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The Campanian Ignimbrite and Codola tephra layers: Two temporal/stratigraphic markers for the Early Upper Palaeolithic in southern Italy and eastern Europe

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A R T I C L E   I N F O

A B S T R A C T

Tephra layers from archaeological sites in southern Italy and eastern Europe stratigraphically associated with cultural levels containing Early Upper Palaeolithic industry were analysed. The results confirm the occurrence of the Campanian Ignimbrite tephra (CI; ca. 40 cal ka BP) at Castelcivita Cave (southern Italy), Temnata Cave (Bulgaria) and in the Kostenki–Borshchevo area of the Russian Plain. This tephra, originated from the largest eruption of the Phlegrean Field caldera, represents the widest volcanic deposit and one of the most important temporal/stratigraphic markers of western Eurasia. At Paglicci Cave and lesser sites in the Apulia region we recognise a chemically and texturally different tephra, which lithologically, chronologically and chemically matches the physical and chemical characteristics of the Plinian eruption of Codola; a poorly known Late Pleistocene explosive event from the Neapolitan volcanoes, likely Somma–Vesuvius. For this latter, we propose a preliminary age estimate of ca. 33 cal ka BP and a correlation to the widespread C-10 marine tephra of the central Mediterranean. The stratigraphic position of both CI and Codola tephra layers at Castelcivita and Paglicci help date the first and the last documented appearance of Early Upper Palaeolithic industries of southern Italy to ca. 41–40 and 33 cal ka BP, respectively, or between two interstadial oscillations of the Monticchio pollen record – to which the CI and Codola tephras are physically correlated – corresponding to the Greenland interstadials 10–9 and 5. In eastern Europe, the stratigraphic and chronometric data seem to indicate an earlier appearance of the Early Upper Palaeolithic industries, which would predate of two millennia at least the overlying CI tephra. The tephrostratigraphic correlation indicates that in both regions the innovations connected with the so-called Early Upper Palaeolithic – encompassing subsistence strategy and stone tool technology – appeared and evolved during one of the most unstable climatic phases of the Last Glacial period. On this basis, the marked environmental unpredictability characterising this time-span is seen as a potential ecological factor involved in the cultural changes observed.

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1. Introduction

Since the first recognition of exceptional climatic instability during the Last Glacial period, well documented by the North Atlantic and Greenland records (e.g. Bond et al., 1992; Dansgaard et al., 1993; Grootes et al., 1993), the study of the spatial and temporal distribution as well as the impact of the sub-orbital oscillations – Bond cycles, Dansgaard/Oeschger (D/O) cycles and Heinrich events (HE) – has been the subject of sustained attention from a growing number of Quaternary scholars. Concurrently, the ensuing research revealed marked and rapid variations in the Late Pleistocene terrestrial and marine palaeobiotic systems of the Mediterranean area (e.g. Watts et al., 1996; Allen et al., 1999; Chaco et al., 1999; Paterne et al., 1999), which, according to more recent studies, appear to be in phase with the abrupt oscillations characterizing high latitude regions (Sánchez Goñi et al., 2000; Roucoux et al., 2001; Combourieu Nebout et al., 2002; Moreno et al., 2002; Sánchez Goñi et al., 2002; Moreno et al., 2004; Tzedakis et al., 2004; Tzedakis, 2005).

In archaeological studies, the evidence of pronounced climatic instability has recently aroused considerable interest concerning its role as a potential, relevant factor involved in human–environmental

interactions, hence Late Pleistocene bio-cultural evolution (van Andel, 2002; van Andel and Davies, 2003; D'Errico and Sánchez Goñi, 2003; Davies and Gollop, 2003; Jöris et al., 2003; Giaccio et al., 2004; Fedele and Giaccio, 2007). In this subject, the correct assessment of what may have happened depends on the possibility of a precise correlation between archaeological sequences and regional to super-regional high-resolution palaeoclimatic records (e.g. Greenland isotope stratigraphy).

The most common geo-chronometer in archaeology has so far been radiocarbon-dating. However, it needs be stressed that, due to the significant uncertainties in the calibration of ^{14}C dating beyond its present limit of about 21 ka ^{14}C BP (e.g. Reimer et al., 2004), any chronometric-based correlation purely derived from radiocarbon now appears to be inadequate (e.g. Giaccio et al., 2006). In this context, tephrostratigraphy affords a different method to achieve reliable correlation between archaeological and palaeoclimatic records. The tephra layers allow investigators to obtain unambiguous synchronisms independent of the temporal uncertainties of the natural and cultural records. Furthermore, if a palaeoclimatic record containing a given tephra has sufficient resolution to exhibit the unmistakable signature of sub-orbital oscillations, it may allow to determine the position and age of natural or cultural layers within the so-called Event Stratigraphy (e.g. Walker et al., 1999), i.e. in terms of the D/O oscillations.

Several recent studies have shown the importance of the Campanian Ignimbrite tephra (CI; ca. 40 ka BP, calendar age; De Vivo et al., 2001; Thon-That et al., 2001) as a formidable tool for assessing the age and environmental context of archaeological layers attributed to the so-called Early Upper Palaeolithic in south-eastern Europe (e.g. Fedele et al., 2003; Giaccio et al., 2006; Pyle et al., 2006; Anikovich et al., 2007; Fedele et al., in press). One aim of the present paper is to report new chemical and stratigraphic data that support and clarify the previously inferred CI identification in archaeological settings. To this effect we present a brief review of the CI lithostratigraphic and chemical markers. This is necessary because, in spite of the CI chemical composition having been firmly established by a number of studies (e.g. Civetta et al., 1997; Signorelli et al., 1999; Pappalardo et al., 2002; Marianelli et al., 2006; cfr Melluso et al., 1995, for the "Breccia Museo" unit of the CI), some confusion about the chemistry of the CI, misleading the identification of its distal ash, still persists.

In addition, the paper also presents significant new data concerning the deposits of the Codola eruption and recognition of its distal tephra layers in the archaeological sequences of southern Italy. The new data presented, and a critical evaluation of previous knowledge, allow a preliminary and tentative definition of the age, stratigraphic position, and equivalent marine tephra, of the until now poorly known Codola pyroclastics. It will be shown that Codola has considerable potential as a marker horizon for Quaternary studies in the central Mediterranean area, particularly in connection with the study of the Early Upper Palaeolithic.

2. The Campanian Ignimbrite and Codola marker tephra layers

2.1. The Campanian Ignimbrite

2.1.1. Lithostratigraphic and chemical markers

The Campanian Ignimbrite is now regarded as one of the largest Late Quaternary explosive events and an example of super-eruption (Sparks et al., 2005). Distal tephra layers have been traced over an area of about 5,000,000 km^2, comprising the whole central and eastern Mediterranean basin – where the CI marine tephra is known as C-13 and/or Y-5 (Thunnel et al., 1979; Ton-That et al., 2001) – and a large area of eastern Europe (Fig. 1; Thunnel et al., 1979; Narcisi and Vezzoli, 1999; Fedele et al., 2003; Giaccio et al., 2006; Pyle et al., 2006). Although this catastrophic event has been the subject of studies for well over a century (e.g. Scacchi, 1890; Franco, 1900), disagreements

still persist about its eruptive mechanisms and the precise location of the vent. Several studies indicate that the CI eruption originated from the Phlegraean Fields area, immediately west of Naples in southern Italy, and was accompanied by a caldera collapse (e.g., Rosi and Sbrana, 1987; Barberi et al., 1991; Fisher et al., 1993; Orsi et al., 1996; Rosi et al., 1996; Ort et al., 1999; 2003; Pappalardo et al., 2002). Other authors claim that the CI was an eruption of fissural type, vented along the pre-existing fault system bounding the Campanian Plain (e.g. De Vivo et al., 2001; Rolandi et al., 2003).

In the intermediate-distal area, i.e. the Campanian Plain and its surroundings (Fig. 1), the CI sequence includes Plinian fallout deposits at the base (CI Basal Pumices), with highly vesicular grey pumices, overlain by pyroclastic-flow units. These represent the two main phases of the eruption, which began with the formation of a ultraplinian column (e.g. Rosi et al., 1999), followed by generation of dilute pyroclastic density currents (PDCs). The PDCs, moving radially from the vent, were able to surmount high relief (above 1500 m a.s.l.), and lay down ignimbrite deposits up to distances exceeding 80 km from the source (Fisher et al., 1993). The ignimbrite units are represented by a greyish, partially welded tuff (CI Grey Tuff), or a yellowish coherent tuff lithified by zeolites (CI Yellow Tuff), containing both light and dark pumices with very elongated vesicles, as well as transparent curved or platy shards (Fisher et al., 1993). Throughout its areal distribution, both its sedimentological characteristics and features of juvenile fragments make the CI one of the most important stratigraphic markers in the late Pleistocene stratigraphic successions.

In proximal areas around the Phlegrean Fields, the CI deposits comprise lithic breccia and welded ignimbrites, known as "Breccia Museo" and "Piperno" (e.g., Di Girolamo et al., 1984; Rosi and Sbrana, 1987; Rosi et al., 1996). These deposits had been previously interpreted by some scholars as products of a different and significantly younger eruption (Lirer et al., 1991), but now they are definitively interpreted as near-vent facies of the CI (Ort et al., 1999; cfr. Ort et al., 2003; De Vivo et al., 2001).

Chemical data of the CI pyroclastics are available from a number of studies (Di Girolamo, 1970; Barberi et al., 1978; Melluso et al., 1995; Civetta et al., 1997; Signorelli et al., 1999; Pappalardo et al., 2002; Marianelli et al., 2006). Most of compositional data are whole rock XRF analyses, which can substantially differ from microanalyses on glass shards, commonly performed on distal tephra. Therefore, new microanalyses were performed on glass from ashes and pumices of CI PDC deposits collected at three different sites located between 40 and 80 km from Phlegrean Fields (Fig. 1; Table 1).

The new data point out a slightly compositional variability of the CI pyroclastics from trachytic to trachytic-phonolitic (Table 1; Fig. 2), in agreement with already published compositions (Di Girolamo, 1970; Barberi et al., 1978; Melluso et al., 1995; Civetta et al., 1997; Signorelli et al., 1999; Pappalardo et al., 2002; Marianelli et al., 2006). In particular, Civetta et al. (1997), which investigated mainly the PDCs deposits, described three main composition groups, not systematically arranged according to the stratigraphy of deposits, but distinguished according to their areal distribution and distance from the vent. In terms of major element composition, the difference among these groups mainly concerns the K_2O/Na_2O ratio and the relative abundance of CaO, Fe_2O_3, MgO and Cl. More precisely, the authors distinguish a less evolved magma with $K_2O/Na_2O>2$, CaO=3.5–4.5% Fe_2O_3=4–5.5%, MgO=1–1.55% and Cl=0.3–0.4%, and a most evolved magma with K_2O/Na_2O=1–1.35, CaO=1.6–1.95% Fe_2O_3=~3–3.5%, MgO=0.3–0.45% and Cl=0.7–0.9% (Table 1). The third group exhibits a value for the K_2O/Na_2O ratio and the concentrations of the other elements intermediate between the two end-members. The study of the interstitial glasses and melt inclusions of the CI fallout and breccia deposits (Signorelli et al., 1999; Marianelli et al., 2006) indicates a similar compositional variability also for these eruptive units.

