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1 Evidence for a large magnitude eruption from Campi Flegrei caldera (Italy) at 29 ka

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16 ABSTRACT

17 The 40 ka caldera-forming eruption of Campi Flegrei (Italy) is the largest known eruption in
18 Europe during the last 200 kyr, but little is known about other large eruptions at the volcano
19 prior to a more recent caldera-forming event at 15 ka. At 29 ka a widespread volcanic ash
20 layer, termed the Y-3 tephra, covered >150,000 km² of the Mediterranean. The glass
21 compositions of the layer are consistent with Campi Flegrei being the source but no
22 prominent proximal equivalent in the appropriate chrono-stratigraphic position had been
23 previously identified. Here we report new glass chemistry data and ⁴⁰Ar/³⁹Ar ages (29.3 ± 0.7
24 ka [2σ]) that reveal the near-source Y-3 eruption deposit in a sequence at Ponti Rossi and a
25 nearby borehole (S-19) in Naples. The dispersal and thickness of the deposits associated
26 with this eruption, herein named the Masseria del Monte Tuff, were simulated using a tephra
27 sedimentation model. The model indicates that ~16 km³ DRE (dense rock equivalent) of the
28 magma erupted was deposited as fall. This volume and the areal distribution suggest the
29 Masseria del Monte Tuff was a magnitude 6.6 eruption (corresponding to VEI 6), similar to
30 the 15 ka caldera-forming Neapolitan Yellow Tuff (M6.8) eruption at Campi Flegrei.
31 However, the lack of coarse, thick, traceable, near-vent deposit suggests peculiar eruption
32 dynamics. Our reconstruction and modelling of the eruption show the fundamental role that
33 distal tephrostratigraphy can play in constraining the scale and tempo of past activity,
34 especially at highly productive volcanoes.

35 INTRODUCTION

36 Near-vent volcanic successions often provide fragmentary records of past explosive
37 volcanism due to the intense volcano-tectonic and syn-eruptive sedimentary processes they
38 experience. This means they are not always representative of the full range in scale and
39 tempo of past activity. Statistical analysis of existing eruptive databases verifies under-
40 recording, including large magnitude eruptions (Kiyosugi et al., 2015), which is problematic
41 for hazard assessments. Fortunately, explosive eruption deposits are recorded as ash
42 (tephra) layers in sedimentary records. In the Mediterranean region the distal
43 tephrostratigraphic record has been widely used as a key tool for studying past volcanism,

44 reconstructing long-term eruption histories and constraining the tempo and dynamics of
45 explosive eruptions (e.g., Paterne et al., 1988; Wulf et al., 2004).

46 Although some of the most widespread Mediterranean ash layers are correlated to near-
47 source deposits, e.g., the Y-5 marine tephra linked to the Campanian Ignimbrite (CI)
48 eruption of Campi Flegrei caldera (CFc) at 40 ka (e.g., Giaccio et al., 2017), many other
49 widely dispersed tephra do not have counterparts near source. One of the most widespread
50 layers not confidently correlated to a particular eruption deposit is the Y-3 tephra. This last-
51 glacial tephra layer was first reported in the sediments of the Ionian Sea (Keller et al., 1978),
52 and has been traced across the Mediterranean (**Fig. 1A; Table S1**). A precise age of
53 28,690-29,420 cal yrs BP was obtained for the Y-3 in the Tenaghi Philippon peat sequence,
54 Greece (Albert et al., 2015). The glass compositions of the Y-3 tephra are consistent with
55 CFc, but within the so-called 'Tufi Biancastri' (TB) succession (Orsi et al., 1996; Tomlinson
56 et al., 2012) – encompassing all the eruption deposits between the ~15 ka Neapolitan Yellow
57 Tuff (NYT; Deino et al., 2004) and CI (**Fig. 1B**). No deposit with the full range of
58 compositions (phono-trachytic to trachytic) diagnostic of the distal layer had been found at
59 source (see Albert et al., 2015). Here we report the characteristics of a mid-proximal TB
60 deposit that correlates with the Y-3 distal layer, and helps verify the eruption was a large
61 magnitude event.

