Quaternary Science Reviews 25 (2006) 2713–2728

Wide dispersal and deposition of distal tephra during the Pleistocene 'Campanian Ignimbrite/Y5' eruption, Italy

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Received 10 June 2005; accepted 28 June 2006

Abstract

A trachytic volcanic ash layer is widely distributed across south-western Russia, where it is found both in well-characterised archaeological contexts close to the Don River (the Paleolithic sites of Kostenki-Borschevo (51.4°N, 39.0°E), and in undisturbed geological contexts. This ash layer has all of the characteristics of a distal tephra fall deposit: it is fine grained and unimodal with a grain size of 60–170 μm, dominated by strongly elongate glass shard fragments.

Chemical analysis confirms that this ash layer is a distal equivalent of the deposits of the ca 39.3 ka Campanian Ignimbrite eruption of the Phlegrean Fields, Italy, and correlates with the widely recognised Y5 ash layer in marine cores in the south-eastern Mediterranean. This work shows that ash particles can be dispersed over considerable distances (>2500 km) and areas ($>1.5–3\times10^6\,km^2$) during large-magnitude explosive eruptions. The volume of the products associated with this event (31–50 km^3 of magma erupted as fallout tephra, and a total volume of 105–210 km^3 of magma, or $2.5–5\times10^{14}$ kg) confirms the Campanian Ignimbrite/Y5 eruption as the most significant known volcanic eruption in Europe of the past 100 ka. This correlation places tight constraints on the absolute ages of a number of important archaeological horizons in southern Russia.

1. Introduction

Quaternary tephra have been used extensively to develop a high-resolution stratigraphy for the late Pleistocene and Holocene across the eastern Mediterranean (e.g. Keller, 1971; Keller et al., 1978; Federman and Carey, 1980; Paterne et al., 1988; Vezzoli, 1991). While early work focussed mainly on samples from marine cores, recent work on terrestrial contexts (including Italian maars, Greek, Bulgarian and Italian cave sites, and Greek and Turkish lakes; e.g. St. Seymour and Christianis, 1995; Narcisi and Vezzoli, 1999; St. Seymour et al., 2004; Wulf et al., 2004; Margari et al., 2006) has considerably improved the prospects of developing a long, high-resolution tephra stratigraphy that will link marine and terrestrial records of Pleistocene age across eastern Europe.

The largest known European eruption of the last 100,000 yr was the Campanian Ignimbrite (Barberi et al., 1978) at ca 39–41 ka BP (De Vivo et al., 2001; Ton-That et al., 2001). The vent for this eruption is generally thought to have been located in the Campi Flegrei (Phlegrean Fields) region of southern Italy, close to the present day Bay of Naples (Fig. 1a), and the extensive proximal ignimbrite deposits from this event are correlated with a widespread ash horizon, Y5, that is recognised in cores across the eastern Mediterranean. While the axis of deposition for the distal tephra associated with this eruption was originally thought to trend to the southeast, away from the central Italian source region and along the axis of the Eastern Mediterranean (e.g. Keller et al., 1978; Federman and Carey, 1980; Cornell et al., 1983), this was

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0277-3791/$ - see front matter
doi:10.1016/j.quascirev.2006.06.008

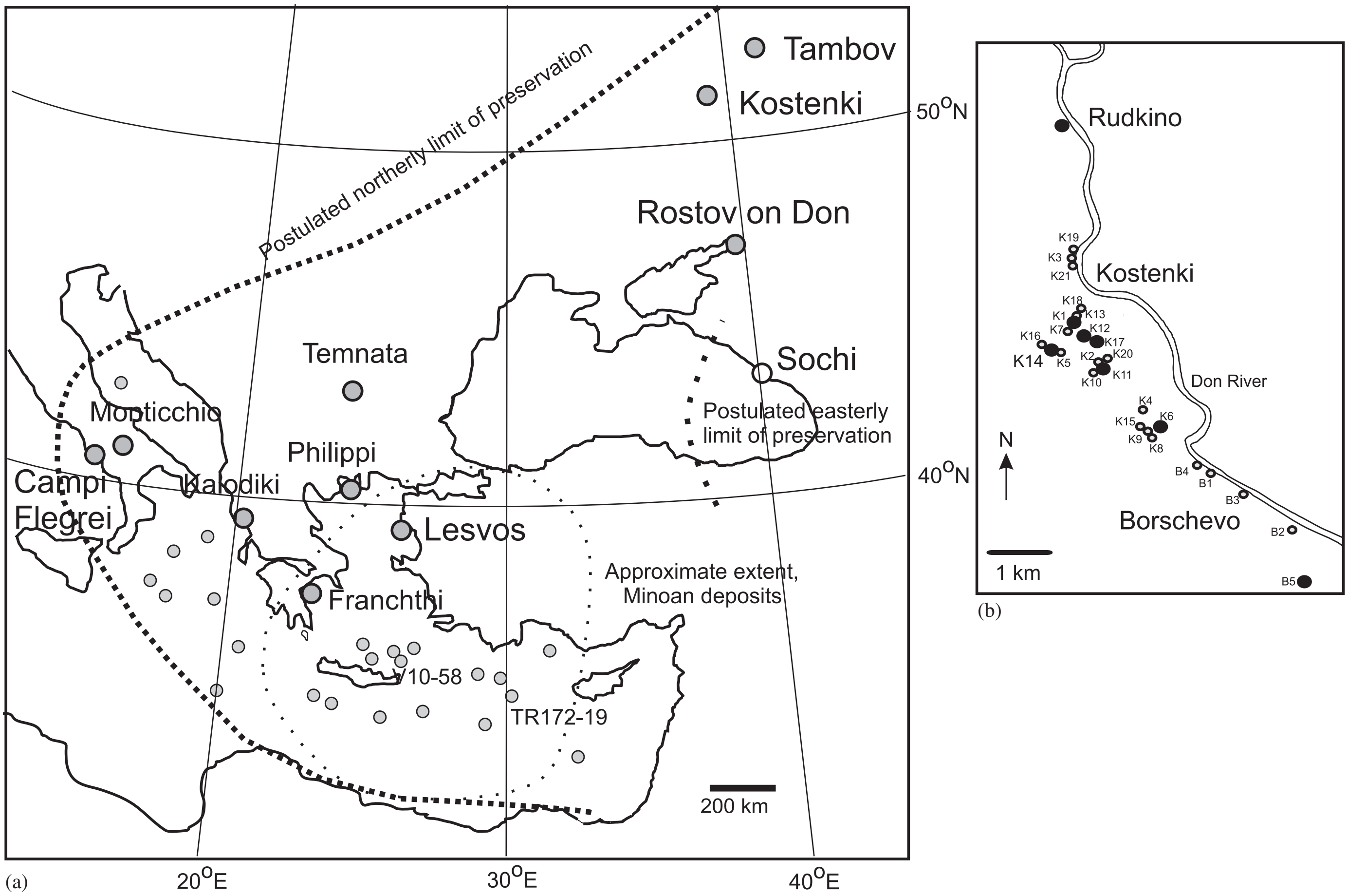

Fig. 1. (a) Map to show location of Kostenki and the general distribution of the Y5 tephra layer and correlated tephra horizons. The approximate southerly 1 cm isopach is based on marine core data (Cornell et al., 1983); the suggested northerly and easterly limits are discussed in the text. Grey-filled circles indicate selected localities where terrestrial deposits of Y5 tephra have been recognised: Kalodiki fen and Philippi peat bogs, Greece (St. Seymour and Christianis, 1995; St. Seymour et al., 2004); Paleolithic contexts in caves at Temnata (Bulgaria) and Franchthi (Greece; Pawlikowski, 1992; Paterne, 1992; Federman and Carey, 1980; Vitaliano et al., 1981). The approximate extent of deposition of a discrete tephra layer during the ca 3.7 ka BP Minoan eruption of Santorini is shown for comparison. (b) Location map showing the outline distribution of archaeological sites (Kostenki: *K* numbers; Borschevo: *B* numbers) in the Don river region between Rudkino and Borschevo. Filled circles indicate localities where tephra have been recognised (adapted from Sinitsyn, 2003). Kostenki lies at approximately 51.4°N, 39.0°E.

brought into question with the recognition of a trachytic ash layer with a composition similar to Y5 in southern Russia (Melekestsev et al., 1984; Fig. 1a). This Russian work and its implications have been overlooked until recently (e.g. Narcisi and Vezzoli, 1999; Fedele et al., 2003). Here, we present new descriptions and analyses of this Russian tephra unit; demonstrate that this can be correlated with the Y5/Campanian Ignimbrite eruption, and use this to draw some conclusions about the volume of the original eruption, and implications for the dating of Palaeolithic archaeological sequences across eastern Europe.