The analyses of the Breccia Museo, outcropping in the western sector of the Phlegrean Fields, revealed a stratigraphic arrangement
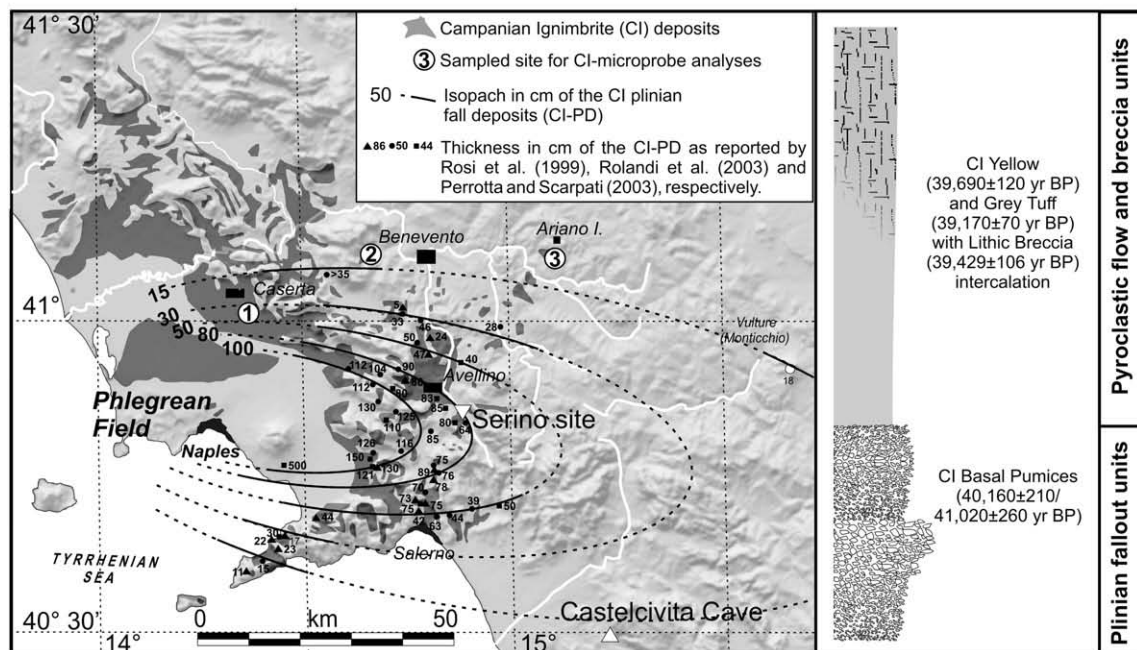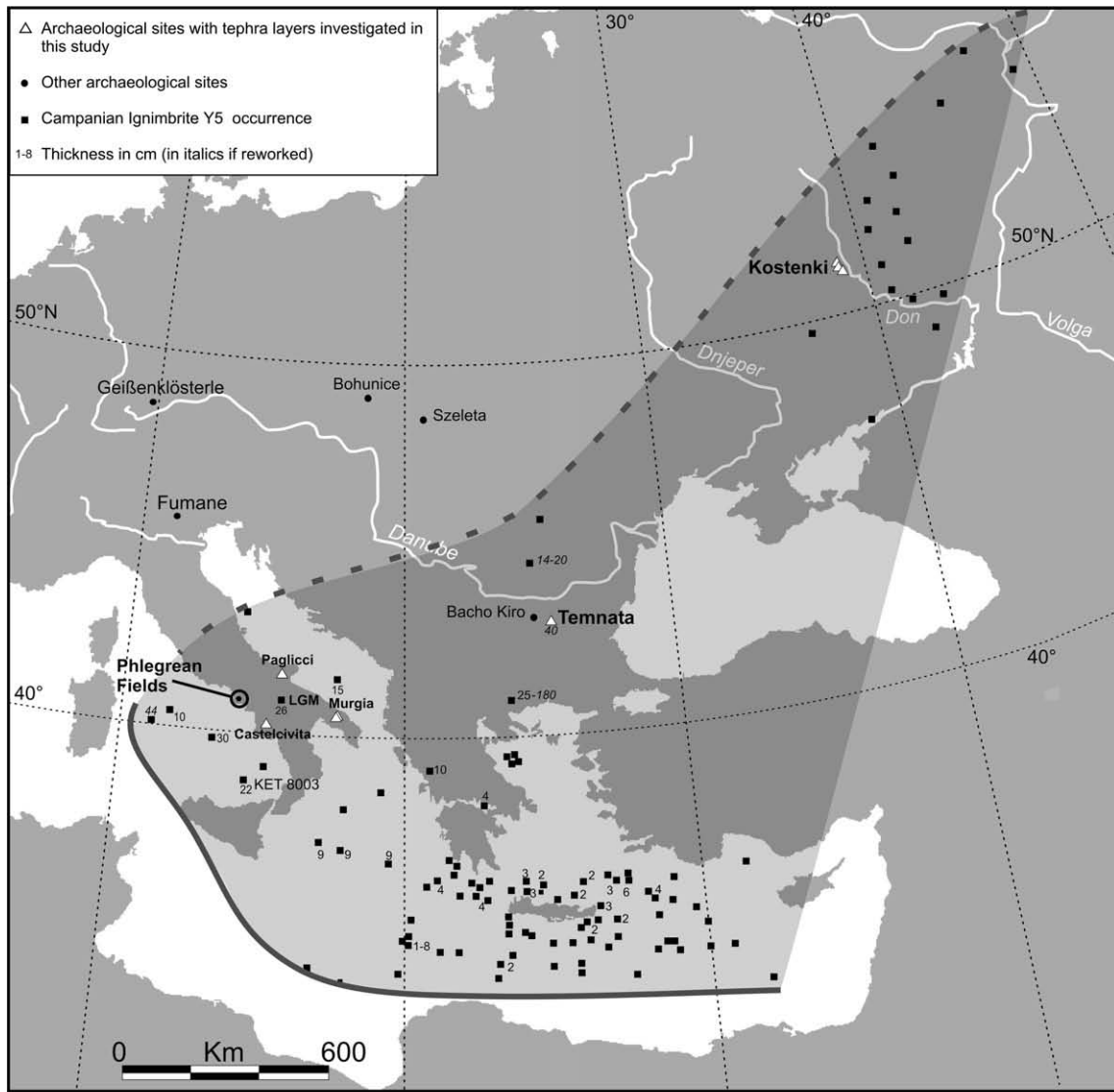
Table 1
Representative chemical composition of pumices and glass shards from the Campanian Ignimbrite (CI) fall (Signorelli et al., 1999), proximal (Pappalardo et al., 2002) and mid-distal pyroclastic density current (PDC) deposits (this study; see Fig. 1 for location of samples), showing the compositional variability of erupted magma

	CI fall units (FU)[a]				CI proximal units[b]						CI PDC units[c]					
	Lower FU		Upper FU		Unit IV	Unit III		Unit II		Unit I	$n=34$	SD	$n=22$	SD	$n=4$	SD
SiO_2	61.02	61.20	61.55	61.71	57.66	60.10	60.37	61.06	61.14	61.11	61.81	0.62	61.74	1.02	60.68	0.90
TiO_2	0.40	0.31	0.40	0.41	0.46	0.40	0.45	0.44	0.42	0.43	0.42	0.03	0.38	0.03	0.37	0.05
$Al2O_3$	19.06	19.03	18.55	18.62	18.07	18.75	18.64	18.65	18.70	18.62	18.32	0.31	18.35	0.34	18.63	0.31
FeO	3.25	3.50	2.98	3.11	5.00	4.06	3.93	3.70	3.62	3.50	2.97	0.17	3.24	0.28	3.45	0.26
MnO	0.24	0.00	0.26	0.23	0.08	0.14	0.21	0.20	0.20	0.20	0.27	0.06	0.14	0.04	0.13	0.02
MgO	0.36	0.77	0.36	0.37	1.45	0.77	0.59	0.40	0.40	0.36	0.35	0.08	0.60	0.13	0.67	0.11
CaO	1.61	2.73	1.70	1.78	4.39	2.98	2.26	1.92	2.01	1.63	1.81	0.18	2.27	0.31	2.57	0.16
Na_2O	5.34	3.09	6.10	5.75	2.78	4.11	5.23	5.75	5.77	6.43	5.56	0.25	4.68	0.24	3.64	0.40
K_2O	7.61	8.74	7.22	7.06	9.19	8.52	8.21	7.79	7.75	7.65	7.48	0.17	7.94	0.39	9.36	0.61
P_2O_5	0.03	0.15	0.05	0.03	–	–	–	–	–	–	0.06	0.04	0.11	0.07	0.14	0.01
F	0.27	0.12	0.00	0.00	0.29	0.15	0.11	0.09	0.09	0.08	0.15	0.10	0.10	0.09	0.02	0.03
Cl	0.80	0.33	0.79	0.84	–	–	–	–	–	–	0.75	0.10	0.40	0.10	0.34	0.03
SO_2	–	–	–	–	–	–	–	–	–	–	0.06	0.05	0.08	0.04	0.07	0.02
Original total	99.99	99.97	99.96	99.91	99.37	99.98	100.00	100.00	100.10	100.01	98.89	0.78	98.76	0.97	99.66	0.03
K_2O/Na_2O	1.42	2.83	1.18	1.23	3.31	2.07	1.57	1.35	1.34	1.19	1.35	0.06	1.70	0.14	2.60	0.43

n: number of analysed shards.
SD: standard deviation.
[a] Signorelli et al. (1999).
[b] Pappalardo et al. (2002).
[c] This study.

of this compositional variability parallel to an upward increase of the less evolved products (Melluso et al., 1995), a connection that was later recognised by Pappalardo et al. (2002) in another proximal sequence of the CI at Ponti Rossi, east of the Phlegrean Fields.

As a whole, the variability in the CI rock composition indicates that the CI eruption was fed by a trachytic magma chamber which included two chemically different magmatic layers: a more evolved upper magma layer, and a less evolved lower layer (e.g. Civetta et al., 1997). During the main stages of the eruption, the two layers were extruded either contemporaneously or separately, generating chemically different products arranged both vertically in proximal area and according to the distance from the vent in mid-distal setting. The most evolved and intermediate products are at great extend volumetrically predominant in the mid-distal area – 20–80 km from the vent (Civetta et al., 1997; Pappalardo et al., 2002) – while the deposits generated by the less evolved magma, extracted only at end of the eruption, are dispersed close to the source. The presence of a double composition is a peculiar characteristic that constitutes a chemical marker for tracing the CI tephra up to very distal settings.

2.1.2. Age and stratigraphic position

This point is crucial for tephrostratigraphic purposes. However, since it has been dealt with extensively elsewhere, the reader is referred to Fedele et al. (2003) and Giaccio et al. (2006) for both a comprehensive account and details. Summary information on the age and stratigraphic position of the CI is reported in Fig. 3. According to these studies, the most reliable age determinations of the CI eruption cluster around 40,000 cal yr BP. This age is supported by a number of $^{40}Ar/^{39}Ar$ measurements on sanidine crystals of proximal to intermediate deposits of CI (De Vivo et al., 2001; Rolandi et al., 2003; Lanphere, 2003), as well as by the close stratigraphic relationship of the CI distal tephra with several independently dated events recognized as temporal/stratigraphic markers. These events include: (i) the onset of Heinrich Event 4 (HE4); one of the sudden cooling events connected to Arctic ice discharge; (ii) the Laschamp Geomagnetic Excursion; and (iii) a distinct peak of ^{10}Be and other cosmogenic nuclides, ^{14}C included.

2.2. Codola eruption

2.2.1. Previous knowledge

Contrary to the CI, current knowledge on the Codola eruption is rather scarce. This eruption and related deposits are in fact sporadically mentioned in studies concerning the whole eruptive history and geochemical evolution of the Somma–Vesuvius volcano (e.g. Ayuso et al., 1998; Rolandi, 1998; Paone, 2006), or in overviews of tephrostratigraphy in the Campanian region (Sulpizio et al., 2003; Di Vito et al., 2008), but until now no systematic study of this eruption has been carried out. Authors disagree even about its source, the eruption being related either to Somma–Vesuvius (e.g. Santacroce, 1987; Rolandi, 1998) or Phlegrean Fields (Sulpizio et al., 2003) activity.

First mentioned by Alessio et al. (1974), the Codola eruption was later described by Santacroce (1987) as a layered Plinian fallout deposits with a basal layer of whitish vesicular pumices grading upward into blackish, less vesicular scoria clasts. Although not yet well defined in their areal distribution, the Codola deposits would have a volume quite comparable to the material of other major Plinian eruption of Mount Vesuvius (Santacroce, 1987).

Chemical analyses of the Codola pyroclastics are available from several recent studies (Brocchini et al., 2001; Sulpizio et al., 2003; Munno and Petrosino, 2004; Paone, 2006; Di Vito et al., 2008; Santacroce et al., 2008; Table 2). According to these studies, the composition of the Codola products ranges from trachytic-phonolithic, for the predominant vesicular juvenile clasts (white and dark pumices), to tephri-phonolitic for the obsidian-like brown glass shards.

2.2.2. New stratigraphic and chemical data

In order to improve the knowledge about the Codola eruption, new field and chemical investigations was carried out. The chosen outcrop was located in the eponymous area near the Codola village, at the south-eastern margin of the Campanian Plain (Fig. 4a).