62 **PROXIMAL STRATIGRAPHY AND CHEMICAL COMPOSITIONS OF THE DEPOSITS**

63 The distal Y-3 tephra has two volcanic glass compositional end-members, higher-SiO₂
64 trachytic (Component 1) and lower-SiO₂ phono-trachytic (Component 2) glasses, with the
65 phono-trachytic glasses being particularly distinctive. Chemical analyses (methods see Data
66 Repository 1) of TB units identified in a borehole (S-19) and an outcrop at Ponti Rossi (PR;
67 **Fig. S1**), northeast of CFc in central Naples, show the two compositional end-members are
68 consistent with the distal tephra (**Fig. 2; Table S2**).

69 The S-19 TB sequence is 14 meters thick with 6 primary tephra units that range from a few
70 cm to 3.4 m in thickness. The thickest unit is the third above the CI, found at 25.90-22.50 m
71 (3.40 m thick) and it presents the glass compositions of the distal Y-3 tephra (**Fig. 2**). The
72 TB sequence at PR has eight eruption units separated by eruption hiatuses marked by soil
73 formation (paleosols; Fig. 2). Similarly, the thickest unit in the TB succession at PR (90 cm),
74 the fourth unit (CF131/132) above the CI, chemically corresponds to the distal Y-3 tephra
75 (**Fig. 2; Fig. S2**).

76 The features of the S-19 drill core (25.9-22.50 m) and PR (CF131-132) units are similar.
77 Both are characterised by a lower sub-unit of fall containing a bed of moderately sorted
78 pumice lapilli (5-10 cm thick), and an upper sub-unit (up to 3.30 m thick in S-19) of poorly-
79 sorted ash-dominated pyroclastic density current (PDC) deposits. The PDC sub-unit
80 contains abundant, distinctively large (up to 3 cm diameter) accretionary lapilli which are
81 exclusive to these TB units. The main difference between the two localities is the thickness;
82 the PDC sub-unit of S-19 is considerably thicker than at PR (50cm), either reflecting
83 paleotopography or post-depositional erosion. Detailed descriptions of the S-19/PR tephra
84 successions are provided in Data Repository 1.

85 The compositional glass data for the PR (samples CF131 and CF132) and S-19 (samples
86 25.8m and 22.9m) units verify their lithostratigraphic correlation. They are the only TB

87 eruption deposits to contain three compositional groupings (**Fig. 2A**). The Component 1
88 glasses are high-SiO₂ (~61.6-62.4 wt.%) trachytic glasses with ~8.3-8.7 wt.% K₂O (**Fig. 2A**),
89 they are enriched in incompatible trace elements (e.g., ~30-33 ppm Th), and match the
90 trachytic end-member of the distal Y-3 (**Fig. 2**). Component 2 glasses are lower in SiO₂
91 (~59.8-60.6 wt.%), have higher K₂O contents (~9.7-10.3 wt.%; **Fig. 2**), and lower levels
92 incompatible trace element enrichment (e.g., ~14-15 ppm Th) - consistent with the distinctive
93 phono-trachytic end-member of the Y-3 tephra (**Fig. 2**).

94 The third, less abundant and more chemical variable component, are lower SiO₂ trachytic
95 glasses (~57.6-60.8 wt.%) and show the lowest K₂O contents (~7.9-8.3 wt.%; **Fig. 2**)
96 observed in the investigated deposits.. The Component 3 glasses are not observed in the
97 upper portion of the thicker S-19 borehole (25.8-22.50 m) unit, or the widespread Y-3 tephra,
98 this implies the widespread ash dispersal is not associated with the earliest phase of the
99 eruption.

100 ⁴⁰Ar/³⁹Ar GEOCHRONOLOGY

101 Sanidine crystals from three near-source pyroclastic samples stratigraphically and
102 chemically related to the distal Y-3 were dated using ⁴⁰Ar/³⁹Ar methods at the Laboratoire
103 des Science du Climat et de l'Environnement (LSCE), France (sample 22.9m - top of the S-19
104 borehole unit) and at the Berkeley Geochronology Centre (BGC), USA (sample 25.8m -
105 base of the S-19 unit; sample CF132 upper portion of the PR unit). Weighted mean ages are
106 calibrated to the age of the Alder Creek Sanidine (ACs) = 1.1891 ± 0.0008 Ma (1σ, Niespolo
107 et al., 2017) and calculated using the decay constants of Renne et al. (2011). Analytical
108 methods and instrumentation used are fully outlined in the Data Repository 1, along with
109 probability diagrams (**Fig. S3-7**), and *R*-values (**Table S3**). The ⁴⁰Ar/³⁹Ar weighted mean
110 ages are presented in a summary age probability diagram at 2σ uncertainty (**Fig. 3**).