2. Tephra at Kostenki, Don river, Russia

The plains of southwestern Russia extend from the Ukraine to the Caucasus mountains, and contain abundant archaeological evidence for human occupation over the past 30–60,000 yr. One well-known cluster of Palaeolithic archaeological sites is at Kostenki, Voronezh (51.39°N, 39.04°E; Fig. 1b). Here, numerous archaeological sites have been investigated over the past 125 yr (Sinitsyn, 1996, 2002; Praslov and Sulerzhitskii, 1999; Anikovich and Platonova, 2004). During the 1970s and 1980s, a tephra layer was found in a number of locations, both within archaeological contexts and elsewhere, extending from Kostenki as far south as Rostov on Don (47.1°N 39.5°E; Kholmovoy, 1989; Tsekhovskii et al., 1998), and as far north as Tambov (52.5°N, 41.5°E) (Melekestsev et al., 1984).

In the site Kostenki 14 (Markina Gora), the tephra layer forms a key stratigraphic horizon (Fig. 2). Here, the tephra layer lies above a palaeosol, which contains evidence for the Laschamp magnetic excursion (Gernik and Guskova, 2002; locally recognised as the Kargapolovo excursion, Pospelova et al., 1998), which is currently dated (elsewhere) to 40.3–41.7 ka Cal BP (Voelker et al., 2000). The tephra layer also lies stratigraphically above cultural layers that contain artifacts with Upper Palaeolithic affinities (Sinitsyn, 2003). Uncalibrated ^{14}C dating of charcoal from a cultural layer that is intimately associated with the tephra horizon yields an apparent ^{14}C age of $32{,}420 \pm 440$ yr (Sinitsyn, 2003).

At Kostenki 14, and at the nearby sites of Borschevo 5 and Rudkino, the volcanic ash layer forms a more-or-less continuous stratigraphic layer (Figs. 2 and 3). The tephra horizon ranges in colour from grey to pale yellow, depending on the extent of admixture with the surrounding chalky loam, and ranges up to 10 cm in thickness. From the exposed sections, and from detailed observations of the excavated planform of the tephra deposit, it is clear that much of the variability in thickness and outcrop relates to the periglacial phenomena that affect many of the sites at Kostenki (e.g. cryoturbation; Sinitsyn, 1996; Holliday 2004, p. 280). Within Kostenki 14, the mean ash layer thickness is 1.4 cm, based on measurements of exposed ash layer in the archaeological sections. In thin section, the clear glassy and tricuspate shards of the tephra horizon can be clearly seen (Fig. 4). While there is some contamination of the tephra horizon with both organic and inorganic material, the basal contact of the tephra horizon on the underlying sediment is sharp, and the lowest 1–2 mm of the unit appears to be particularly clean.

The same tephra horizon has also been noted at a number of other sites at Kostenki (Fig. 1b); and a lateral equivalent was discovered at a new site at Borschevo 5 during excavations in 2002 (Sinitsyn, 2003, Fig. 3). The same tephra horizon is also found locally in non-archaeological contexts, particularly in the region around Rudkino where erosion of a massive sequence of fine-grained 'loessic' sediments exposes a continuous tephra layer, several metres below the present-day surface (Fig. 3c). Here, while the ash layer appears to be of more or less uniform thickness (1–2 cm) over many tens of metres, it also forms discrete and complexly folded lenses where the tephra layer reaches 30 cm in thickness. At Rudkino, the cleanest tephra layer has an in situ bulk density of 985 kg/m^3. The exposed thickness variations are ascribed primarily to aeolian reworking of the deposit shortly after emplacement, while the further complexities of the deposit are interpreted as due to periglacial disturbances (cryoturbation).

3. Analysis of samples

Volcanic ash samples collected from Kostenki 14 and Rudkino were analysed in Cambridge for their grain size characteristics, for particle morphology, and for their chemical compositions by electron microprobe and ICP-MS.

3.1. Electron probe micro-analysis

Tephra samples from Kostenki and Rudkino were wet sieved to separate the 53–106 μm grain size fraction, dried and mounted in epoxy resin. Polished and carbon coated

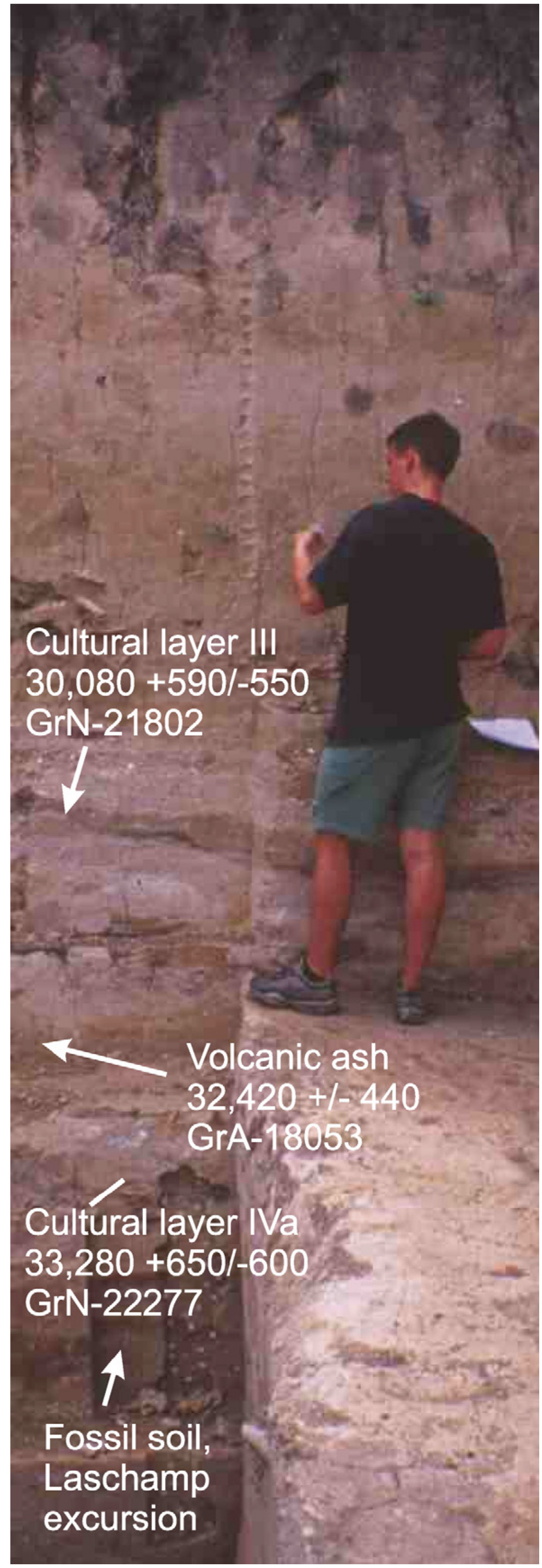

Fig. 2. Partial stratigraphy of the Kostenki 14 (Markina Gora) archaeological section. The indicated dates are all un-calibrated radiocarbon dates. The volcanic ash layer (32,420 ^{14}C yr), overlies the level of the Laschamp excursion identified in a palaeosol. Also note the presence of the cultural layer (IVa) below the ash layer. (After Sinitsyn, 1996, 2002, 2003).