The base of the succession covers a brown palesol while its top is truncated and buried by reworked pyroclastic material. The maximum thickness of the primary deposit is ca. 180 cm and comprises an alternation of fine to coarse ash and coarse pumice

Fig 1. a) Distribution of the Campanian Ignimbrite (CI) distal tephra layer and location of the investigated archaeological sites (Fedele et al., 2003, and Giaccio et al., 2006 and references therein); b) intermediate-proximal deposits with superimposed isopachs of the Plinian fallout. The sites of the analysed samples of CI deposits are shown. Inset: generalised columnar section of the CI deposits in mid-distal areas, with its distinctive units and related $^{40}Ar/^{39}Ar$ (De Vivo et al., 2001).
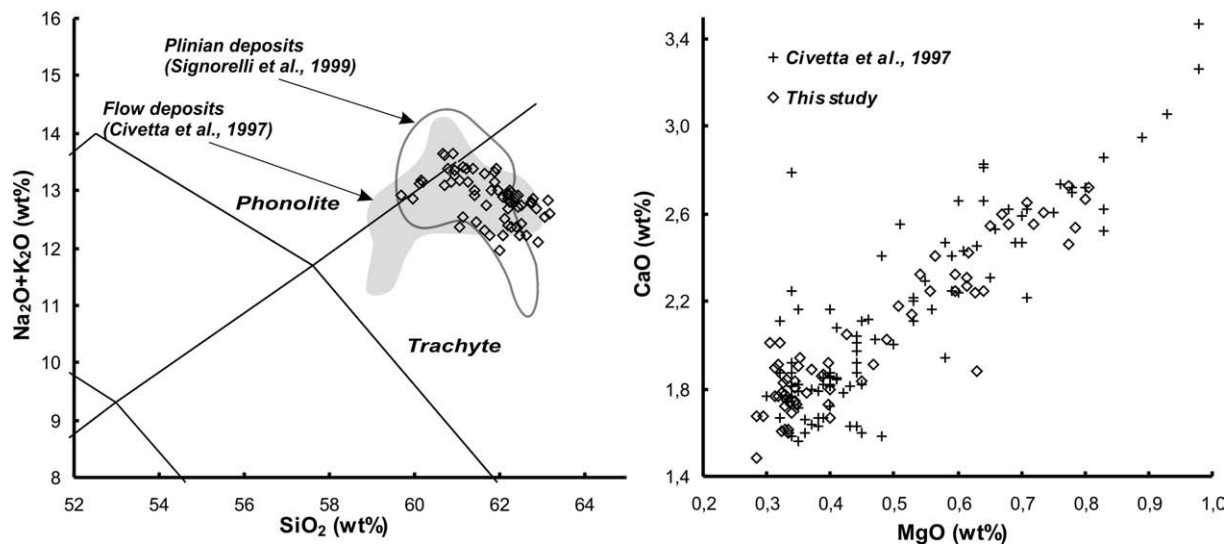
Fig 2. Total alkali silica (TAS, Le Bas et al., 1986) and CaO vs. MgO (microprobe analyses) diagrams of pumices and glass fragments from the CI pyroclastics, defining the compositional variability field of the erupted magma. Civetta et al. (1997) whole rock XRF analyses, Signorelli et al. (1999) microprobe analyses.

and scoria lapilli, which defines five main layers (Fig. 4c). The basal layer (C1; ca. 15 cm-thick) is made up by a grey massive fine ash containing two thin pumice lapilli layers in its upper part. Upward follows a pumice lapilli fallout layer (C2), which has a maximum thickness of 35 cm. This crudely stratified layer is the coarsest in the whole succession (maximum diameter of ca. 3 cm) and contains pumice fragments, smaller black scoria lapilli and grey lava litich clasts. An abrupt change in grain-size marks the passage to the upper part of the stratigraphic succession (layers C3, C4 and C5; Fig. 4c), which mainly comprises fine to coarse grey ash beds and subordinate thin lapilli beds (Layer C4; Fig. 4c) containing dark

brown to black dense scoria fragments (Fig. 4c). The ash layers are usually cohesive, and contain accretionary lapilli and scoria fragments with ash coating on their surface.

Although currently the number of measured sections is not enough to trace reliable isopach maps for the Codola deposits, the available thickness data would suggest a possible vent location in the Somma–Vesuvius area (Fig. 4a).

Microprobe chemical analyses, performed on two samples collected from the layers C2 and C5, showed a variable composition from tephri-phonolite, to latite-trachyte-phonolite similar to those reported in Santacroce et al. (2008; Table 2; Fig. 5).
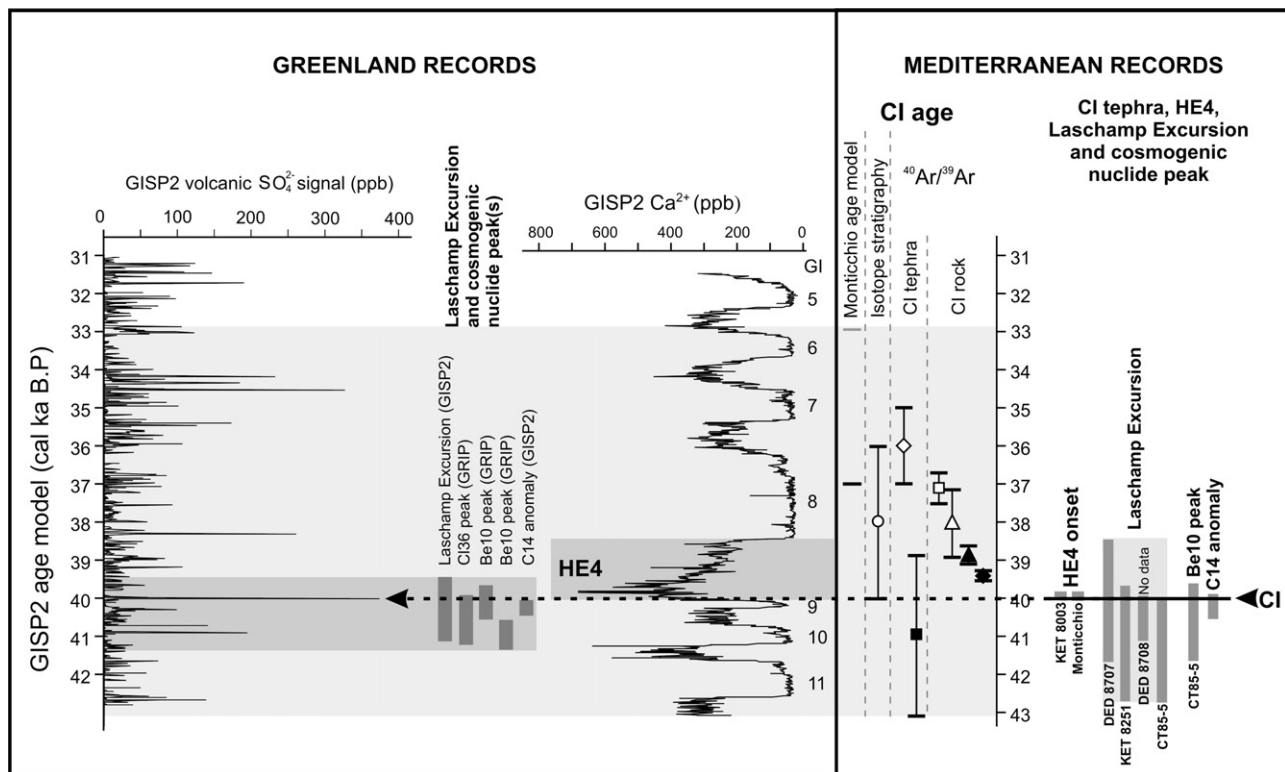
Fig. 3. A summary of the age and position of the Campanian Ignimbrite (CI) with respect to some stratigraphically and chronologically well constrained palaeoclimatic, palaeomagnetic and cosmogenic nuclide events of Marine Isotope Stage 3 (details and complete references in Fedele et al., 2003, and Giaccio et al., 2006). The identification of the putative CI peak within the volcanogenic record of the GISP2 ice-core is also shown.

2.2.3. Age, stratigraphic position and possible marine equivalents

Currently, a single radiocarbon measurement is available for the Codola pyroclastics on land, which would indicate for this event an age of 25,100±400 ^{14}C years BP (Alessio et al., 1974), corresponding to about 29 cal ka BP (Fairbanks et al., 2005). However, further indications towards assessing the Codola age can be obtained by considering the chronology and stratigraphy of the sedimentary archives which contain its distal tephra.

In distal setting, ash deposits correlated to Codola eruption were recognised in the Lago Grande di Monticchio lacustrine record, about 100 km eastward from Somma–Vesuvius and Phlegrean Fields volcanoes (Wulf et al., 2004; Fig. 4a). According to the authors, in the Lago Grande di Monticchio succession Codola deposits comprise two different tephra layers (TM-16b=Codola base and TM-16a=Codola top) separated by more than half a meter of lacustrine sediments spanning a temporal interval of about 650 years. However, this conflicts with stratigraphic succession of Codola eruption, which indeed does not show any occurrence of a similar long break during the eruption such as pedogenesis, erosion and/or intercalation of colluvial/volcaniclastic deposits. Furthermore, the TM-16a tephra layer comprises glasses with $SiO_2 > 62\%$, a chemical character which would seem inconsistent with Codola composition (Table 2). On this ground, we suggest that TM-16a tephra layer is a distal equivalent of a different eruption slightly younger than Codola one.

Distal occurrence of the Codola tephra is also reported by Munno and Petrosino (2007), which recognized a layer with the same composition of the most evolved products of Codola eruption in the lacustrine deposits of San Gregorio Magno basin, a inter-mountain depression ca. 80–100 km south-east from the Campanian volcanoes (Fig. 4a).

In both distal Monticchio and San Gregorio Magno records the Codola tephra occurs between the CI and Y-3 tephra layers (Fig. 6). Taking into account this tephrostratigraphic constrain, in the Tyrrhenian and Adriatic records the eventual marine equivalent of the Codola deposits should occur between the tephra layers C-13 (i.e.

the CI; Thon-That et al., 2001) and C-7, which, according to a recent study (Zanchetta et al., 2008) corresponds to Y-3 tephra (Fig. 6). In Tyrrhenian and Adriatic tephrostratigraphic records five tephra layers from Campanian volcanoes occur between C-13 and C-7 layers, labelled from base to top C-12, C-11, C-9, C(i)-5 and C-10 (Paterne et al., 1988) (Fig. 6). Among these, only the C-10 layer shows chemical affinity with the most evolved composition of Codola deposits (Tables 2 and 3). Furthermore, the composition of C-10 tephra layer in Adriatic Sea core CM9242 (Calanchi et al., 1998) replicates the whole spectrum of variability of Codola products on land (Table 3). Therefore, we tentatively propose Tyrrhenian tephra C-10 as a plausible marine counterpart for Codola deposits.

Noteworthy, the C-10 is one of the most widespread tephra layer in Tyrrhenian and Adriatic sea, as it was previously attributed to the CI deposits (e.g. Paterne et al., 1988), which are by now definitively correlated to C-13 tephra layer (Thon-That et al., 2001; Sulpizio et al., 2003). Therefore, the proposed correlation of the Codola eruption with the C-10 tephra layer would elevate the Codola deposits to the rank of regional marker for the whole central Mediterranean area, and provides an age constraint at about 34 cal ka BP. A radiocarbon measurement performed on foraminifera collected in Tyrrhenian core KET80-03 at −300 cm, the same depth as the C-10 layer (cfr. Paterne et al., 1999), yielded an age of 29,300±700 ^{14}C years BP, corresponding to 34,110±1030, or 34,270±870 cal years BP, according to the CalPal2005_SFCP (Jöris and Weninger, 1998, and updating available on-line) and the Fairbanks et al. (2005) calibration curve, respectively.