111 The ages of individual crystals analysed from the S-19 22.9 m sample show a bimodal
112 distribution with a dominant younger population (~29 ka) and an older population at ~40 ka
113 (**Fig. 3**). The ⁴⁰Ar/³⁹Ar weighted mean age determined for this upper portion of the eruption
114 deposit is 29.0 ± 0.8 ka [2σ] (MSWD=0.4, P=1, n=18). The older crystals cluster about the
115 age of the CI eruption (40 ka) and are considered xenocrysts from parts of the crystallised
116 magmatic system or deposits of the CI. The whole 2 sigma age range of the CI xenocrysts
117 identified in the S-19 22.9 m sample are used, in conjunction with the stratigraphic position
118 of all correlated samples above the CI, as a basis to exclude CI xenocrysts from the
119 remaining analyses.

120 The exclusion of CI xenocrysts produces a ⁴⁰Ar/³⁹Ar weighted mean age of 28.4 ± 2.1
121 (MSWD=0.52, P=1, n=44) for the 25.8m basal sample of the borehole unit. The combined
122 ⁴⁰Ar/³⁹Ar weighted mean age for the S-19 25.9-22.5m (samples 25.8m and 22.9m) eruption
123 deposit is 29.0 ± 0.8 ka. The CI xenocrysts excluded ⁴⁰Ar/³⁹Ar age determinations for the PR
124 deposit (sample CF132), are 31.6 ± 2.8 (MSWD=0.33, P=1, n=23) using Nexus, and 31.3 ±
125 2.6 (MSWD=0.15, P=1, n=44) from Noblesse, these ages are statistically indistinguishable
126 from one another. The combined ⁴⁰Ar/³⁹Ar weighted mean age for the PR eruption deposit
127 (CF131/132) is 31.4 ± 1.9 ka.

128 The S-19 and PR ⁴⁰Ar/³⁹Ar ages are statistically indistinguishable at the 95.4% confidence
129 level and can be combined to provide a ⁴⁰Ar/³⁹Ar weighted mean age of 29.3 ± 0.7 ka

130 (MSWD=0.5, P=1, n=96) for the eruption deposit, which perfectly overlap with radiocarbon
131 age determinations for the distal Y-3 tephra (**Fig. 3**), verifying the stratigraphic and chemical
132 correlations.

133 **ASSESSING THE ASH DISPERSAL AND PDC VOLUMES**

134 The ash dispersal was simulated using a semi-analytical dispersal model HAZMAP
135 (Macedonio et al., 2005). Integrating near-source and distal (Y-3) tephra fall deposit
136 thicknesses (**Table S1**) within a HAZMAP model allows us to constrain the eruption
137 parameters (**Table S4**; Costa et al., 2009). Some reported Y-3 localities could not be used
138 because either layer thicknesses are not reported, or they are likely inflated due to the
139 depositional setting (e.g. marine canyons).

140 The modelled dispersal pattern for the Y-3 tephra (**Fig. 1A**) reproduced the recorded
141 thicknesses within an order of magnitude, with all but one of the modelled thickness values
142 being between 1/3 and 3 times the observed thickness at each locality (**Fig. S8**). The
143 limitations of this modelling approach are outlined in Matthews et al. (2012), and the
144 uncertainties are large due to the lack of data and assumptions (e.g. deposit density does
145 not change over the area, assumed bulk granulometry). However, these results place
146 constraints on the order of magnitude of the eruption, revealing that the fall comprised ~16
147 km³ DRE (assuming a rock density of 2350 kg/m³) of ejected magma, from a column that
148 reached ~59 km high. The volume of the near-source PDC was estimated at a minimum of
149 ~1 km³ DRE using the Delaunay Triangulation method of Macedonio and Pareschi, (1991),
150 which is suitable for reconstructing the volume of geological horizons where the thickness
151 values are irregularly-spaced (**Table S1**). Combining the HAZMAP fall volume with that of
152 the PDC indicates that the total volume of the eruption would be ~17 km³ DRE, which
153 equates to a VEI 6 (after Newhall and Self, 1982) or at least a magnitude 6 eruption (M6.6,
154 following Pyle, 2000).

