the local–regional effects of climate change and the connections among different depositional environments (e.g. Margaritelli et al., 2018). This integrated approach also represents a tool to match the possible interaction between climate changes and modifications made by human societies and their adaptive strategies during the last millennia (e.g. Büntgen et al., 2011; Holmgren et al., 2016 and references therein). These are issues of great relevance for the study of the 4.4–2.0 ka time interval characterized by abrupt climatic changes (e.g. the 4.2 ka event; Bini et al., 2019), increasing human activities and, at the same time, recurrent explosive eruptions from different sources that produced widely dispersed tephra. Some of them, such as Agnano Monte Spina, Avellino and FL, have a relevant climatostratigraphic position in Bronze Age (ca. 4.2–2.9 cal ka BP; Zanchetta et al., 2019 and references therein) archives of the central Mediterranean. In this context, our work provides a number of isochronous stratigraphic horizons that have been traced according to our new results integrated with the WdB-Paleo database for the study area (Fig. 9).

The isochron corresponding to the 79 AD event crosses southern Italy and surrounding seas and, at some sites in the southern Tyrrhenian, it locally extends to the Cretaio tephra (1st century AD). This distinctive time horizon is immediately followed by the newly reported horizon, which covers the
2187 ± 37 cal a BP to ca. 1.97k cal a BP time interval linking archives in the southern Tyrrhenian, Gulf of Taranto and southwestern Ionian. It is targeted by the Lipari tephra at all sites and by a very well expressed FG tephra in the Ionian (Figs 5, 8 and 9). The ca. 3.6–3.3 ka time interval can be traced in the whole area and targeted mostly by the AP deposits, locally also by the FL (southern Tyrrhenian and Gulf of Taranto) and the undefined tephra from Vulcano (southern Tyrrhenian). Limitations in the use of this isochron may arise, however, from the chronological ambiguities previously described, and which can be resolved only by further investigations at proximal sites and by critical revision of the data at distal sites for the AP deposits. Similar considerations can be made for the 4422 ± 58 to 4237 ± 44 cal a BP time span targeted by the AAMS group in the southern Tyrrhenian and Adriatic seas, in the Balkans and for the first time in the northern Ionian Sea where the Etna FS tephra also occurs. Critical revision of distal tephra correlations, made according to the updated single glass database, might in fact allow us to discriminate the single event from Campi Flegrei within the AAMS group, thus providing a narrower time interval for the study area.

Concluding remarks

The results presented in this work provide new insights into the chronology and distribution of tephra and cryptotephras in the central Mediterranean during the ca. 4.4–2.0 ka time interval. The analyzed tephras comprised both markers associated with well-known, widespread Plinian events, and other deposits, characterized by narrower areal distributions or documented for the first time in the marine setting. These products have been characterized in detail, mapped and integrated with an existing database to produce a high-resolution tephrostratigraphic framework for the basin. A further outcome was the definition of five isochrons, which have the potential to correlate and synchronize paleoclimate archives. Further research developments to improve the stratigraphic framework presented in this study will probably require enhanced analysis of fine-grained cryptotephras and the resolution of chronological discrepancies for selected Late Holocene volcanic events of the central Mediterranean region.

Supporting information

Additional supporting information may be found in the online version of this article at the publisher’s web-site.

Table S1. Results of the analytical routine of secondarystandards

Table S2. Selected chronological data at both proximaland distal sites

Figure S1. Photographs at the optical microscope of the studied deposits

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Abbreviations. AAMS, Aegna Mt Spina and Astroni eruptions; AMS, accelerator mass spectrometry; AP, Avellino–Pompei; bsd, below sea floor; bsd, below sea level; HKCA, high-K calc-alkaline; SEM-EDS, scanning electron microscopy/energy-dispersive spectrometry; SHO, shoshonitic; SR, sedimentation rate; TAS, total alkali–silica.

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