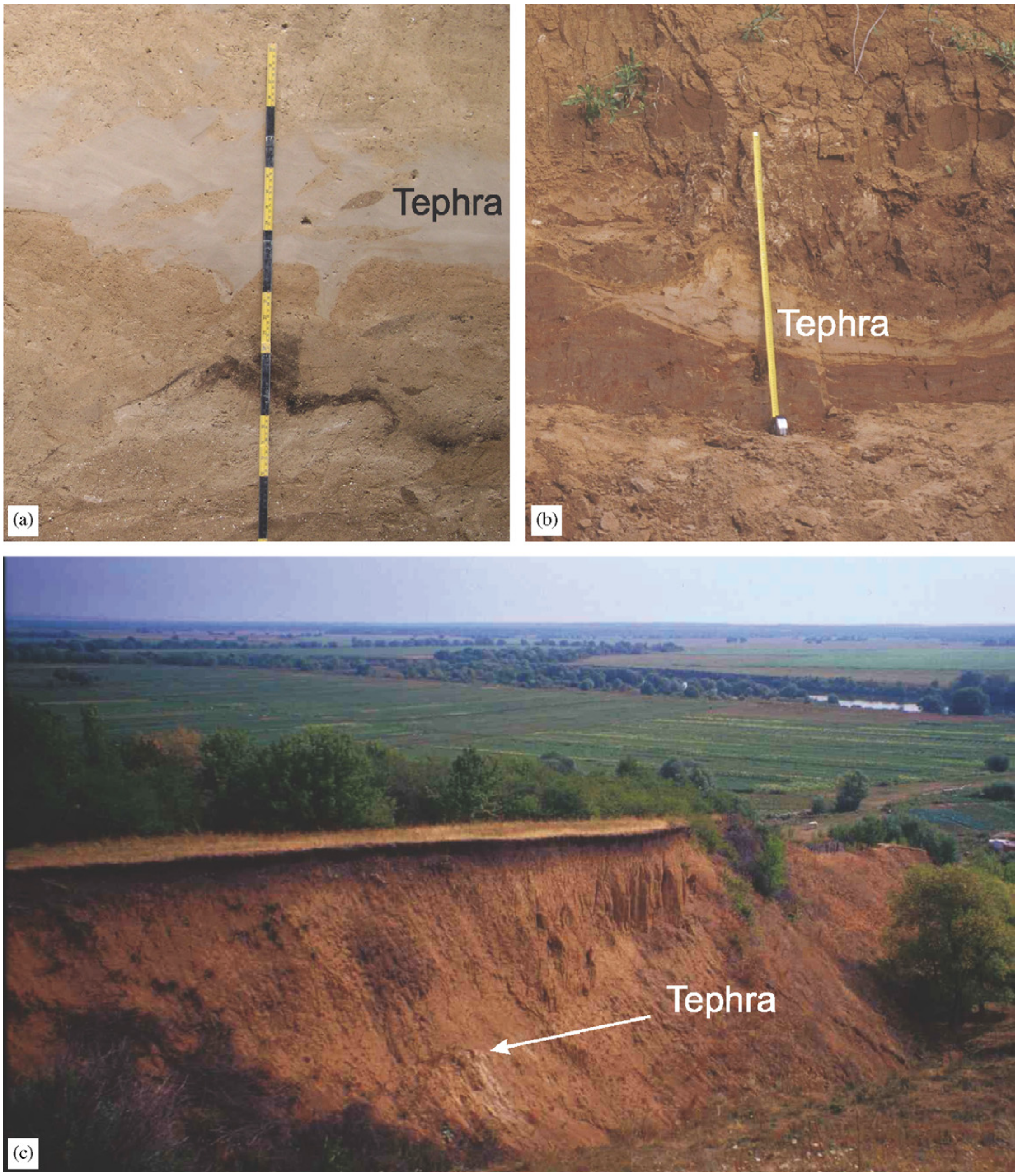

Fig. 3. (a) Stratified tephra layer in the Borschevo 5 excavation. The 10–20 cm thick tephra layer is visible in mid-section. Scale bar with 10 cm divisions. (b) Detail of cryoturbated, 30 cm thick lens of tephra at Rudkino; measuring tape is extended to 1 m. (c) General view, looking North-East, of the tephra horizon at Rudkino. The 1–2 cm thick ash horizon is weathering out, about half-way down a 10 m thick section of young sediments. The Don river is in the background.

samples were analysed by wavelength dispersive spectrometry for their major element constituents using a Cameca SX100 electron microprobe with a 10 μm beam and a 15 kV accelerating voltage. Na, Si, K, Al and Ca were analysed with a 6 nA beam current, and 10 s (Na) or 20 s peak count times. Mg, Cl, P, Ti, Mn and Fe were analysed with a 40 nA beam current, with peak count times of 20–40 s. Internal standards were jadeite (Na), corundum (Al), diopside (Si, Ca), orthoclase (K), periclase (Mg), halite (Cl), apatite (P), and Ti, Fe and Mn metals. Typical reproducibility is 1–2% relative. Samples were analysed in one session, and known samples of Y5 tephra (from Mediterranean marine cores) were analysed at the same time for comparison.

3.2. ICP MS analysis

Samples were analysed for selected trace elements by ICP MS analysis in Cambridge. A total of 0.1 g of cleaned glass shards (>63 μm sieve) was taken into solution using repeated HNO_3/HF acid attack; dried down, and then made up to 50 ml in 2% HNO_3. Solutions

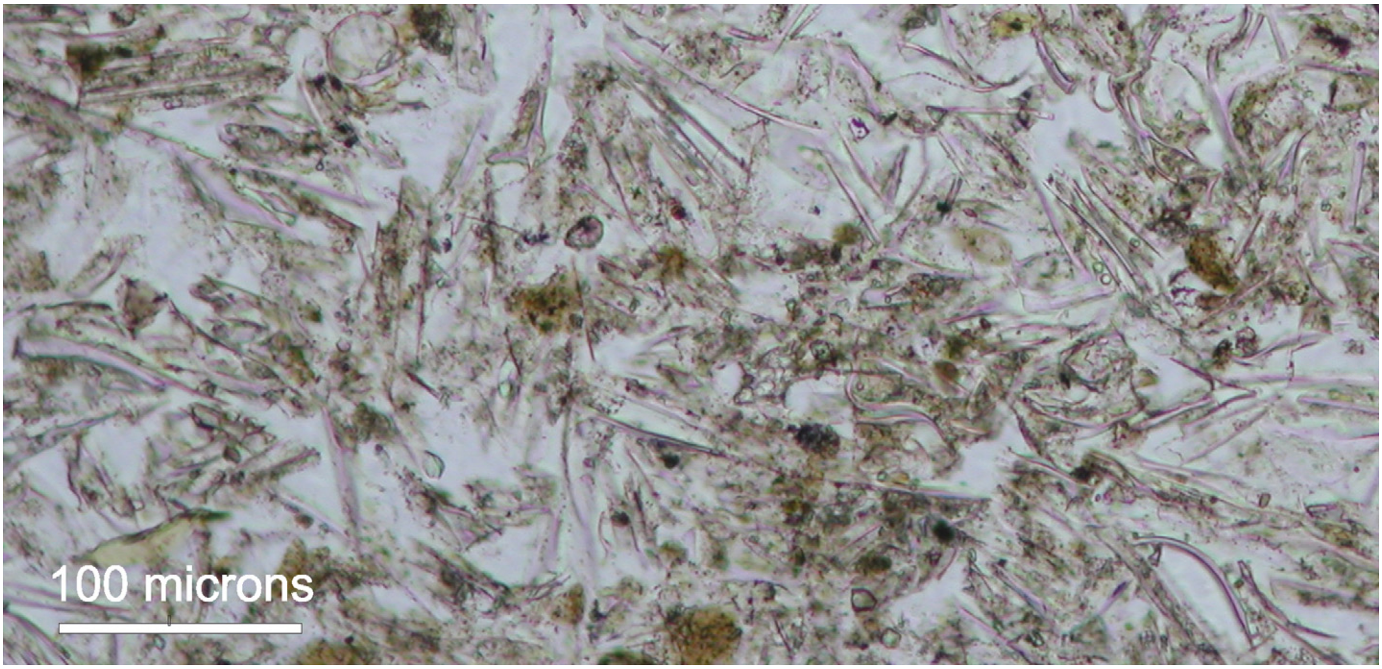

Fig. 4. Photomicrograph of an impregnated soil thin sections from Kostenki 14. Field of view ca 0.5 mm. Many shards are strongly elongate, others are tri-cuspate; both are characteristic of distal tephra.

were automatically taken in to the ICP MS (Perkin Elmer Elan DRC II), and analysed in sequence along with standard reference rock samples and internal calibrations. Typical precision is 0.5–5% relative based on repeat analysis of standard reference materials.