155 **THE MASSERIA DEL MONTE TUFF ERUPTION DYNAMICS AND HAZARDS AT CFc**

156 The modelled eruption parameters (**Table S4**) would imply that the herein named Masseria
157 del Monte Tuff (named after the most proximal TB succession), responsible for the Y-3
158 tephra, is similar in magnitude and more widely dispersed as a visible fall deposit than the
159 younger NYT (**Fig.1A**) caldera-forming eruption (recalculated to ~25 km³ DRE; following
160 Deino et al., 2004) of CFc. Given the amount of magma erupted during the Masseria del
161 Monte Tuff it is likely to have generated a caldera. The lack of physical evidence implies that
162 if one was generated, it must have been within the collapse structure of the younger NYT.

163 Although the Masseria del Monte Tuff and NYT eruptions were a similar order of magnitude,
164 there is a stark contrast between their PDC deposits. At similar distances from the caldera
165 wall, the PDC deposits of the eruption are thin (~ 3.3 m) relative to the ~16 m thick deposits
166 of the NYT. Consequently, it seems likely that the eruption mechanisms of these two large
167 magnitude events were very different; however, due to the limited near-source exposures of
168 the Masseria del Monte Tuff we must use the distal ash fall and ash dispersal modelling to
169 gain a better understanding of the eruption mechanisms.

170 Given the estimated magnitude of the eruption, the area covered by the Y-3 tephra is
171 somewhat restricted, illustrated by its absence in the eastern Mediterranean marine records
172 (**Fig. 1**), this suggests efficient aggregation of fine ash. This premature fallout of the finest

173 material, coupled with the high density of the aggregates (modelled to be 1000 kg/m^3) and
174 the presence of large accretionary lapilli in proximal outcrops is consistent with the presence
175 of liquid water in the plume (Mastin et al., 2016). The modelled column height and the
176 effective diffusion (accounting for the effects of both atmosphere and volcanic plume
177 turbulence) of $\sim 7 \times 10^4 \text{ m}^2/\text{s}$ both imply a large mass flow rate (Costa et al., 2013; 2018),
178 which is consistent with a co-ignimbrite plume in the incipient collapsing regime (estimated
179 between 10^9 and 10^{10} kg/s by Costa et al., 2018). These plumes are transitional between a
180 Plinian and co-ignimbrite column and can extend up to 60 km (cf. Costa et al., 2018). The
181 modelled results are consistent with the lack of a prominent coarse-grain deposit close to the
182 vent, which suggest an unstable eruption column intermittently generating PDCs. The
183 absence of one of the glass populations in the upper portion of the near-source deposits and
184 in the distal Y-3 implies that the widely dispersed ash was largely associated with a co-
185 ignimbrite plume generated by late PDC phase/s. Similarly, the co-ignimbrite plume
186 significantly contributed to the enormous CI ash dispersal across the eastern Mediterranean
187 (Smith et al., 2016). From a hazard perspective, recognition of a large magnitude eruption
188 between the CI (40 ka) and NYT (15 ka) eruptions, drastically reduces the reoccurrence
189 interval of large magnitude events at CFc. With the Masseria del Monte eruption dated at 29
190 ka, the time elapsed between large magnitude eruptions ($\geq M6/VEI 6$) at this densely
191 populated volcano is halved to ~ 12.5 kyr.

192 CONCLUSIONS

193 The Masseria del Monte Tuff erupted at CFc is dated at $29.3 \pm 0.7 \text{ ka}$ [2σ] and was a large
194 magnitude ($M6.6$ or $VEI 6$) event that erupted around $\sim 17 \text{ km}^3$ (DRE) of magma based
195 largely on the distal ash fall covering an area $>150,000 \text{ km}^2$. Reconstructed eruption
196 parameters using the HAZMAP model suggest the deposits are consistent with dispersal
197 from a co-ignimbrite plume in the incipient collapsing regime. The recognition of such a
198 large-magnitude event, only 29 ka ago, illustrates that the near-source record of volcanism
199 at one of the most productive volcanoes in Europe is not fully representative. It also
200 highlights that by integrating distal and near-source records and using ash dispersal models
201 it is possible to better constrain the magnitude, eruptive mechanisms and tempo of
202 volcanism. This is particularly pertinent at volcanoes that commonly experience caldera
203 collapse and the deposition of thick pyroclastic successions, which make the record of past
204 activity hard to access.