A concurrent chronological indication is provided by the high-resolution palaeoclimatic record of the Monticchio lacustrine succession (e.g. Watts et al., 1996; Zolitschka and Negendank, 1996; Allen et al., 1999; Allen and Huntley, 2000; Watts et al., 2000). Chronometric problems aside (see a brief discussion in Giaccio, 2005), this record shows rapid and marked changes similar to the D/O cycles and HEs recognized in Greenland and the North Atlantic, which allow a reliable correlation to be made between the Monticchio pollen diagram and Greenland isotope stratigraphy

Table 2
Average major-element composition of pumice fragments and glass shards of the Codola proximal and distal deposits (wt.% normalized to 100%); see Fig. 4c for the stratigraphic position of the analysed samples

Site	Proximal deposits										Distal tephra			
	Eponymous area										Monticchio[a]		S. Gregorio[b]	
	Layer C5[c]				Layer C2[c]		Pumices[d]		Pumices[e]		TM-16b		S18	
	n=5	SD	n=10	SD	n=15	SD	n=10	SD	n=10	SD	n=6	SD	–	–
SiO_2	51.74	1.12	54.64	1.14	57.78	0.44	58.42	0.22	58.54	0.35	58.58	0.65	58.54	0.35
TiO_2	0.82	0.07	0.61	0.13	0.56	0.06	0.59	0.08	0.54	0.08	0.50	0.06	0.54	0.08
$Al2O_3$	19.24	0.42	19.74	1.01	19.36	0.38	19.84	0.15	19.69	0.22	19.70	0.41	19.69	0.22
FeO	6.58	0.85	5.57	0.78	3.97	0.25	3.38	0.09	3.56	0.24	3.66	0.33	3.56	0.24
MnO	0.13	0.03	0.14	0.05	0.15	0.05	0.17	0.09	0.12	0.05	0.12	0.03	0.12	0.05
MgO	1.65	0.09	1.31	0.34	0.62	0.06	0.60	0.11	0.50	0.06	0.55	0.14	0.50	0.06
CaO	8.18	0.74	6.90	0.68	4.63	0.56	3.84	0.11	3.86	0.30	4.30	0.95	3.86	0.30
Na_2O	3.75	0.11	3.58	0.33	3.53	0.41	3.86	0.17	4.11	0.21	3.40	0.49	4.11	0.21
K_2O	6.93	0.27	6.49	0.64	8.77	0.26	9.29	0.18	9.08	0.34	8.58	0.40	9.08	0.34
P_2O_5	0.32	0.06	0.33	0.06	0.11	0.03	–	–	–	–	–	–	–	–
F	0.22	0.05	0.21	0.09	0.21	0.09	–	–	–	–	0.10	0.04	–	–
Cl	0.40	0.05	0.41	0.12	0.46	0.13	–	–	–	–	0.50	0.08	–	–
SO_2	0.04	0.01	0.05	0.03	0.07	0.03	–	–	–	–	–	–	–	–
Original Total	94.88	1.88	95.70	1.23	96.22	1.27	–	–	–	–	–	–	–	–
Total alkali	10.69	0.21	10.08	0.52	12.30	0.64	13.15	–	13.19	–	11.98	–	13.19	–
K_2O/Na_2O	1.85	0.12	1.84	0.33	2.54	0.37	2.40	–	2.21	–	2.52	–	2.20	–

n: number of analysed shards.
SD: standard deviation.
[a] Wulf et al. (2004).
[b] Munno and Petrosino (2007).
[c] This study.
[d] Di Vito et al. (2008).
[e] Munno and Petrosino (2004).

(GRIP correlation from Watts et al., 1996, 2000; Fedele et al., 2003; Fig. 7). The diagram of Fig. 7 indicates that the Codola tephra occurred in proximity of the onset of the Greenland Interstadial 5 (GI5), dated at ca. 32–32.5 cal ka BP according to the GISP2 (Meese et al., 1997), GRIPSS09sea (Johnsen et al., 2001) and GICC05 (Andersen et al., 2006) Greenland age models or ca. 33–33.5 cal ka BP according
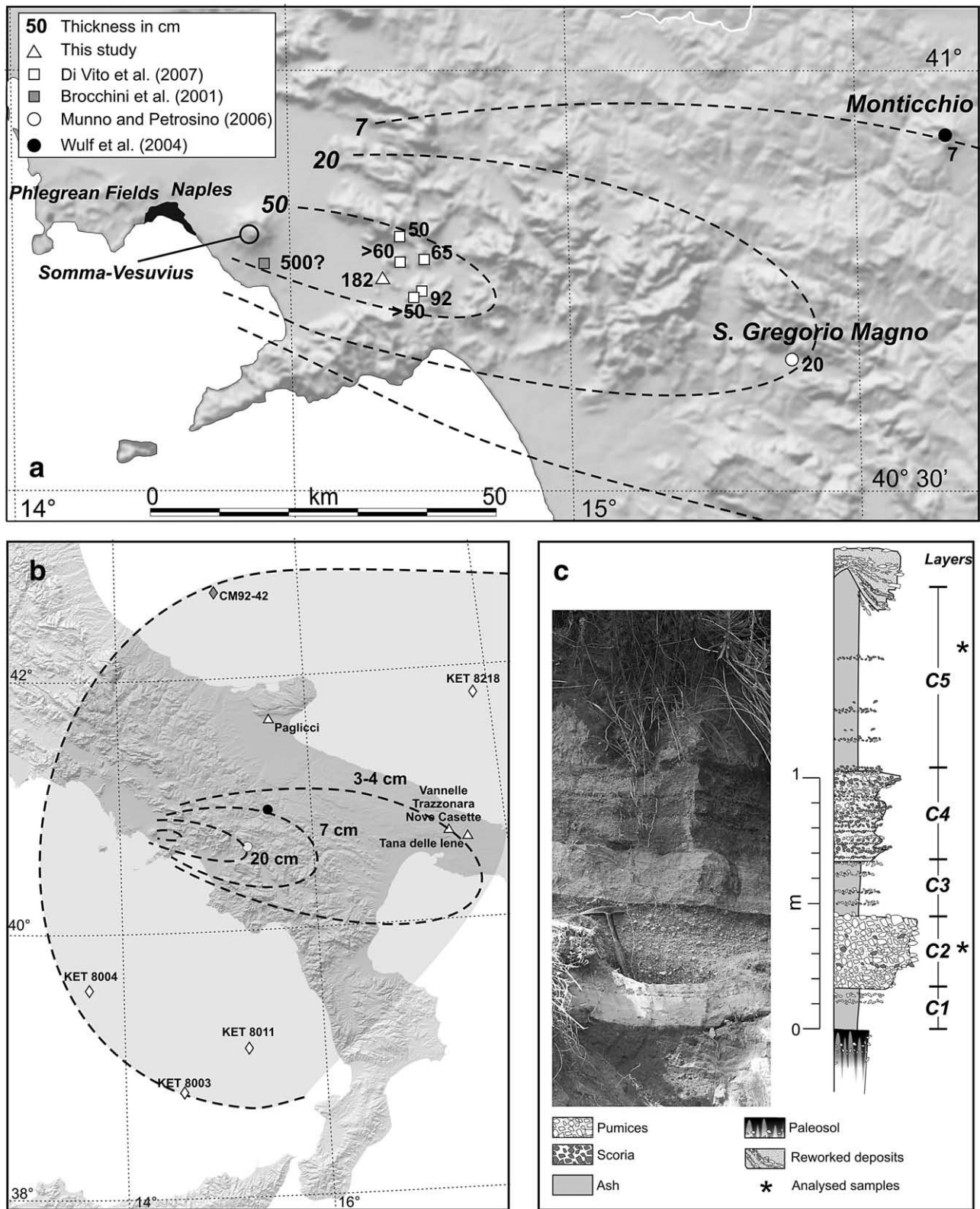
Fig 4. Dispersal and stratigraphic characteristics of the deposits of the Codola eruption. a) Inferred isopach map of the Codola deposits. b) Minimum dispersal of the Codola distal tephra including its marine equivalent C-10 layer. C-10 tephra is reported as white diamonds; other symbols as in Fig. 4a. c) Lithostratigraphy of the Codola deposits at investigated sites in this study (white triangle in Fig. 4a).
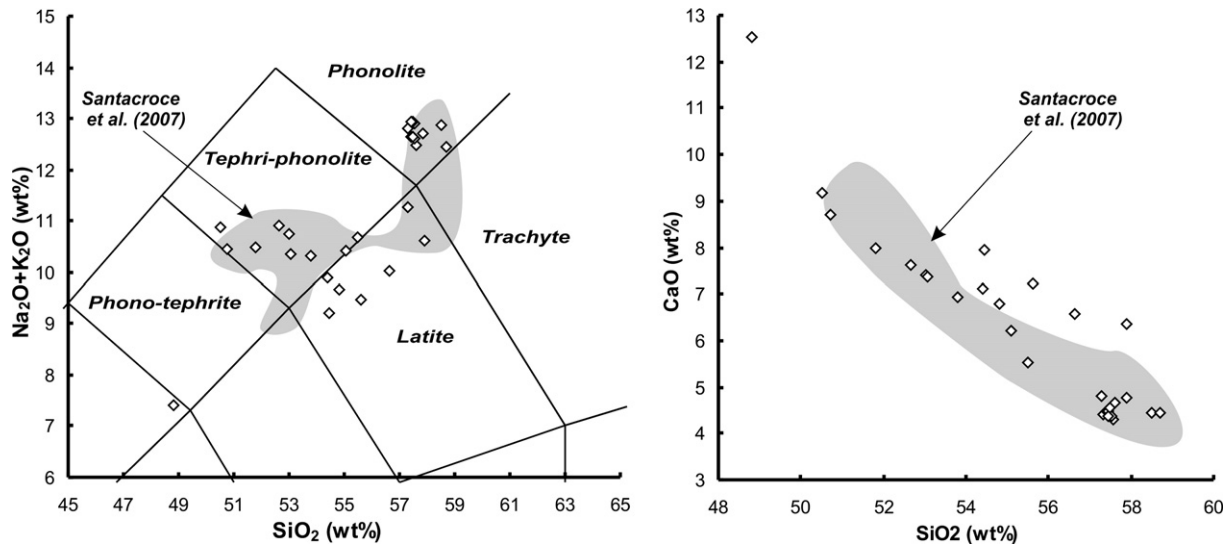
Fig 5. Total alkali silica (TAS; Le Bas et al., 1986) and CaO vs. SiO$_2$ (microprobe analyses) diagrams of pumices, scoria and glass fragments from two samples of the layers C2 and C5 of the Codola pyroclastics (Fig. 4c).

to the Shackleton et al. (2005) time scale. In summary, it can be suggested that the Codola tephra has the same age of the GI5, corresponding to about 33 cal. ka BP. As to the age of 25,100±400 ^{14}C years BP (Alessio et al., 1974), the significant inconsistence with both the tephrostratigraphic and climatostratigraphic position of the Codola tephra casts doubts on its reliability.

## 3. Stratigraphic and chemical characterization of the tephras in archaeological sites

The investigated archaeological sites (Fig. 1) include some of the most complete and informative series containing industries ascribed to the earliest stages of the Upper Palaeolithic in western Eurasia, such as Castelcivita and Paglicci Caves in southern Italy, Temnata Cave in Bulgaria and the Kostenki–Borshchevo site cluster in Russia (Fig. 1). At all the above sites, and lesser locales in Apulia, southern Italy, the analysed tephra layers occur in close stratigraphic relationships with archaeological horizons of the Early Upper Palaeolithic. Below we provide descriptions of their stratigraphic and chronological setting and report the results of the chemical microanalyses (analytical details are reported in the Appendix A).

3.1. Castelcivita Cave

An outline of the morphology and sedimentary setting of Castelcivita Cave is provided in Fig. 8 (for a more comprehensive description see Fumanal, 1997; Giaccio et al., 2006), along with the cave ethno-stratigraphy, i.e. its cultural-stratigraphic succession. The analysed tephra layer occurs at the top of an archaeological series, which includes three main cultural horizons, attributed from base to top to the Mousterian, Uluzzian and Proto-Aurignacian complexes (Gambassini, 1997; Fig. 8). The tephra consists of a basal decimetre-thick layer of millimetre- to centimetre-sized, whitish-grey, highly vesicular and aphiric pumice fragments, overlain by a thicker (Fig. 8), accretionary lapilli-bearing grey ash layer formed by curved or platy, transparent to dark-coloured glass shards. The microprobe chemical analyses of both pumice lapilli and ash layers reported in Table 4 show a slightly variable trachytic-phonolitic composition.

3.2. Kostenki–Borshchevo

More than twenty open-air archaeological sites were found in the area around the village of Kostenki, located on the west bank of the Don River approximately 40 km southwest of the city of Voronezh
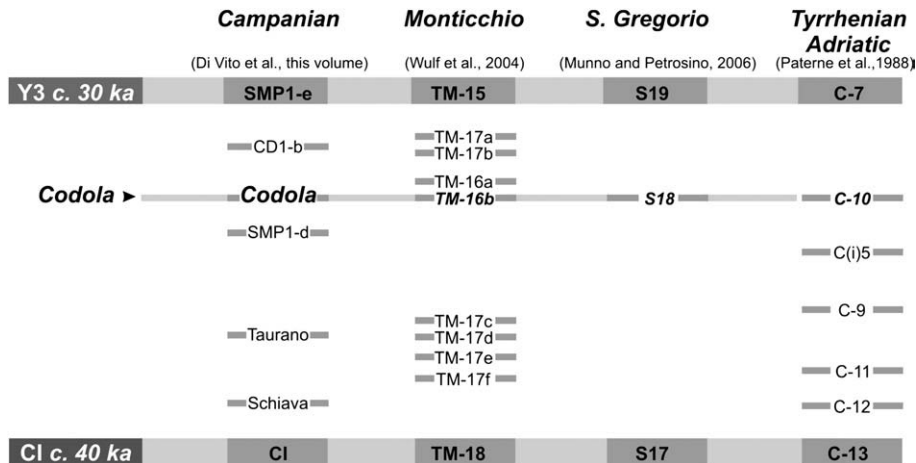
Fig 6. Correlation of some tephrostratigraphic records of the central Mediterranean area within the interval between the Campanian Ignimbrite (CI) and Y-3 marker tephra layers. The position of the Codola deposits and the proposed marine counterpart are shown.