3.3. Particle size analysis

Particle size analysis was performed in the Physical Geography Laboratories, University of Cambridge. Samples were disaggregated in sodium pyrophosphate, placed in a water bath at 90 °C for 3 h, and stirred once with a glass rod. Samples were removed from the water bath and centrifuged at 3500 rpm for 13 min before decanting the liquid. Before analysis using a Malvern Mastersizer 2000, a few drops of de-ionised water were added to each sample in turn, which were agitated until the sediment was in suspension. While the Malvern Mastersizer is not ideal for measuring angular glass shards, the technique was adopted as the best available method of measuring both fine and coarse grains in the same sample.

4. Results

Analysis of tephra samples from the Kostenki region (Rudkino and Borschevo 5) by electron microprobe for major chemical constituents (Table 1, Fig. 5) and ICP-MS (for trace elements, Table 2, Fig. 6) confirms the nature and provenance of the tephra. The tephra are alkali trachytes, typical of tephra from the Campanian province of Italy. Samples span a range of compositions, and overlap extensively both with published analyses of the Y5 tephra (e.g. samples from Kalodiki fen, Greece; St. Seymour and Christianis, 1995; Fig. 5), with the new analyses of known Y5 tephra from marine cores; Fig. 5) and with matrix glasses from the Campanian Ignimbrite (e.g. Signorelli et al., 1999; Fig. 5). The most striking features of several of the bivariate plots in Fig. 5 is that both the scatter of compositions in the analysed samples (e.g. K_2O–FeO, Fig. 5b) and the range (e.g. in Cl contents) matches very closely that measured in proximal ignimbrite matrix glasses. This broad range of compositions is therefore a real reflection of the diversity of melt compositions present in the magma chamber just prior to eruption.

There is also excellent agreement between our analyses of the rare earth and other trace elemental constituents of tephra both from Russia (Kostenki 14 and Rudkino), a Greek lake sequence (Lesvos; Margari et al., 2006) and known Y5 tephra layers from two Mediterranean marine cores (172-11 and 172-19), which gives further confidence to the correlation. Normalised rare earth element compositions are clearly distinguished from, for example, compositions of Aegean tephra (Fig. 6).

On the basis of the coherence between the compositional trends of the samples from Kostenki and Rudkino and those from the Y5/Campanian Ignimbrite eruption, we suggest that the Russian tephra layer is a distal portion of the Y5 ash layer.

The size and morphology of the tephra grains confirms that the horizon is a distal ash fall deposit. Grains are almost exclusively of vitric ash, and are uniformly thin and elongated (Fig. 4), comprising pipe-vesicle bubble wall shards or, more rarely, tri-cuspate fragments. In thin section, the typical aspect ratio of the glass shards is 4.9.

Table 1
Electron microprobe analyses of tephra from Borschevo and Rudkino, Russia

	Marine Y5 layer in core TR 172-19 PC						
Wt.%	1	2	3	4	5/1	6/1	7/1
SiO_2	58.9	57.4	61.0	58.7	57.8	57.9	57.5
TiO_2	0.49	0.49	0.51	0.40	0.48	0.47	0.51
Al_2O_3	17.9	17.6	18.1	16.8	17.7	17.7	17.5
FeO	3.04	3.10	2.89	2.85	2.95	2.97	3.02
MgO	0.35	0.40	0.34	0.52	0.34	0.35	0.35
MnO	0.26	0.25	0.23	0.13	0.23	0.26	0.25
CaO	1.73	1.75	1.59	1.93	1.59	1.68	1.66
K_2O	7.26	7.30	7.39	8.34	7.19	7.28	7.85
Na_2O	6.52	5.83	6.64	4.47	6.22	5.64	5.24
P_2O_5	0.05	0.04	0.05	0.10	0.07	0.06	0.06
Cl	0.83	0.84	0.83	0.45	0.84	0.83	0.80
Total	97.28	95.00	99.57	94.72	95.40	95.17	94.79

	Rudkino										
Wt.%	1/1	3/1	5/1	6/1	7/1	8/1	9/1	13/1	14/1	18/1	20/1
SiO_2	59.7	60.3	58.2	59.4	58.8	59.9	60.4	58.4	59.2	59.2	59.7
TiO_2	0.50	0.40	0.41	0.49	0.50	0.49	0.41	0.48	0.50	0.42	0.42
Al_2O_3	18.2	18.1	17.6	17.8	17.9	18.2	17.7	17.6	17.7	17.6	18.1
FeO	3.14	2.90	3.47	3.02	3.08	3.01	3.25	3.11	3.07	2.83	3.48
MgO	0.35	0.55	0.78	0.36	0.36	0.34	0.64	0.35	0.34	0.43	0.76
MnO	0.26	0.12	0.13	0.24	0.27	0.29	0.12	0.25	0.23	0.17	0.13
CaO	1.68	2.03	2.45	1.59	1.72	1.70	2.28	1.68	1.77	1.83	2.44
K_2O	7.37	9.48	9.96	7.22	7.19	7.40	9.81	7.50	7.42	7.55	8.59
Na_2O	6.52	4.00	2.95	6.45	6.21	6.73	3.70	5.94	6.23	4.97	4.26
P_2O_5	0.06	0.11	0.17	0.06	0.04	0.05	0.13	0.04	0.06	0.07	0.16
Cl	0.81	0.40	0.34	0.81	0.84	0.83	0.37	0.84	0.84	0.54	0.31
Total	98.55	98.44	96.41	97.47	96.89	98.90	98.72	96.24	97.38	95.61	98.33

	Rudkino										
Wt.%	21/1	22/1	24/1	25/1	26/1	27/1	28/1	29/1	30/1	31/1	32/1
SiO_2	59.2	59.6	58.7	59.4	60.8	57.7	58.9	59.7	60.2	59.6	59.2
TiO_2	0.43	0.43	0.44	0.50	0.46	0.40	0.45	0.46	0.50	0.51	0.50
Al_2O_3	18.2	17.6	17.5	18.1	17.8	17.1	17.1	17.5	18.0	17.9	18.1
FeO	3.60	3.54	3.35	3.05	2.83	3.39	2.85	2.87	3.10	3.06	3.09
MgO	0.81	0.78	0.65	0.34	0.41	0.69	0.40	0.40	0.34	0.35	0.33
MnO	0.13	0.13	0.14	0.27	0.15	0.12	0.18	0.19	0.27	0.26	0.27
CaO	2.61	2.58	2.27	1.71	1.76	2.39	1.73	1.62	1.73	1.67	1.70
K_2O	8.52	8.32	9.17	6.83	7.92	9.50	7.53	8.06	7.31	7.07	7.06
Na_2O	4.13	4.24	3.69	6.43	5.55	3.26	5.32	5.21	6.63	6.43	6.53
P_2O_5	0.15	0.16	0.12	0.04	0.07	0.15	0.06	0.06	0.07	0.06	0.06
Cl	0.34	0.33	0.41	0.85	0.58	0.36	0.59	0.60	0.87	0.85	0.86
Total	98.09	97.74	96.44	97.58	98.26	95.07	95.12	96.65	99.00	97.71	97.64

	Rudkino										
Wt.%	21/1	22/1	24/1	25/1	26/1	27/1	28/1	29/1	30/1	31/1	32/1
SiO_2	59.2	59.6	58.7	59.4	60.8	57.7	58.9	59.7	60.2	59.6	59.2
TiO_2	0.43	0.43	0.44	0.50	0.46	0.40	0.45	0.46	0.50	0.51	0.50
Al_2O_3	18.2	17.6	17.5	18.1	17.8	17.1	17.1	17.5	18.0	17.9	18.1
FeO	3.60	3.54	3.35	3.05	2.83	3.39	2.85	2.87	3.10	3.06	3.09
MgO	0.81	0.78	0.65	0.34	0.41	0.69	0.40	0.40	0.34	0.35	0.33
MnO	0.13	0.13	0.14	0.27	0.15	0.12	0.18	0.19	0.27	0.26	0.27
CaO	2.61	2.58	2.27	1.71	1.76	2.39	1.73	1.62	1.73	1.67	1.70
K_2O	8.52	8.32	9.17	6.83	7.92	9.50	7.53	8.06	7.31	7.07	7.06
Na_2O	4.13	4.24	3.69	6.43	5.55	3.26	5.32	5.21	6.63	6.43	6.53
P_2O_5	0.15	0.16	0.12	0.04	0.07	0.15	0.06	0.06	0.07	0.06	0.06
Cl	0.34	0.33	0.41	0.85	0.58	0.36	0.59	0.60	0.87	0.85	0.86
Total	98.09	97.74	96.44	97.58	98.26	95.07	95.12	96.65	99.00	97.71	97.64