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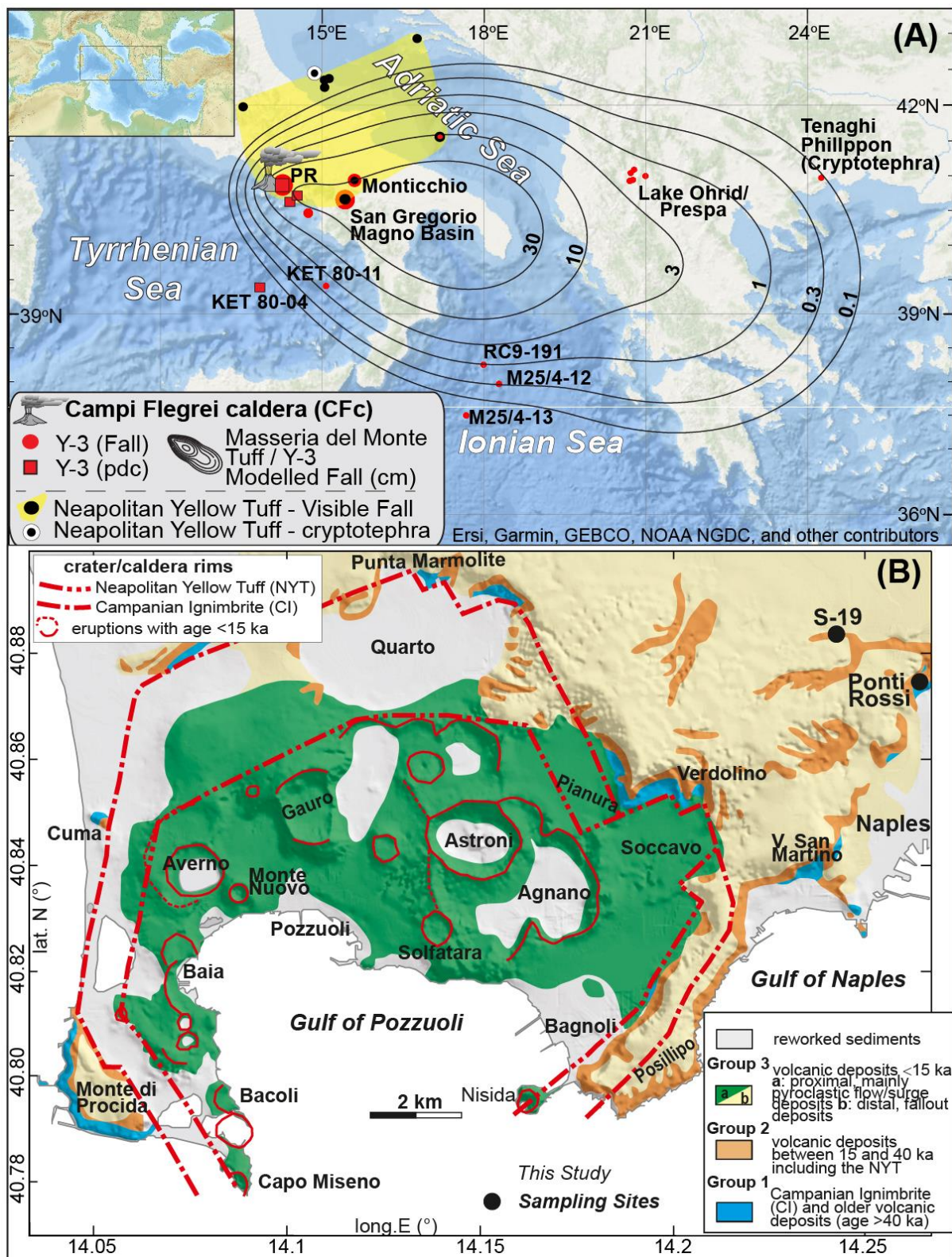
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