(Klein, 1969; Praslov and Rogachev, 1982). An additional five sites have been discovered near Borshchevo, which is located several km southeast of Kostenki. At least seven of the Kostenki–Borshchevo sites (Kostenki 1, 6, 11, 12, 14, 17; and Borshchevo 5) contain a discontinuous tephra layer which is the object of this study (Fig. 9).

The high west bank of the Don River comprises mainly Cretaceous sand and marl, which has been incised by small spring-fed tributary streams, which created a complex of ravines around Kostenki and Borshchevo (Lazukov, 1982; Holliday et al., 2007). Three river terraces (8–10 m, 15–20 m, and 35–40 m above the present Don level); archaeological sites containing the tephra layer are confined to the second terrace in both the main valley and along the ravines. Its stratigraphic suite comprises three main litho-pedostratigraphic (Holliday et al., 2007, and references therein) and chronological (Sinitsyn and Hoffecker, 2006) units, from bottom up:

Unit 1) coarse alluvium and colluvium overlain by fine-grained sediments (≥50 cal ka BP);

Unit 2) alternating silt sediments and organic-rich soil horizons, also known as Humic Beds (see Holliday et al., 2007), including the tephra layer (~50–30 cal ka BP);

Unit 3) silt with four poorly developed buried soils, including a Gmelin Soil, and loess-like loam with associated modern cherno-zem (<30 cal ka).

Unit 2, a complex pedo-sedimentary succession deriving from both pedogenetic and colluvial/solifluction processes (Holliday et al., 2007), is divided by the tephra layer into the Lower and Upper Humic Beds.

Palaeolithic occupation layers at the Kostenki–Borshchevo sites were recognised within Unit 2 and in Unit 3. Artefacts assigned to the Gravettian technocomplex lie in the Unit 3 sediments (<30 ka cal). An assemblage containing some typical Aurignacian elements lies within and below a buried soil at Kostenki 1 (Rogachev et al., 1982), which is the stratigraphic equivalent of the Upper Humic Bed (~32–27 ^{14}C ka BP; Sinitsyn and Hoffecker, 2006). Finally, an Aurignacian "Dufour" assemblage is buried within and below the tephra layer at Kostenki 14 (Sinitsyn, 2003a).

The other assemblages recovered from Unit 2 do not have close parallels to Upper Palaeolithic industries of central and western Europe. They include the Gorodtsov assemblages in the Upper Humic Bed (e.g., Kostenki 14, Layers II, Kostenki 15 and Kostenki 12, layer I), the Spitsyn assemblages in the Lower Humic Bed (e.g., Kostenki 17, Layer II), and the Strelets assemblages, which may be considered "transitional," in both the Upper and Lower Humic Beds (Praslov and Rogachev, 1982; Anikovich, 1992; Hoffecker, 2002: 167–173). At Kostenki 14, the lowermost occupation layer (Layer IVb), at the base of the Lower Humic Bed stratigraphic equivalent, has yielded an assemblage containing burins, small bladelets, bone awls, and other items that apparently represent another previously unrecognized industry, non-transitional in character (Sinistyn, 2003b; Anikovich et al., 2007).

Calibrated radiocarbon ages and a new series of Optical Stimulated Luminescence age determinations indicate that the Lower Humic Bed (i.e., below the tephra layer) predate 39 cal ka BP (Holliday et al., 2007). This is consistent with the stratigraphic position of the Laschamp geomagnetic excursion, correlated to the GI 10–9 in the Greenland ice core record (ca. 40–42 GISP2 ka BP; Fig. 3) and dated elsewhere at 40.4±2.0 cal ka BP (Guillou et al., 2004), which has been tentatively identified in the Lower Humic Bed at several Kostenki sites (e.g. Gernik and Guskova, 2002; Pospelova, 2005). According to palynology from Kostenki 12, the lowermost occupations at Kostenki overlie a very warm climate interval that is tentatively correlated to Greenland GI12 (Levkovskaya et al., 2005; Anikovich et al., 2007).

The tephra layer from Borshchevo 5 has a thickness of 15 cm, and mainly comprises elongated and Y-shaped glass shards with associated rare K-feldspar crystals and rounded grains of quartz of aeolian and/or colluvial origin. The chemical data, reported in Table 4, point out a slightly variable composition from trachyte to phonolite.

3.3. Temnata Cave

Temnata Cave is one of several cavities forming the Prohodna–Temnata Karst system, located near Karlukovo in Bulgaria (Fig. 1); another major cave nearby is Cave 16. It is regarded as one of the most

Table 3
Average major-element chemical composition of glass shards from the C-10 marine tephra layer (wt.% normalized to 100%). A significant chemical affinity with the Codola pyroclastic products (Table 2) can be noted

	Adriaditic Sea						Tyrrhenian Sea		
	CM9242[a]						KET 8218[b]	KET 8003[b]	KET 8011[b]
	400 cm (a)		400 cm (b)		400 cm (c)				
	$n=9$	SD	$n=6$	SD	$n=13$	SD			
SiO_2	50.39	0.29	53.49	0.67	59.83	1.14	60.27	60.24	59.73
TiO_2	0.94	0.07	0.06	0.07	0.42	0.15	0.53	0.4	0.36
$Al2O_3$	20.19	0.21	19.62	0.82	19.41	0.33	19.09	20.12	20.13
FeO	6.64	0.21	6.77	0.39	3.03	0.35	4.15	2.59	2.72
MnO	0.04	0.03	0.12	0.08	0.12	0.05	–	–	–
MgO	1.59	0.24	2.21	0.58	0.35	0.14	0.16	0.08	0.07
CaO	8.32	0.06	6.98	0.27	3.03	0.82	3.64	3.37	3.55
Na_2O	3.28	0.31	3.21	0.19	4.27	1.09	3.60	3.91	4.58
K_2O	7.97	0.32	7.13	0.81	9.01	0.62	8.52	9.25	8.84
P_2O_5	0.57	0.11	0.00	0.00	0.00	0.00	–	–	–
Cl			0.41	0.15	0.53	0.15	–	–	–
Total	100.00		100.00		100.00		99.96	99.96	99.98
Total alkali	11.3	–	10.34	–	13.28	–	12.12	13.16	13.42
K_2O/Na_2O	2.43	–	2.22	–	2.11	–	2.37	2.37	1.93

n: number of analysed shards.
SD: standard deviation.
[a] Calanchi et al., 1998; Calanchi and Dinelli (2008).
[b] Paterne et al. (1988).
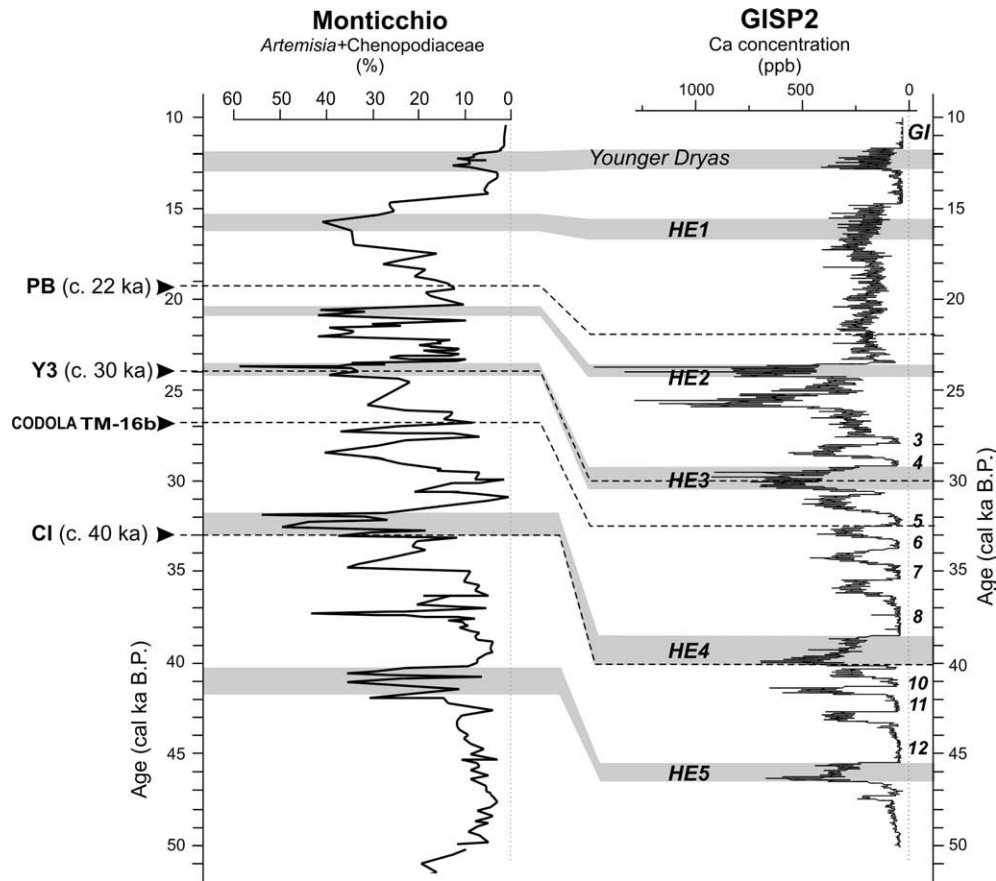
Fig 7. Correlation between the Artemisia and Chenopodiacea pollen sum from Lago Grande di Monticchio, southern Italy (age-model according to Zolitschka and Negendank, 1996) and the calcium concentration in the GISP2 ice-core (Mayewski et al., 1997; cfr GRIP correlation in Watts et al., 1996; Watts et al., 2000). A close stratigraphic relationship between Codola tephra TM-16a and the Monticchio interstadial oscillation possibly corresponding to Greenland Interstadial 5 (GI5; ca. 32–33 ka GISP2 BP) can be noted. The position and the "best ages" (number in parenthesis) of the Campanian Ignimbrite (CI), Y-3 and Somma–Vesuvius Pomici di Base (PB) tephra layers in the Monticchio record are also reported.

important European sequences containing Middle, "Transitional" and Upper Palaeolithic industries (e.g. Kozlowski, 1998). Following Ginter and Kozlowski (1992), and retaining their terminology, four main phases of human occupation can be distinguished:

a. Middle Palaeolithic — dated between 105 and 67 cal ka BP;
b. Early Palaeolithic — comprising three different groups:

b1. Initial Upper Palaeolithic — dated at >38 ^{14}C ka BP and characterized by both Mousterian-like and Upper Palaeolithic-like industries;

b2. Early Aurignacian — dated between 46 ^{14}C ka BP and 32 ^{14}C ka BP;

b3. Upper Palaeolithic or Late Aurignacian (Kozlowski, 1998) — dated between 32 ^{14}C ka BP and 28 ^{14}C ka BP;

c. Gravettian — dated between 29 ^{14}C ka and 20 ^{14}C ka BP;
d. Epigravettian — dated between 20 ^{14}C ka and 13 ^{14}C ka BP.

The tephra layer from Cave 16 was sampled and analysed. It mainly comprises white and highly vesicular micro-pumices, transparent to dark-coloured platy/curved glass shards and rare feldspar crystals. The same ash layer was recognised in several archaeological and paleontological excavation trenches in Temnata and used as marker for inter- and intra-sites correlations (e.g. Ferrier, 2000). In the most complete archaeological sections, the tephra layer separates the Early Aurignacian layers from the Upper Palaeolithic ones; elsewhere it occurs between the Late Aurignacian–Early Aurignacian and Gravettian layers, or between the layers containing industries of Initial Upper Palaeolithic and archaeologically sterile. Cave 16 contains an important micro-mammal record (Popov,

1994, 2000) but no archaeological remains. Mayor element analyses of the sampled tephra (Table 4), reveal a rather homogeneous trachytic composition.

3.4. Southern Murge sites

The investigated localities comprise an excavated cave site (Tana delle Iene; Giaccio and Coppola, 2000) and a group of three dolines (Vannelle, Trazzonara and Nuove Casette) clustered in the southern sector of the Murge Plateau karst area (Fig. 10; Fedele et al., 2002). At all doline sites, where the karst morphology acted as a geological trap, the volcanic deposits show the same sedimentary succession, which comprises a basal centimetre-thick massive, undisturbed ash fallout layer, overlain by one or more layers of laminated, reworked ash with variable thickness from some decimetres to several metres (Fig. 10). The contact between the two units may be either concordant or erosional. At Tana delle Iene, due to the cave setting, only the reworked unit was recognised. Here the ash deposits seal a sequence containing remains of a hyena-lair occupation and sporadic Mousterian- and/or Upper Palaeolithic-like stone artifacts. At other open-air locations the volcanic ash overlies paleosols or colluvial deposits, which contain scattered Mousterian-like or undiagnostic lithic artefacts.