Table 1 (*continued*)

Wt.%	Borschevo 5 12/1	13/1	14/1	15/1	17/1	19/1	20/1	21/1	22/1	23/1	24/1
SiO_2	59.3	58.6	59.2	59.3	59.3	58.4	59.6	59.9	60.5	59.1	58.5
TiO_2	0.46	0.47	0.48	0.49	0.49	0.48	0.42	0.49	0.41	0.40	0.50
Al_2O_3	17.5	17.4	17.7	17.8	17.9	17.9	17.6	17.6	17.4	17.5	17.8
FeO	2.84	2.88	2.99	2.98	3.03	2.95	2.88	2.97	2.84	3.12	3.13
MgO	0.37	0.37	0.35	0.35	0.36	0.36	0.46	0.34	0.48	0.64	0.33
MnO	0.20	0.23	0.27	0.25	0.27	0.25	0.15	0.22	0.14	0.14	0.23
CaO	1.81	1.66	1.67	1.68	1.73	1.69	1.88	1.61	1.92	2.36	1.71
K_2O	7.09	7.27	6.94	7.21	7.50	7.35	8.01	8.16	8.52	9.16	8.34
Na_2O	5.93	5.46	6.15	6.41	6.13	6.10	4.80	5.96	4.61	3.77	5.77
P_2O_5	0.06	0.06	0.06	0.04	0.05	0.06	0.08	0.06	0.08	0.12	0.05
Cl	0.69	0.67	0.79	0.84	0.82	0.80	0.48	0.84	0.49	0.39	0.83
Total	96.28	95.06	96.57	97.37	97.64	96.33	96.37	98.16	97.48	96.77	97.22

Wt.%	Borschevo 5 25/1	26/1	27/1	29/1	30/1
SiO_2	58.3	58.6	57.8	59.9	58.4
TiO_2	0.50	0.50	0.49	0.51	0.51
Al_2O_3	17.7	17.9	17.8	18.0	17.7
FeO	3.02	3.01	2.98	3.01	3.08
MgO	0.36	0.35	0.35	0.36	0.36
MnO	0.22	0.23	0.26	0.28	0.28
CaO	1.71	1.69	1.77	1.67	1.74
K_2O	7.34	7.20	7.45	7.46	7.02
Na_2O	6.09	6.37	5.69	6.73	6.36
P_2O_5	0.05	0.06	0.06	0.05	0.06
Cl	0.84	0.84	0.84	0.83	0.83
Total	96.09	96.79	95.42	98.81	96.27

Particle size data (Fig. 7) show that the fall deposit has a simple unimodal grain size distribution. The fine modal particle size (60–170 μm, or 3.5–5 ϕ units) and good sorting is characteristic of distal tephra-fall deposits (e.g. Rose et al., 2003). The particle size mode of the ash at Kostenki (~2500 km from the postulated source) is similar to the fine mode of the Y5 ash in Mediterranean marine cores between 750 and 1500 km from the presumed Phlegrean field source area (ca 5 ϕ units; Sparks and Huang, 1980; Cornell et al., 1983), while the lack any evidence for a bi-modal grain size distribution is consistent with the unimodal nature of the most distal tephra samples analysed by these authors (see Pyle, 1989).

5. Discussion

5.1. Correlation of the Kostenki tephra with the Y5/Campanian Ignimbrite eruption deposits

The alkali trachytes of southern Italy have a very distinctive composition that allows them to be readily distinguished from tephra from other sources in the Mediterranean (e.g. Keller et al., 1978). In terms of chemical fingerprinting, the trace-elemental characteristics are the key to distinguishing the provenance of the source region (Clift and Blusztajn, 1999), and the Nb/Zr ratios of the Kostenki and Rudkino tephra (~0.2, Table 2) clearly identify these samples as having an Italian source (as with Y5, Table 2), rather than a source in the Aegean or Turkey (Clift and Blusztajn, 1999). The trachytic composition of the Kostenki tephra also rules out a more 'local' derivation, for example from the young Caucasian volcanoes of south-west Russia and Georgia. These volcanoes, which include the >5000 m high stratocones of Kazbek and Elbrus, are calc-alkaline in nature and lie about 1000 km south-east of Kostenki. Their eruptive history extends into the Holocene (e.g. Chernyshev et al., 2002), and while little is known about the detailed eruptive histories of these volcanoes, there is no evidence for widespread tephra originating from eruptions of these centres having been deposited far upwind (beyond the Caucasus mountains), although some Pleistocene tephras are reported from archaeological contexts in northern Ossetia (Hidjrati et al., 2003). For these reasons we concur with Melekestsev et al. (1984): the most likely source of the Kostenki tephra was a large eruption in the Campanian province of Italy.

The stratigraphic relationships of the Kostenki tephra are consistent with a correlation with the Y5 ash layer. The reported ^{14}C ages (Sinitsyn, 2003); the association of the tephra layer with cultural sequences of Aurignacian affinity (Sinitsyn, 2003); and the observation that the tephra layer is just a little younger than the Laschamp excursion (Gernik and Guskova, 2002) are all consistent with