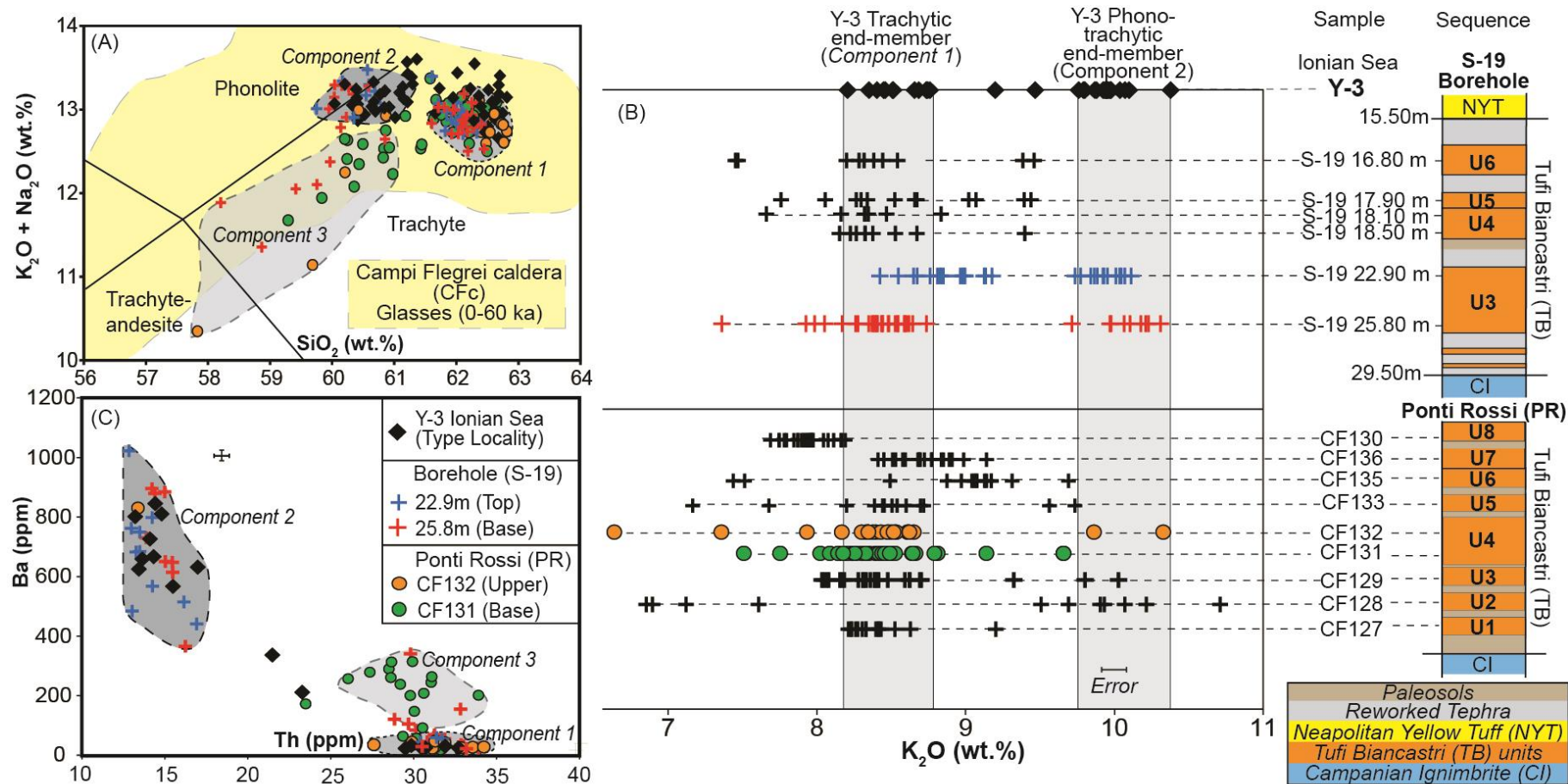
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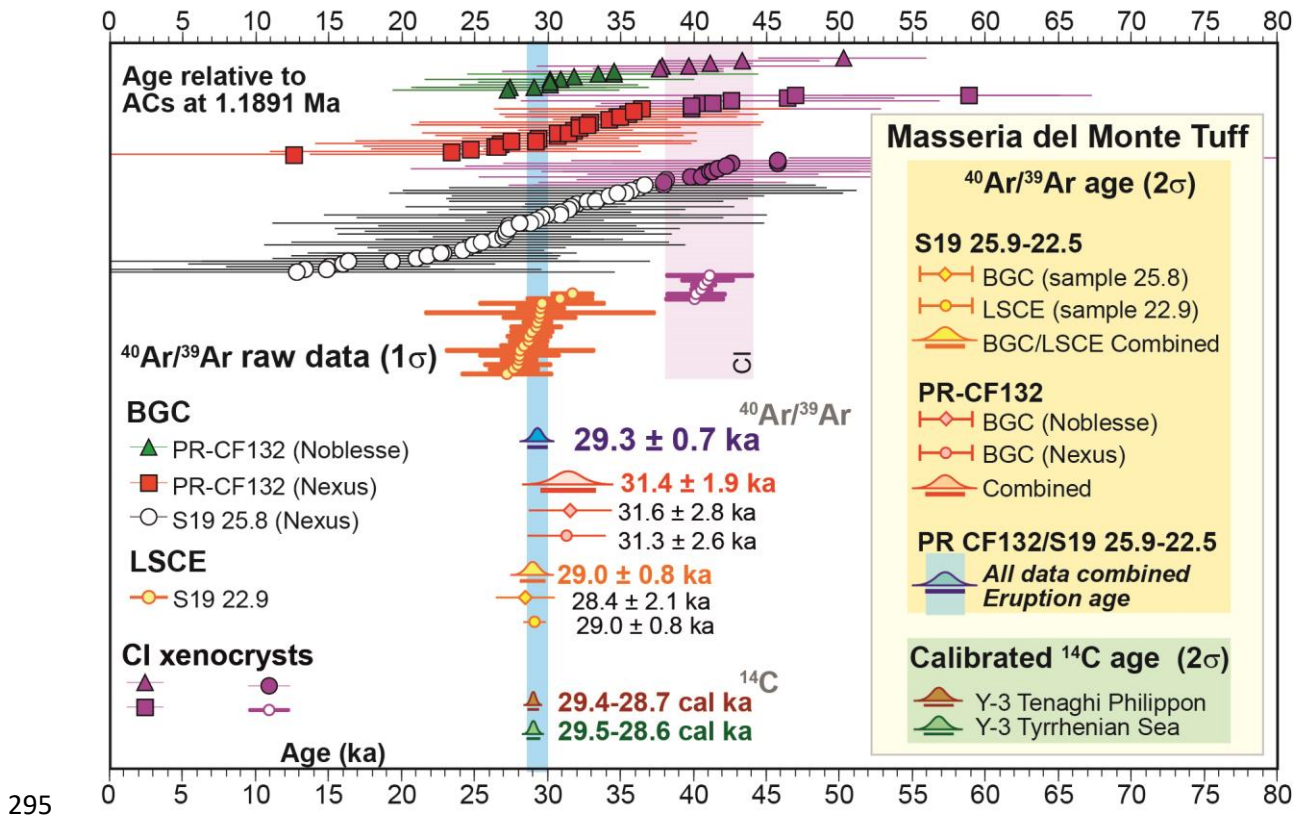