The fall unit has a constant thickness of about 3–4 cm (Fig. 10). It shows a basal layer of whitish and moderately vesicular micro-pumice and an upper layer with both whitish and dark-coloured, incipiently vesicular micro/scoria. Non-vesicular, brownish glass shards also occur in the upper layer. These textural features characterize the tephra layer in
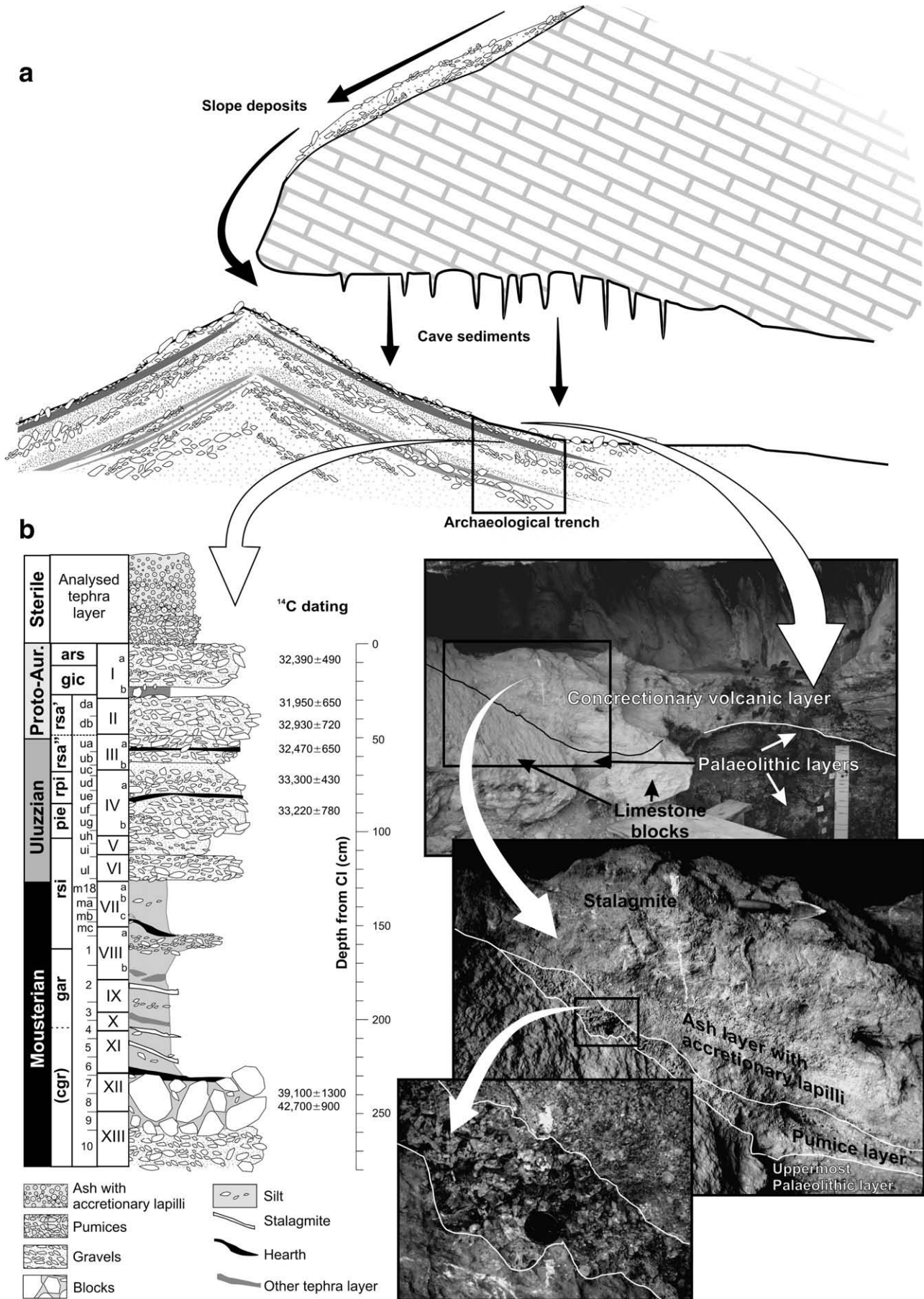
all the four investigated localities, reworked unit included. Microanalyses of two samples from both fall and reworked units of the Vannelle site (Fig. 10) reveal a predominantly trachytic-phonolitic composition with a sporadic occurrence of more mafic glass fragments (Table 5).

3.5. Paglicci Cave

In European archaeology, Paglicci Cave represents one of the most complete and informative sequences for the middle-late Upper Palaeolithic, comprising all stages of the Gravettian and Epigravettian industries (e.g. Palma di Cesnola, 2001). Recent excavations of the deposits underlying the lowermost Gravettian layers further extended the Upper Palaeolithic record down to the earlier phase of the Aurignacian (Palma di Cesnola, 1990, 1993, 2004).

The sampled tephra corresponds to the layer 23C2 at the top of the sedimentary succession containing the Aurignacian industry (layers 24C, 24B and 24A; Fig. 11), dated between ca. 34 and 29 ^{14}C ka BP (Fig. 11). The tephra is overlain by the sediments of layer 23, which represent the base of the Gravettian series dated to 28–26 ^{14}C ka BP (Palma di Cesnola, 1990, 1993, 2004; Fig. 11).

The tephra layer comprises poorly vesicular, grey micro-scoria fragments, non-vesicular, dark-coloured glass shards and crystals of clinopyroxene and feldspar. The grey micro-scoria fragments was weathered and unsuitable for microprobe analyses. Therefore, the compositions reported in Table 5 refer only to the dark-colored glass shards.

3.6. Serino

A further example of occurrence of volcanic deposits in conjunction with a southern Italian Palaeolithic site is Serino, an open-air "Proto-Aurignacian" camp site in the Campania region (Accorsi et al., 1979). Here the thick pyroclastic deposits that cover the Palaeolithic layer unmistakably show the typical internal succession and textural characteristics of the CI, including both Plinian and PDC deposits (Fedele et al., 2002, 2003; Giaccio et al., 2006). Therefore its attribution to the CI does not require additional chemical data in support of the correlation.

4. Discussion

The tephra layers from Castelcivita Cave, Borshchevo 5 and Temnata-Cave 16 show strong similarity with the CI deposits in terms of both textural characteristics and composition (Tables 1 and 4; Fig. 12). In particular, the basal pumice layer at the Castelcivita Cave has a homogeneous trachytic composition identical to those of the most evolved magma of the CI. On the contrary, the overlying ash level exhibits a variable composition, which replicates almost the whole range of the CI magma (Table 4; Fig. 12), with the exception of the less evolved products that, according to the reconstructed eruptive dynamics (e.g. Pappalardo et al., 2002), occur only in the near vent area. This correlation is further supported by the stratigraphic characters of the tephra layer exposed at Castelcivita site, which replicates the fallout and PDC deposits succession of the CI in near vent outcrops and in other relatively close localities of the Cilento area (Giaccio, 2005).

The composition of the Borshchevo 5 tephra layer also shows a compositional range that resembles that of the CI products. In particular the 68%, 16% and 16% of the glasses are characterized by the same composition of the more evolved, intermediate and less evolved CI magmas, respectively (Table 4; Fig. 12). These results

corroborate the previous correlation of these tephra to the CI based on ethno-stratigraphic, magneto-stratigraphic and chronological data (Fedele et al., 2003), and chemical analyses (Melekestzev et al., 1984; Pyle et al., 2006).

As to Temnata-Cave 16 tephra, the chemical results reveal that more than 90% of the analysed glass shards have the same composition of the most evolved CI magma, but a single glassy fragment, although not very compelling, would indicate the presence of products chemically similar to the least evolved CI magma (Table 4; Fig. 12).

According to previous tephrostratigraphic studies (Paterne, 1992; Pawlikowski, 1992), the identification of tephra layer from Temnata Cave and its correlation to a known eruption, at that time, was hardly tenable. In fact, although the chemical analyses reported by Paterne (1992) show the composition of the CI, the author interpreted the chemical variability as a possible mixing of glasses related to two different, sub-contemporaneous eruptions, originating from the Ischia and Phlegraean Field volcanoes. Alternatively, Paterne (1992) suggested a correlation with a tephra of similar chemical composition from the record of the Adriatic Sea (tephra layers C-13, C-14, C-16 or C-17). As much as uncertain were the conclusion of Pawlikowski (1992), which suggested not well-defined eruptions from Ischia Island as possible source(s) of the Temnata Cave tephra.

About Paterne's (1992) conclusion, clearly layers C-16 and C-17, dated to ca. 51 and 55.4 cal ka BP respectively (Paterne et al., 1988), do not fit with the ethno-stratigraphic position and the radiocarbon chronology available for the sediments at the base of the Temnata Cave tephra (ca. 32–33 ^{14}C ka BP). Furthermore, although the age of tephra layer C-14 (ca. 41.8 cal ka BP) would be consistent enough with the age and stratigraphic position of the Temnata Cave tephra, more recent chemical analyses (Paterne and Guichard, 1993) of this marine tephra pointed out substantial compositional difference with the Temnata-Cave sample here reported, especially in terms of the K_2O/Na_2O ratio (cfr. Table 2a of Paterne and Guichard, 1993). In conclusion, among the four possible options proposed by Paterne (1992) only layer C-13, i.e. the CI, is chronologically and chemically consistent with the correlation.

The other two analysed layers from the Murge sites and Paglicci Cave show composition and micro-textural features comparable to those of the products of the Codola eruption (Tables 2 and 5; Fig. 13). This correlation is particularly robust for the fallout unit layer of the Murge sites (Fig. 10), which also shows similarities with Codola products in terms of stratigraphy and vertical variability of the colour and vesicular degree of the juvenile clasts. From a chemical viewpoint, the micro-pumices from Vannelle site are indistinguishable from the predominant phonolitic composition of the most evolved Codola products (Table 2; Fig. 13). In contrast, the non-vesicular, dark-coloured glass shards of the sample from Paglicci Cave mostly show a composition within the range of the obsidian-like, brown-black glass of the Codola pyroclasts. The correlation to Codola deposits (or to their marine equivalent C-10 tephra layer) is further supported by the available radiocarbon measurements for the archaeological layers immediately above and below the Paglicci tephra, respectively dated to ca. 28 and 29 ^{14}C ka BP, i.e. ca. 33 and 34 cal ka BP according to the Fairbanks et al. (2005) curve. This age range matches the best age estimate for Codola eruption proposed in Section 2.2.3.

As mentioned in the initial section of this paper, previous studies (e.g. Fedele et al., 2002, 2003) have convincingly led to the recognition of the CI tephra at Castelcivita Cave, Temnata Cave and Kostenki, and tentatively in a number of southern Italian sites including Paglicci Cave and the cluster on the Murge Plateau. Those studies, however, were especially

Fig 8. Castelcivita Cave. a) Geomorphological and stratigraphic reconstruction (not to scale); the location of the investigated archaeological succession at the base of a debris cone made by slope deposits is shown. b) Stratigraphic succession showing the position of the analysed tephra layer (location in Fig. 1). Cultural stratigraphy and ^{14}C dating according to Gambassini (1997).