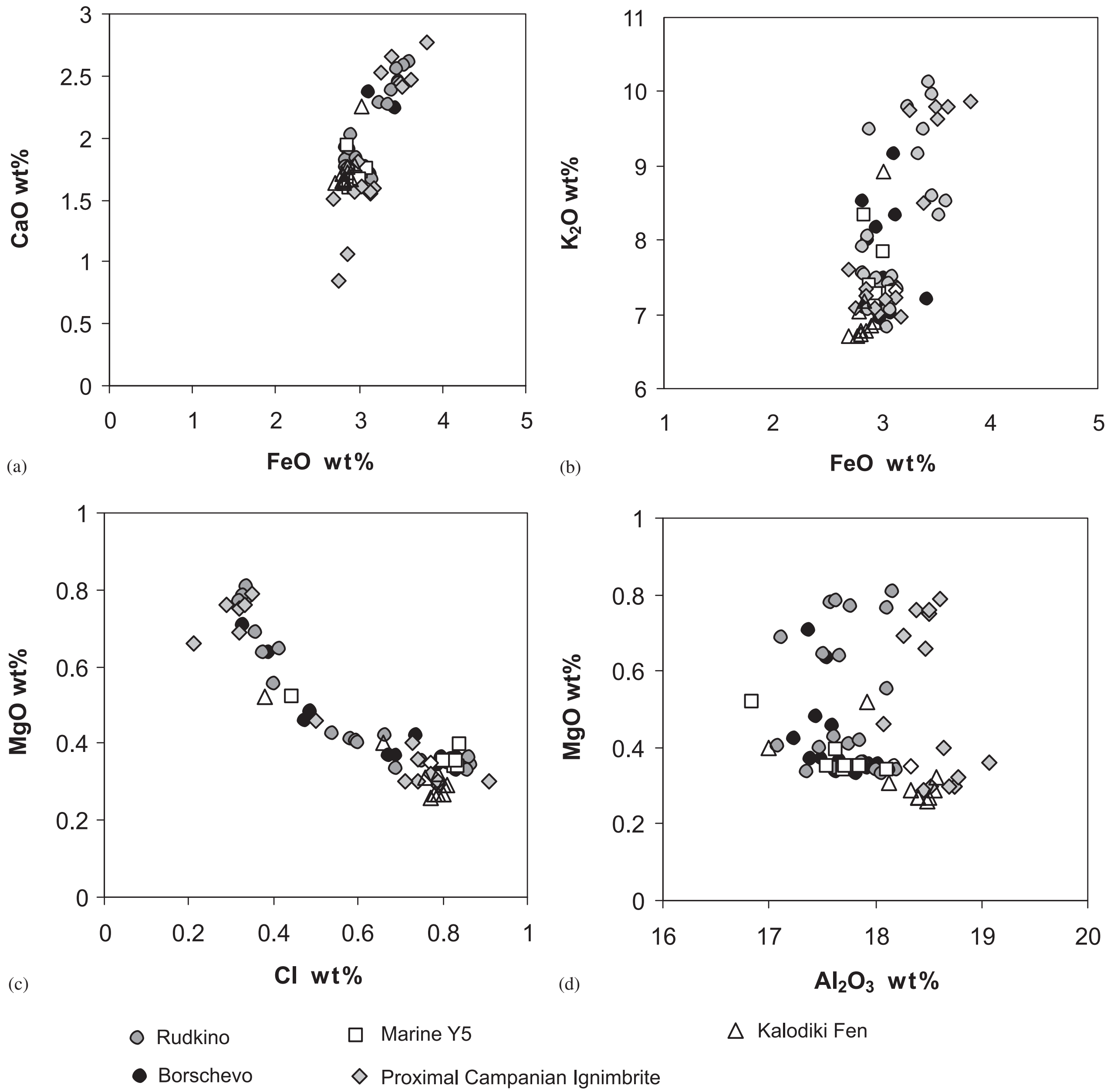

Fig. 5. Bivariate chemical plots to show the major elemental analyses of glass shards from Rudkino and Kostenki compared to samples of Y5 tephra/Campanian Ignimbrite matrix glasses from the proximal Campanian Ignimbrite eruption fall unit and flow units b and c (Signorelli et al., 1999); Y5 tephra from marine core TR 172 19PC, and Kalodiki (Greece, St. Seymour and Christianis, 1995). Note the extensive overlap between Kostenki and Rudkino samples and other Y5 samples; in particular, note the tight correlation between Mg and Cl, and the broad range of compositions, reflecting the chemical zonation of the pre-eruptive magma chamber (cf. Signorelli et al., 2001).

stratigraphic relationships of the Y5 layer as documented in marine cores in the Mediterranean (e.g. Castagnoli et al., 1995) and in archaeological sequences across southern Italy (e.g. Mussi, 1999; Fedele et al., 2003). We suggest, therefore, that the Kostenki tephra are distal equivalents of the Y5 ash and the Campanian Ignimbrite eruption deposits.

As we have shown, the compositions of analysed samples are consistent with such an interpretation. It is difficult to *prove* a correlation, however, simply on the basis of analyses of the glasses due, in part, to the heterogeneous nature of the materials erupted during the eruption. A second, and more fundamental, reason why the major element compositions of glasses may not always provide decisive fingerprints for correlation is due to the natural tendency of volcanic rock sequences from the same magmatic province to follow similar pre-eruption crystallisation paths, and to end up with closely similar compositions. This can be seen, for example, on the triangular compositional variation plot shown in Fig. 8. This plot compares the K, Fe and Ca contents of glasses (normalised to Al) from this study with 'averaged'

Table 2
Trace elemental compositions of bulk tephra samples from Kostenki and Rudkino, determined by ICP MS

ppm	Rudkino	Kostenki	172-11	172-19	CI 104c	CI 104d
Be	15.4	16.2	14.0	13.3		
Sc	4.9	4.9	5.0	8.1	6	4
V	51	48	59	60	58	19
Zn	112	116	100	104		
Rb	294	297	211	235	338	445
Sr	276	262	220	215	460	50
Y	47	47	37	38	27	52
Zr	437	450	425	407	232	579
Nb	81	84	89	81	33	93
Cs	21	22	16	17		
La	82.1	83.9	65.4	69.9	56	116
Ce	166	169	155	155	106	217
Pr	18.1	18.4	15.1	15.7		
Nd	62.3	63.3	51.9	53.8	42	81
Sm	10.8	11.2	9.3	9.6	7	14
Eu	1.6	1.7	1.4	1.4	2.3	1.6
Gd	9.2	9.1	7.8	7.9	6	12
Tb	4.5	4.6	3.8	3.9		
Dy	7.7	7.9	6.5	6.6	5	9
Ho	2.9	2.9	2.4	2.4		
Er	4.3	4.3	3.5	3.6	2.4	4.9
Tm	2.4	2.4	2.0	2.0		
Yb	4.2	4.2	3.5	3.5	2.4	5.1
Lu	4.8	4.9	5.5	5.0	0.4	0.8
Ta	4.0	4.1	5.6	5.1		
Pb	47	48	50	50		
Th	35.8	36.1	45.5	42.6		
U	10.5	10.6	7.9	8.7		

172-11 and 172-19: Y5 ash layers from Trident marine cores (at 1 and 1.27 m depths, respectively, Hardiman, 1999). CI 104c, 104d—trace elemental compositions of separated glasses from Campanian Ignimbrite deposits at San Nicola (Civetta et al., 1997).

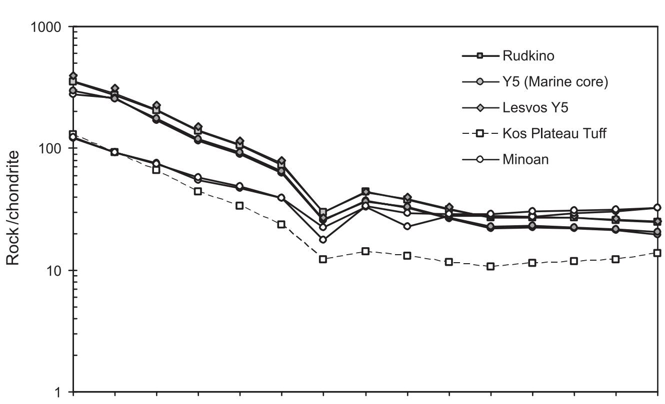

Fig. 6. Chondrite-normalised rare-earth element plot for Rudkino samples, showing the close correspondence with samples of Y5 tephra from marine cores (samples from Trident cores 172-11, 172-19; Table 2) and Lesvos (Margari et al., 2006). The high REE abundances contrast with lower abundances in Aegean tephra (for example, the Kos Plateau Tuff; Margari et al., 2006), and the La/Yb ratios are considerably higher than, for example, in rhyolitic tephra from the Minoan eruption of Santorini (Data from Eastwood et al., 1999). Normalisation factors from McDonough and Sun, 1995.

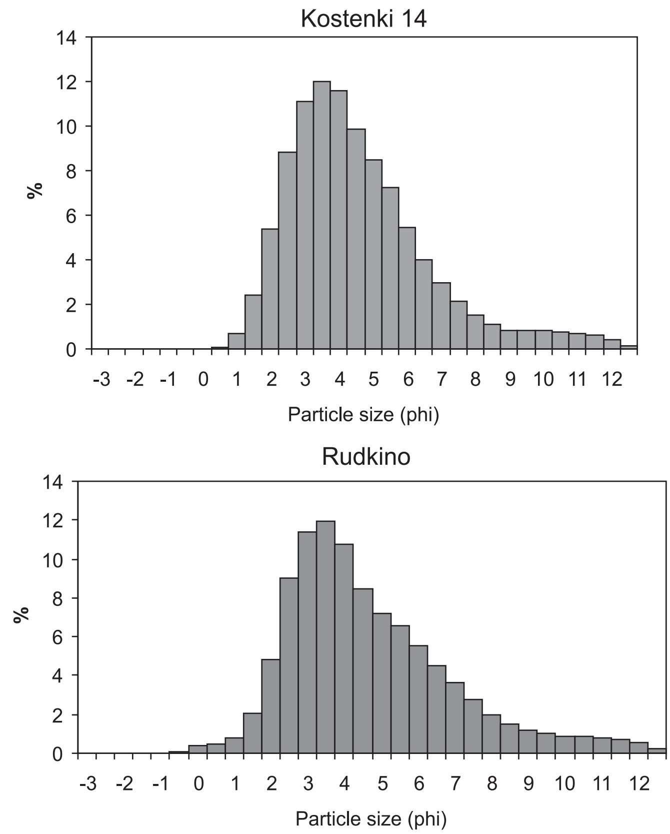

Fig. 7. Grain size analyses of tephra layers at Kostenki 14 and Rudkino. Samples are unimodal, with a broad mode of 3.5–5 ϕ units (grain size of 60–170 μm) and a fine-grained tail.

compositions of other young samples from southern Italy (Y3, Y7, the Neapolitan Yellow Tuff and Vesuvius; Wulf et al., 2004), along with an older Campanian sample (X5) and Aegean tephra from Santorini (Y2; Wulf et al., 2002). On this plot, the compositions of the young, southern Italian trachytes and phonolites cannot satisfactorily be distinguished. To compound the problem, the major chemical discriminants that have been found to distinguish the products of different southern Italian eruptions are the alkalis (Na, K; e.g. Keller et al., 1978; van den Bogaard et al., 1999) which are, of course, most prone to volatilisation during analysis, or to post-depositional alteration (e.g. Federman and Carey, 1980; Hardiman, 1999; Hunt and Hill, 2001; Pollard et al., 2003).