283 **Figure 1:** (A) The distribution of Y-3 tephra occurrences across the central Mediterranean
 284 (Table S1), and for comparison the Neapolitan Yellow Tuff(NYT). Overlain is the HAZMAP
 285 isopach map of the Masseria del Monte Tuff linked to the Y-3 tephra. (B) A map of Campi
 286 Flegrei caldera (CFc) and it major structures, and sampling localities are shown.



287

288 **Figure 2:** (A) The distal Y-3 tephra has two dominant components, a trachytic (Component 1) and phono-trachytic (Component 2) end-member, both
 289 consistent with CFC glasses (Smith et al., 2011; Tomlinson et al., 2012). The TB units related here to the distal Y-3 at Ponti Rossi (PR) (CF131/132)
 290 and in the S-19 Borehole (25.9-22.5m) have the same two components, plus a population of lower SiO_2 trachytes (Component 3). (B) The two end-
 291 members of the distal Y-3 are distinguished using their K_2O content of their volcanic glasses (grey boxes), only the third unit in borehole S-19, and
 292 the third (CF129) and fourth unit (CF131-132) in the PR sequence have both component 1 and 2 compositions. The thin ash unit (3; CF129)
 293 underlying Unit 4 at PR is inconsistent with the Y-3 tephra based on its levels of trace element enrichment (Fig. S1E-F). (C) Trace elements analysis
 294 verifies that both end-members of the Y-3 (Component 1 and 2) are observed in the thickest near-source units at PR and in the S-19 borehole.



295

296 **Figure 3:** $^{40}\text{Ar}/^{39}\text{Ar}$ ages (2σ) of proximal CFc samples of the Masseria del Monte Tuff, and
 297 terrestrial (Albert et al., 2015) and marine (Ramsey et al., 2015) ^{14}C ages of the distal Y-3.
 298 Individual sanidine age determinations are shown with 1σ errors and xenocrysts (mostly 40
 299 ka Cl crystals) are removed from all age calculations.

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