Table 4

Average major-element composition of pumice fragments and glass shards from the tephra layers of Castelcivita Cave, Temnata-Cave 16 and Borshchevo 5 (wt.% normalized to 100%; see Appendix A for analytical details). The analysed samples show two or three chemically different populations of glasses, compositionally similar to the Campanian Ignimbrite deposits (Table 1)

	Castelcivita Cave						Borshchevo 5						Temanta-Cave 16			
	Pumice		Ash-1		Ash-2		BOR-1		BOR-2		BOR-3		C16-a		C16-b	
	n=4	SD	n=6	SD	n=4	SD	n=16	SD	n=4	SD	n=4	SD	n=17	SD	n=1	SD
SiO$_2$	61.16	0.42	61.20	0.40	61.36	0.53	61.24	0.15	62.09	0.26	61.57	0.63	61.84	0.21	62.05	–
TiO$_2$	0.44	0.04	0.39	0.04	0.39	0.08	0.41	0.03	0.36	0.01	0.36	0.07	0.38	0.04	0.27	–
Al2O$_3$	18.61	0.11	18.55	0.11	18.33	0.04	18.44	0.08	18.31	0.19	18.43	0.20	18.61	0.22	18.12	–
FeO	2.85	0.19	2.90	0.11	3.10	0.32	3.12	0.09	3.05	0.04	3.50	0.18	3.02	0.08	3.05	–
MnO	0.27	0.03	0.26	0.04	0.15	0.05	0.26	0.03	0.15	0.03	0.14	0.02	0.24	0.04	0.16	–
MgO	0.32	0.05	0.36	0.02	0.66	0.14	0.36	0.02	0.51	0.06	0.68	0.08	0.35	0.02	0.58	–
CaO	1.79	0.04	1.79	0.03	2.44	0.30	1.85	0.07	2.10	0.16	2.52	0.14	1.78	0.05	2.31	–
Na$_2$O	5.94	0.20	5.89	0.28	4.47	0.54	5.97	0.29	4.92	0.07	3.39	0.49	5.68	0.30	3.78	–
K$_2$O	7.62	0.15	7.68	0.10	8.32	0.45	7.29	0.31	7.85	0.09	8.86	1.17	6.97	0.11	9.22	–
P$_2$O$_5$	0.04	0.05	0.04	0.04	0.11	0.06	0.06	0.03	0.08	0.04	0.11	0.08	0.03	0.02	0.08	–
Cl	0.72	0.08	0.76	0.07	0.38	0.07	0.74	0.04	0.41	0.06	0.40	0.06	0.79	0.03	0.39	–
F	0.16	0.10	0.07	0.07	0.18	0.05	0.28	0.11	0.16	0.07	0.04	0.05	0.32	0.09	0.00	–
SO$_3$	0.07	0.04	0.11	0.06	0.11	0.02										
Original total	98.70	0.65	98.31	1.56	99.00	0.63	97.24	1.80	97.92	0.96	94.13	3.01	96.38	1.36	97.96	–
K$_2$O/Na$_2$O	1.28	0.07	1.31	0.08	1.89	0.36	1.23	0.11	1.59	0.01	2.69	0.71	1.23	0.36	2.44	–

n: number of analysed shards.
SD: standard deviation.

addressing the potential impact of the CI eruption on climate and human ecosystems, while more comprehensive tephrostratigraphic studies were necessarily avoided. The new analyses here reported on one hand confirm the recognition of the CI at Castelcivita, Kostenki and Temnata sites, and, on the other hand, reject the contention of its occurrence at Paglicci Cave and on the Murge Plateau (cfr. Giaccio et al., 2006).

Partly to clear the field from previous misunderstandings, the Paglicci tephra deserves additional comments. Although associated with an ethno-stratigraphic position and a radiocarbon age similar to those of the CI at Castelcivita Cave and Serino open-air sites, the Paglicci ash layer is at least 6000–7000 years younger than the Castelcivita Cave and Serino one. At the same time it is invaluable because of its relationships
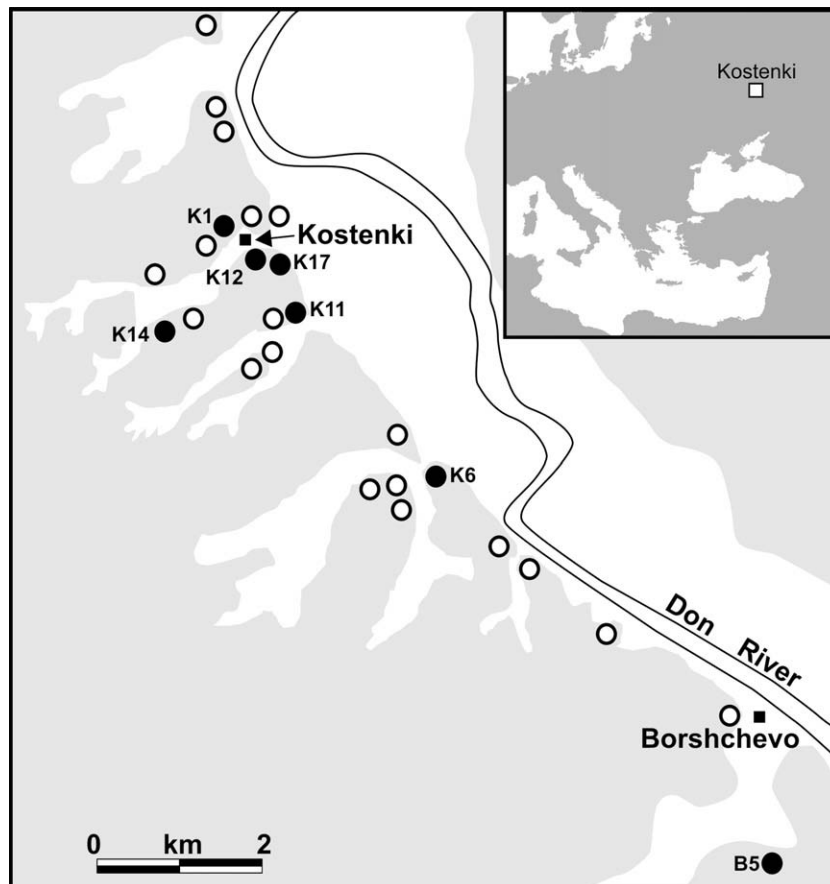
Fig 9. Reference map of the Kostenki–Borshchevo archaeological area. Black circle: locations of the Palaeolithic sequences with the tephra layer, including Borshchevo 5 (B5) investigated in this study. White circle: other archaeological sites.
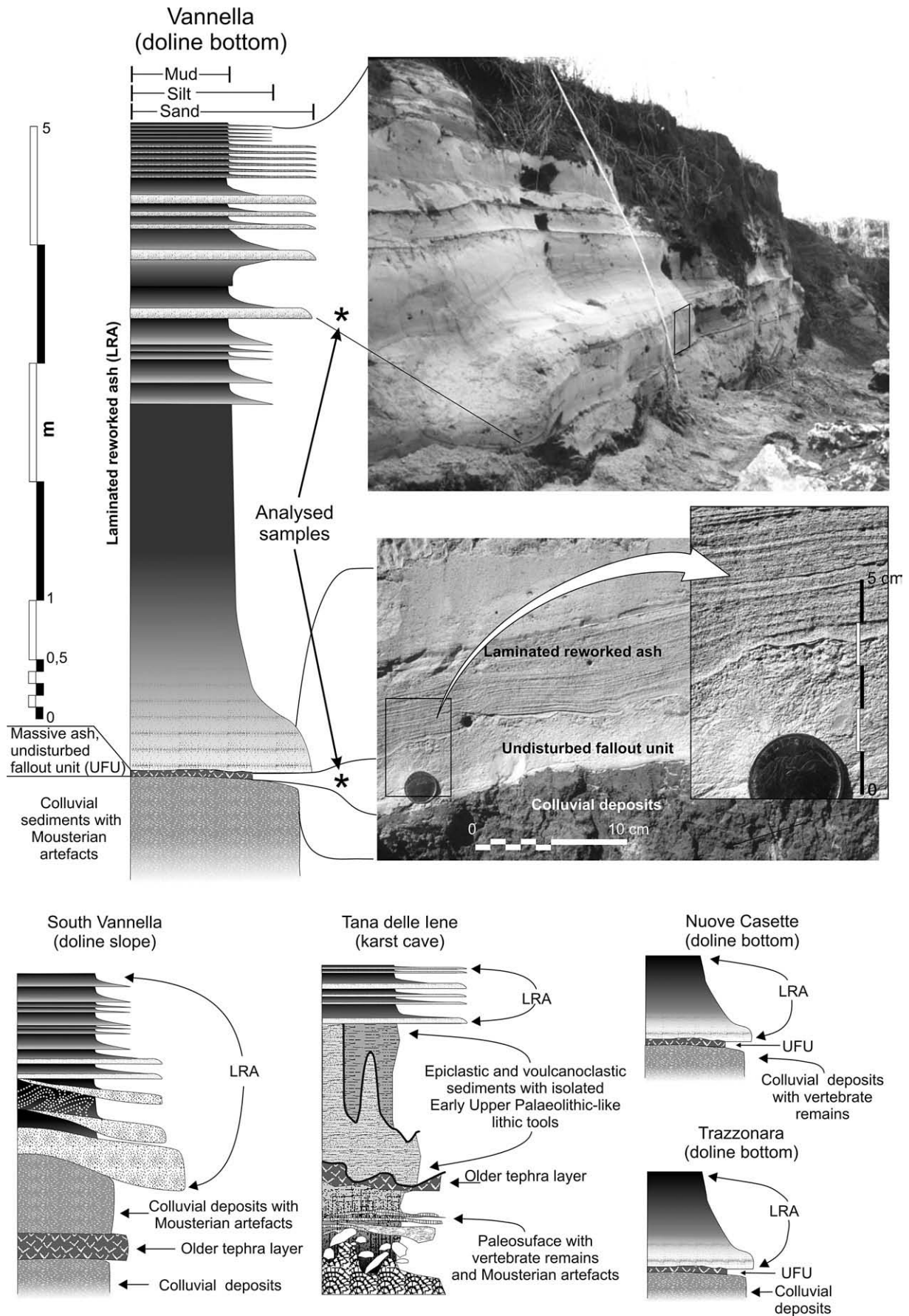
Fig 10. Simplified stratigraphic sections of the investigated tephra layers in the southern Murge area (Fig. 1). The position of the analysed samples (Table 5) is also shown.

Table 5
Average major-element composition of micro-pumices and glass shards from the Vannelle and Paglicci tephra layers (wt.% normalized to 100%). A significant chemical affinity with the Codola pyroclastic products (Table 2) and C-10 marine layer (Table 3) can be observed

| Site	Vannelle							Paglicci Cave					
Unit	UFU		LRA					PAG-a		PAG-b		PAG-c	
	$n=19$	SD	$n=2$	SD	$n=1$	$n=23$	SD	$n=11$	SD	$n=12$	SD	$n=3$	SD
SiO_2	58.39	0.71	52.11	0.49	54.18	58.74	0.75	50.56	0.54	53.05	0.88	56.24	0.32
TiO_2	0.54	0.18	0.85	0.12	1.47	0.49	0.09	0.77	0.04	0.75	0.10	0.63	0.18
$Al2O_3$	19.05	0.24	17.96	1.01	18.36	19.22	0.38	19.68	0.40	18.87	0.40	19.34	0.95
FeO	3.79	0.59	7.49	0.44	6.49	3.54	0.50	6.80	0.50	6.80	0.66	5.19	0.78
MnO	0.15	0.05	0.17	0.05	0.20	0.15	0.05	0.20	0.04	0.17	0.03	0.16	0.06
MgO	0.60	0.43	2.91	0.56	3.10	0.51	0.18	1.57	0.11	2.05	0.58	1.52	0.53
CaO	4.01	0.45	8.76	0.31	3.16	4.00	0.73	8.27	0.29	6.61	0.88	5.30	0.89
Na_2O	3.72	0.54	2.69	0.00	2.97	3.75	0.61	3.62	0.38	3.37	0.26	3.59	1.36
K_2O	8.81	0.31	5.95	0.31	9.13	8.71	0.41	7.14	0.41	7.05	0.78	7.04	1.15
P_2O_5	0.10	0.05	0.42	0.24	0.07	0.07	0.04	0.40	0.17	0.47	0.16	0.50	0.24
Cl	0.56	0.07	0.57	0.06	0.49	0.54	0.07	0.61	0.15	0.44	0.12	0.26	0.19
F	0.30	0.07	0.11	0.03	0.38	0.27	0.11	0.37	0.10	0.35	0.14	0.22	0.02
Original total	96.98	1.81	98.49	0.93	98.65	97.15	1.78	96.60	1.37	97.69	2.71	97.31	0.41
Total alkali	12.53	0.64	8.65	0.30	12.10	12.46	0.58	10.76	0.32	10.42	0.90	10.64	0.21
K_2O/Na_2O	2.41	0.31	2.21	0.12	3.07	2.39	0.46	2.00	0.29	2.10	0.23	2.35	1.55

n: number of analysed shards.
SD: standard deviation.

with the so-called Early Upper Palaeolithic, which enable us better to define the stratigraphic and temporal span of this particular cultural stage of European prehistory, a subject of continuing debate.

At Castelcivita Cave, the base of the Aurignacian or Proto-Aurignacian layers is about 50 cm below the CI tephra, which marks the interruption of human occupation in the area. According to the observations in Giaccio (2005), this half-a-metre interval must encompass only a brief span of time, no more than a few centuries. Therefore, the CI deposition would approximately coincide with the first appearance of Early Upper Palaeolithic industries at Castelcivita and possibly in southern Italy. In its turn, the Codola tephra at Paglicci Cave seals the last documented layers containing Aurignacian industry, thus marking the end of this cultural manifestation as well as the beginning of the following Gravettian stone-tool tradition. In other words, together the CI and Codola tephra may be regarded as

good temporal-stratigraphic markers for the beginning and the end – respectively – of the Early Upper Palaeolithic in southern Italy. They help in dating this cultural stage between ca. 41 and 33 cal ka BP, i.e. between Greenland Interstadials 9–10 and 5 (Fig. 7). This significant temporal extent differences between the Aurignacian of Castelcivita and Paglicci – of few centuries and several thousand of years, respectively – poses relevant questions about the regional archaeological scenarios and its relationships with the broader European framework. However an extensive treatment of this subject is out the scope of this work, and will be deal with in a near future elsewhere.