The suggestion that a tephra horizon from Upper Paleolithic archaeological contexts might correlate with the Y5 tephra was previously proposed for deposits in Franchthi, Greece (Vitaliano et al., 1981) and Temnata, Bulgaria (Paterne, 1992), but was ruled out for Kostenki 14 by Pawlikowski (1992). Pawlikowski analysed tephra that were reportedly from Kostenki, but the analyses that were published were of a basaltic composition. We find no evidence for tephra of this composition at Kostenki, and suggest that Pawlikowski was mistaken. Instead, our analyses confirm the very widespread nature of the

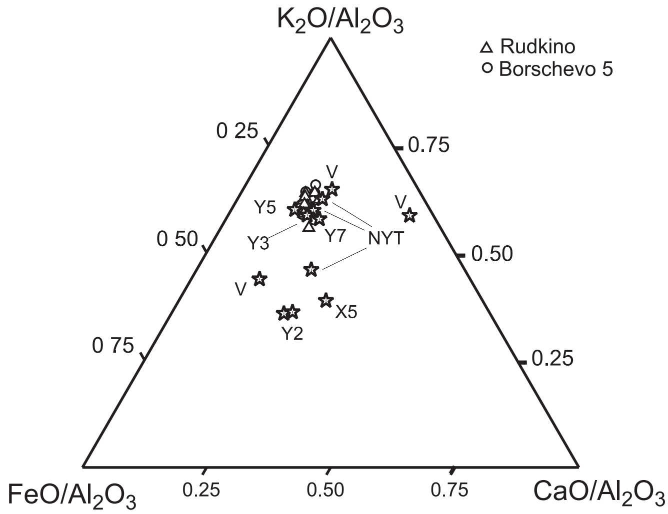

Fig. 8. Ternary compositional plot (K_2O/Al_2O_3–CaO/Al_2O_3–FeO/Al_2O_3) for the Rudkino and Borschevo samples, showing the close affinity with other young trachytic and phonolitic volcanic rocks from southern Italy: Y3 and Y7 (Campanian region), Neapolitan Yellow Tuff (NYT) and Vesuvius (V) tephra cannot be distinguished easily on the basis of their major constituents, while Aegean tephra (Y2, Santorini) and older Campanian samples (X5) may be. Analyses from Wulf et al. (2002, 2004).

Y5/Campanian Ignimbrite eruptive products across eastern Europe and western Russia.

As a number of workers have previously documented very clearly, the Campanian Ignimbrite/Y5 eruption evacuated a reservoir of melts whose composition ranged substantially (from trachyte to phonotrachyte; e.g. Barberi et al., 1978; Civetta et al., 1997) through the course of the eruption. The difficulty of finding a well exposed complete eruptive sequence has meant that the chemical stratigraphy has been hard to unravel. Nonetheless, it seems likely that the eruption evacuated a chemically zoned magma body (Civetta et al., 1997; Signorelli et al., 1999; Pappalardo et al., 2002), which tapped a less-evolved trachytic layer (~56 wt.% SiO_2 and 4–2.7 wt.% CaO; 0.3–0.4 wt.% Cl) at the beginning and again towards the end of the eruption, while a volumetrically dominant and chemically evolved endmember (phonotrachyte, ~62 wt.% SiO_2 and 2.1 wt.% CaO; 0.9 wt.% Cl) was tapped throughout the whole eruption. Overall, melt Na_2O contents ranged from 2.5 to 7 wt.%, while Zr and Ba ranged from 200 to 600 ppm and 1200 to 0 ppm, respectively (e.g. Civetta et al., 1997; Signorelli et al., 1999; Pappalardo et al., 2002). The analyses presented here suggest that all phases of the eruption contributed to the distal tephra deposited in Russia; this may not necessarily have been the case elsewhere across the eastern Mediterranean, depending on the nature of the winds at the time.

The wide range of compositions means that there is no single, simple and secure chemical criterion that will separate all CI/Y5 samples from other alkali tephra sources from southern Italy. Instead, correlation must rely (as in this case) on additional age/stratigraphic information, or on assumptions about the likely scale and extent of the eruption involved.

5.2. Age and significance of the Y5 ash layer at Kostenki

The correlation of the Kostenki tephra with the Y5 ash has some very important consequences in terms of the age of the deposit. The age of the Y5 ash is now very well constrained: an age probability maximum isochron based on $^{40}Ar/^{39}Ar$ laser heating analyses of sanidine crystals from the Y5 layer in a core in the Tyrrhenian Sea has dated the eruption to 41.1 ± 2.1 ka (Ton-That et al. (2001). $^{40}Ar/^{39}Ar$ dating by step heating and total fusion of sanidines from 20 samples of the proximal deposits gives a weighted mean age of 39.28 ± 0.11 (De Vivo et al., 2001). These two ages are statistically indistinguishable, and are consistent with marine core $\delta^{18}O$ stratigraphy (suggesting an age of 38 ± 2.5 ka, Thunnell et al., 1979), and with the observation that Y5 is younger than the Laschamp excursion (Fedele et al., 2002, 2003). We propose that the age of 39.3 ka be adopted for the Y5 ash layer (De Vivo et al., 2001), and we propose that this represents the age of the eruption. Younger ages have been reported for the Y5/Campanian ignimbrite eruption; however these do not stand up to scrutiny. An age of ca 33 ka BP for the equivalent of the Y5 layer (TM-8) in Lago di Monticchio, based on estimates of sedimentation rate, is only a minimum age due to the absence of varves or laminae from the appropriate section of the core (Allen et al., 2000; Wulf et al., 2004). A widely cited $^{40}Ar/^{39}Ar$ age for the Y5 eruption of ca 37 ka originates from a meeting abstract (Deino et al., 1994), the full details of which have not been published, and which is presumably superceded by the more recent work of Ton-That et al. (2001), and De Vivo et al. (2001).

The $^{40}Ar/^{39}Ar$ age of Y5 is considerably greater than the uncalibrated ^{14}C determinations which the Russian team have been working with thus far, which place the eruption at ca 32 ka BP (Fig. 2, Sinitsyn 1996, 2003). This is a simple consequence of the variation of ^{14}C production rates over the period 45–35 ka, which included the Laschamp excursion. When the magnetic field strength fell, cosmogenic isotope production increased, leading to enhanced levels of atmospheric ^{10}Be and ^{14}C. The ^{10}Be peak can be found in Greenland ice-cores (thereby linking the GISP record to marine and terrestrial records); while the elevated levels of ^{14}C have the consequence of making ca 39,000 Cal yr carbon appear to be much younger than it actually is (e.g. Castagnoli et al., 1995; Finkel and Nishiizumi, 1997; Voelker et al., 2000; Beer et al., 2002; Fedele et al., 2002). On the basis of the Kostenki 14 age determination ($32{,}420 \pm 440$ ^{14}C yr, Sinitsyn 2003), the offset between calibrated and uncalibrated ^{14}C ages is 6880 (± 450) yr at 39.3 ka.

The magnitude of this offset between uncalibrated ^{14}C and the $^{40}Ar/^{39}Ar$ age is consistent with the most recent attempts to develop a ^{14}C 'calibration' for the period

30–45 ka (e.g. Jöris and Weninger, 1998; van Andel et al., 2003; Bard et al., 2004; Fairbanks et al., 2005), and is consistent with the recent Greenland ice core chronology of Shackleton et al. (2004).