Differently from the Italian sites, in the studied archaeological sequences of eastern Europe only one of the two Early Upper Palaeolithic tephra markers has been recognised. Furthermore, at these sites the first appearance of industries ascribable to a comparable cultural stage seems to be much older than the overlying
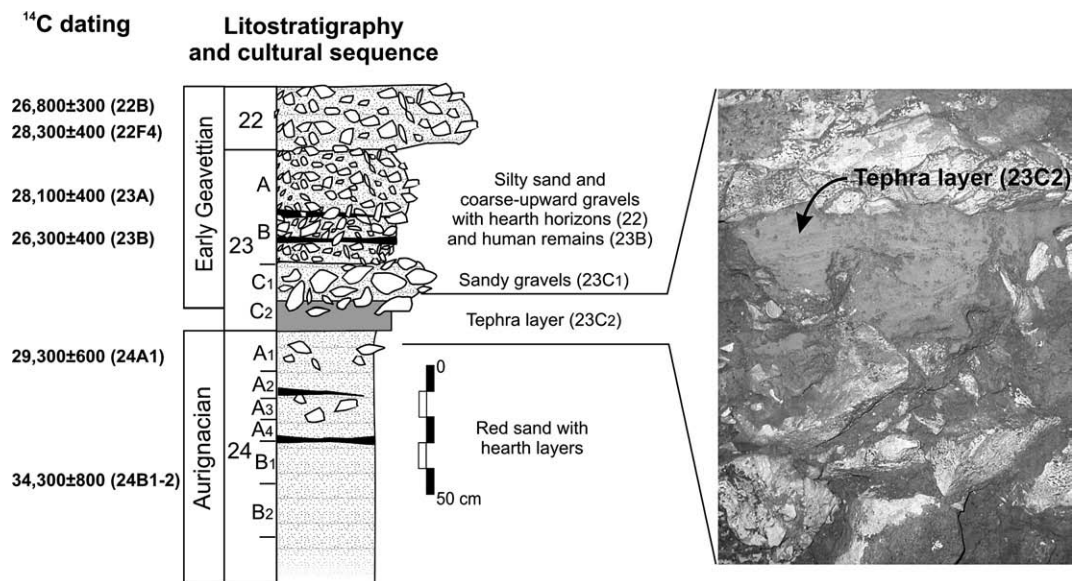
Fig 11. Stratigraphic section of the lowermost part of the Palaeolithic sequence at Paglicci Cave (see Fig. 1 for location), showing the position of the analysed tephra layer. Cultural stratigraphy and ^{14}C dating according to Palma di Cesnola (1990, 1993, 2004).
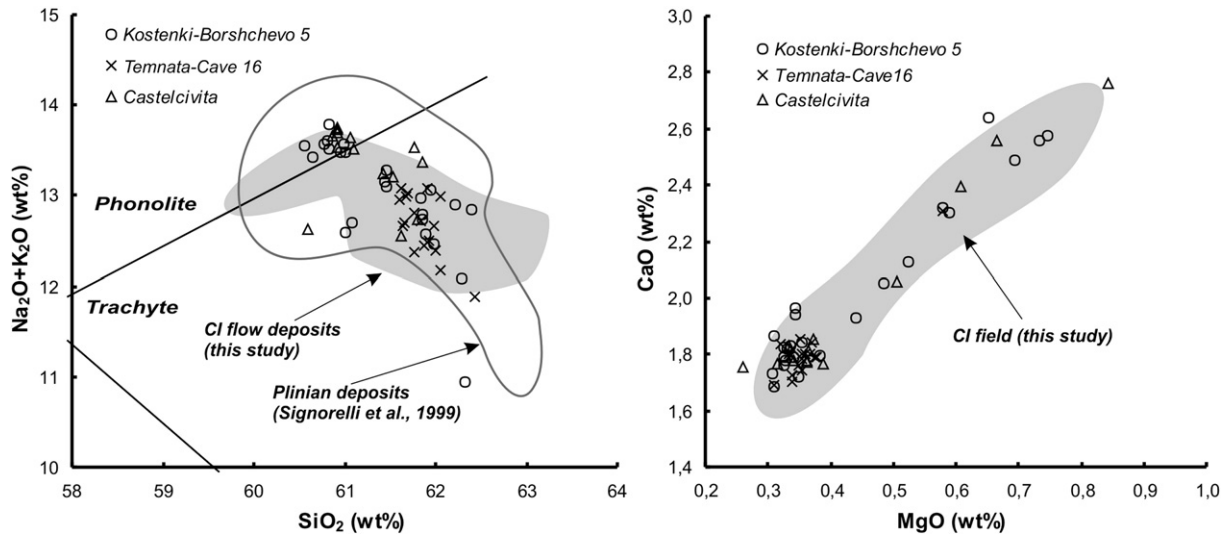
Fig 12. Total alkali silica (TAS; Le Bas et al., 1986) and CaO vs. MgO diagrams of micro-pumices and glass fragments from Castelcivita Cave, Borshchevo and Temnata-Cave 16 distal tephra layers. A significant matching with the corresponding chemical variability fields of the Campanian Ignimbrite (CI) deposits can be observed.

CI tephra. At Kostenki–Borshchevo, for instance, a series of concurrent palaeoclimatic, palaeomagnetic and chronometric data indicates that a developed "Upper Palaeolithic" industry occurs in layers some millennia older than the CI tephra, deposited during or immediately after a relatively mild and wet phase, tentatively correlated to the GI12 interstadial (dated at ca. 45 cal ka BP; Anikovich et al., 2007: 225).

In spite of these chronological differences, the tephrostratigraphic correlations show that the development of the first "Upper Palaeolithic"-type industries in both southern Italy and eastern Europe took place in the course of the last two Bond cycles of Marine Isotope Stage 3 (MIS3; ca. 58–30 cal ka BP), i.e. during one of the most unstable climatic phases of the whole Last Glacial period. This MIS3 interval was indeed characterized by exceptional instability and by a progressive trend towards the colder and drier, but much more uniform conditions of the Last Glacial Maximum. This raises the distinct possibility of an intriguing parallelism between changes in the socio-cultural domain and climatic processes. In a human ecosystem perspective (cfr. Fedele and Giaccio, 2007; Fedele et al., in press), the innovations and changes

that characterize the so-called Early Upper Palaeolithic (in tool making, circulation patterns, subsistence strategies, etc.) may represent, at least partially, adaptive devices to cope with the marked unpredictability of environments and landscapes in the second half of MIS3.

5. Conclusion

In this paper we have presented the chemical and micro-textural analyses of tephra layers recognized in strict stratigraphic relationships with the Early Upper Palaeolithic layers of important archaeological sequences of southern Italy and eastern Europe. The results confirm the recognition of the Campanian Ignimbrite tephra at Castelcivita Cave, Temnata Cave and in the Kostenki–Borshchevo site group, corroborating its additional value as a stratigraphic marker. The same results exclude its occurrence at both Paglicci Cave and lesser sites of the Murge Plateau of Apulia (Tana delle Iene Cave and dolines in the surrounding area). On the basis of chemical and stratigraphic-textural analyses, the tephra occurring in these Apulian sites can be
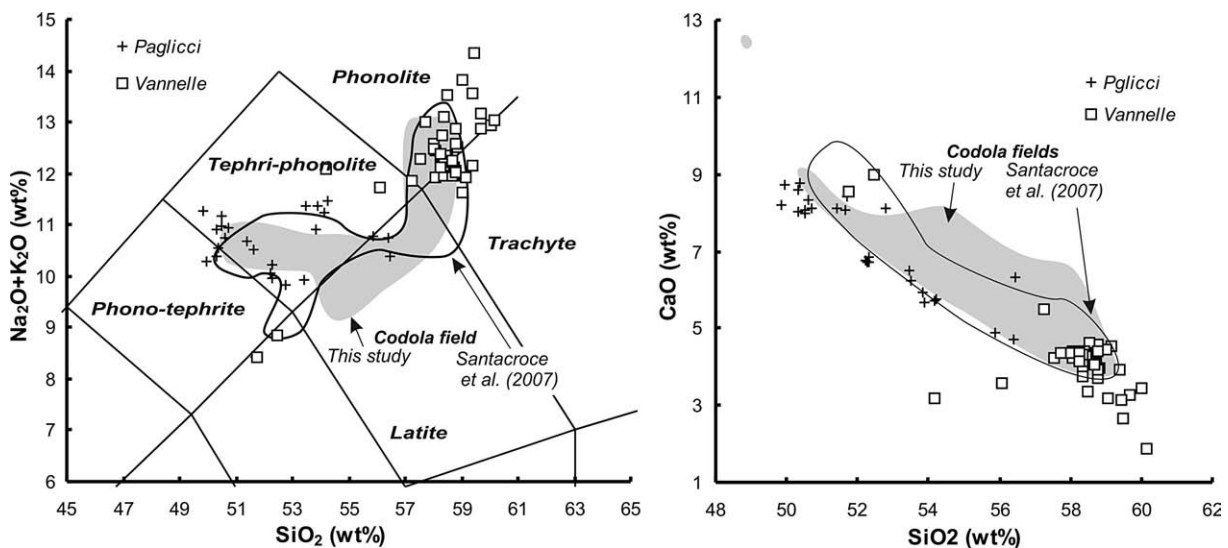
Fig 13. Total alkali silica (TAS; Le Bas et al., 1986) and CaO vs. SiO₂ diagrams of micro-pumices and glass shards from Vannelle and Paglicci distal tephra layers. A good matching with the corresponding chemical variability fields of the Codola deposits can be observed.

attributed to the Codola Plinian eruption. According to the present study, the products of this not well known eruption, probably from Somma–Vesuvius area, can be equated with the widely dispersed C-10 marine tephra layer, dated at ca. 33 cal ka BP and stratigraphically correlated to an interstadial oscillation of the Monticchio pollen record (southern Italy), likely equivalent to Greenland Intersadial 5.

The age and stratigraphic position of the Codola tephra, in conjunction with the recognition that it seals the levels containing the Aurignacian industry at Paglicci Cave, provides a marker of unexpected importance for dating and assessing the climatic context of the final stage of the Early Upper Palaeolithic in the central Mediterranean area. It parallels in significance the role of the Campanian Ignimbrite as a marker for the beginnings of the Early Upper Palaeolithic. By jointly utilizing the CI and Codola tephra as markers, here we dated the first and last documented appearance of Early Upper Palaeolithic industries in southern Italy at ca. 41 and 33 cal ka BP, respectively. That places this stage of human innovation between the Greenland Interstadials 9–10 and 5. At Kostenki–Borshchevo and possibly at Temnata Cave in Bulgaria, the Early Upper Palaeolithic occurs somewhat deeper below the CI tephra, suggesting a beginning of this cultural stage a few millennia earlier. This temporal/stratigraphic assessment of the early stage of the Upper Palaeolithic has several potential implications which indeed need of further close examinations.

Finally, a tephrostratigraphic correlation between archaeological and palaeoclimatic records indicates that the changes in tool making and human ecological strategy which identify the Early Upper Palaeolithic developed during the second half of the MIS3 interval, whose climatic variability is among the most pronounced and rapid of the Last Glacial cycle. We contend that the exceptional climatic-environmental instability of late MIS3 should be considered a potential, selective ecological factor, worth careful examination in future studies of Late Pleistocene biocultural evolution.

Acknowledgements

Appendix A

Analytical methods

Samples of tephra layers were wet sieved, dried, mounted in epoxy resin, polished and carbon coated. Major elements analyses of micropumices fragment and glass shards were performed at the Istituto di Geologia Ambientale e Geoingegneria (CNR, Rome, Italy) with a Cameca SX50 electron microprobe equipped with five wavelength-dispersive spectrometers, using 15 kV accelerating voltage, 15 nA beam current, 10–15 μm beam diameter, and 20 s counting time. The following standards were used: wollastonite (Si and Ca), corundum (Al), diopside (Mg), andradite (Fe), rutile (Ti), orthoclase (K), jadeite (Na), phlogopite (F), baritina (S), and metals (Mn). Ti content was corrected for the overlap of the Ti and Kα peaks.

Individual analyses with total oxide sums lower than 93 wt.% were excluded.

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