The age correlation of the Kostenki ash layer to ~39.3 ka has significant implications for the archaeological chronology of the Kostenki region and the beginnings of the Upper Paleolithic in Europe. Some of these implications, in terms of the Palaeolithic record in Italy, were discussed by Fedele et al. (2002, 2003). The age correlation extends the lower parts of the existing Kostenki chronology back by some 7000 yr. At Kostenki, the lowest occupation levels at Kostenki 14 and the nearby Kostenki 12 are already thought to contain the earliest known Upper Paleolithic assemblages in Eastern Europe (e.g. Sinitsyn et al., 2002; Sinitsyn, 2003). The new constraints place cultural layer IVa (which lies between the volcanic ash and the fossil soil in which the Laschamp excursion is identified) in the age range 39.3–41 ka. Cultural layer IVb is located over 1 m below layer IVa in Kostenki 14 (Fig. 2; Sinitsyn, 2003), which strongly suggests that the lowest Upper Palaeolithic cultural layers in Kostenki 14 date are considerably older than 40,000 yr. In a wider context, the evidence from Kostenki coupled with the $^{40}Ar/^{39}Ar$ age of the tephra at source are consistent with the eruption having occurred during a period that corresponds to Greenland Interstadial 9 (GIS 9), and just prior to Heinrich event 4 (Fedele et al., 2003; Shackleton et al., 2004).

The period 40–35 ka is recognised as the period of transition in Europe from Middle Palaeolithic stone tool traditions to Upper Palaeolithic industry and culture, and the replacement of Neanderthals with 'anatomically modern' *Homo sapiens*. The discovery of Upper Paleolithic contexts older than 39–41 ka at Kostenki may require revision of the assumed timing of this transition (cf. Mellars, 2004). This work confirms the potential of the widespread Y5 marker for studies of the timing of the dispersal of early modern humans across Europe.

5.3. Extent of the Y5 ash layer

As we showed in Fig. 1a, there is strong evidence that the Y5 dispersal axis was not simply to the south and east. Deposits of Y5 are now known from northern Greece; from Palaeolithic cave sites in Bulgaria (Paterne, 1992) and from Romania (P. Cole, pers. comm. 2002). As yet, there is no constraint on the easterly limit of deposition of the Y5 ash. Since there are no reports of discrete tephra that might correspond to Y5 from any of the Palaeolithic sites in the Caucasus, nor from any sediment cores from the eastern Black Sea, nor from any localities in Turkey, we suggest a conservative 'easterly limit of preservation' as shown in Fig. 1a. It remains to be seen whether dispersed 'cryptotephra' horizons can be found in any of these contexts, or further afield in mainland Russia.

The presence of Y5 ash at Kostenki confirms that the area covered by volcanic ash during this eruption was at least 2×10^6 km^2, while the transport distance of the tephra from the source exceeded 2500 km. This areal extent and scale of transport is only matched in the recent geological record by the Younger Toba Tuff (Indonesia) eruption of ca 75,000 yr (Rose and Chesner, 1987). Local variability in the thickness of the ash layer in the Kostenki region (from 0 to 30 cm) is ascribed to aeolian re-working of the ash after initial deposition as a uniform fall deposit, and to subsequent periglacial deformation. We estimate that the primary deposit thickness was unlikely to have exceeded ~1–2 cm.

The extent of dispersal during the Campanian Ignimbrite/Y5 eruption may be a reflection of two parameters: the energetics of the eruption itself, and the nature of the pyroclasts. The glass shards in the ash are uniformly thin and strongly elongated. This morphology would have contributed to a reduced terminal settling velocity, compared to spherical particles on which tephra transport models are largely based, allowing them to travel further within the plume before deposition (e.g. Rose et al., 2003). A contributory factor is that the plume-forming phase of the Campanian Ignimbrite eruption is thought to have been very vigorous, with the plume reaching 44–45 km (Rosi et al., 1999). When coupled with the unusually vesicular nature of many of the pumices (Polacci et al., 2003), we suggest that the eruption produced a particularly high content of fine bubble-wall shards, which were then injected at high levels in the stratosphere and transported rapidly downwind. Overall, the scale of the eruption would probably have been sufficient to induce a regional-scale rotating ash cloud, akin to an ash-bearing hurricane (e.g. Baines and Sparks, 2005).

5.4. Volume of the Y5 ash and of the Campanian Ignimbrite/Y5 eruption

The first isopach map of the Y5 layer was published by Thunnell et al. (1979), in which the most distal recognised deposit was a 1 cm thick layer in a marine core just west of Cyprus. On the basis of the observed thickness of these deposits in marine cores, Thunnell et al. (1979) estimated a total bulk ash volume of 65 km^3 within the 1 cm isopach. Subsequently, Cornell et al. (1983) calculated a total bulk volume for the Y5 ash layer of ~73 km^3, assuming that the Y5 ash layer covered 1.4×10^6 km^2. These, and more recent estimates of the volume and areal extent of the deposits, are summarised in Table 3. As is often the case with the determination of erupted volumes, there is some confusion in the literature between estimates that represent 'bulk ash' as opposed to 'dense rock equivalent' volumes; and there is also a good deal of speculation as to the possible extent of both the primary ignimbrite and primary tephra-fall deposits.

Since we now have a better estimate of the full extent of the Y5 ash deposit, it is worthwhile making an assessment of the original volume of the deposits. The determination of the volume of fine-grained and widely dispersed tephra

Table 3
Summary of published estimates of tephra volume erupted during the Campanian Ignimbrite Y5 eruption

Phase	Volume (bulk) (km^3)	Volume (DRE) (km^3)
Plinian Pumice Fall	15 (Rosi et al.,1999) 20 (Perrotta and Scarpati, 2003)	
Ignimbrite	80 (Rosi et al.,1983) 180[a] (Rolandi et al., 2003)	
Co-Ignimbrite ash fall/Y5 layer	73 (Cornell et al., 1983) 100 (Perrotta and Scarpati, 2003) 140 (Civetta et al., 1997) 74–120 (this work)	140[b] (Rolandi et al., 2003) 31–50 (this work)
Total volume	 320[c] (Rolandi et al., 2003)	150 (Civetta et al., 1997) 200[a] (Rolandi et al., 2003) 105–210 (this work)

[a]Based on estimates of the areal extent and thickness of Campanian Ignimbrite flow deposits.
[b]Total estimated fallout volume across Mediterranean Sea and Russia, assuming considerable extrapolation of distal fallout deposit.
[c]Corrected from Rolandi et al. (2003), who quote a total 'bulk' volume of 310 km^3 instead of 320 km^3 (= 140 + 180, Appendix 4, Rolandi et al. (2003)).

Table 4
Minimum volume of distal fallout tephra

	Bulk tephra volume (km^3)			DRE volume[a] (km^3)
	Best estimate	Minimum	Maximum	Best estimate
Area (km^2)	2×10^6	1.5×10^6	3×10^6	
Minimum ash fall deposit volume	74	56	111	31
Minimum volume enclosed within 1 cm isopach	44	33	66	18

[a]Assuming a bulk deposit density of 1000 kg/m^3 and a magma density of 2400 kg/m^3.

fall deposits is relatively straightforward. It is a general observation that many fallout deposits show exponential decay of thickness (Pyle, 1989). This has the advantage of yielding a number of simple analytical expressions that may be used to estimate not only total deposit volume (i.e. effectively extrapolated to negligible thickness), but also of the minimum volume, and the volume enclosed within finite limits (Pyle, 1995, 1999). An exponentially thinning sheet of tephra may be characterised by two parameters: the maximum thickness at source (T_o), and the linear distance over which the isopach thickness falls by a half, b_t. The total volume of the exponentially thinning sheet is then $13.08 T_o b_t^2$. If the area (A_i) covered by just one isopach (of thickness T_i) is known, this is sufficient to determine the minimum deposit volume ($V_{min} = 3.7 A_i T_i$), or the minimum volume enclosed within the isopach ($2.2 A_i T_i$, Pyle 1999). Table 3 summarises the range of published data, along with our own preferred estimates for the total erupted magma (dense rock) volume and mass, while Table 4 explains the basis for our calculations. Given a best estimate for the minimum area covered by >1 cm of tephra during the Y5 eruption of 2×10^6 km^2 (Fig. 1a), then the minimum volume of distal ash fall is 74 km^3 (bulk) or 31 km^3 (Dense rock equivalent, DRE; Table 4).

An alternative approach is to use information on the rate of thinning (b_t) of distal ash sheets. The most widely dispersed tephra fall deposits are usually regarded as 'co-ignimbrite' fall deposits (e.g. Sparks and Huang, 1980), and they are characterised by thickness half-distance values (b_t) of 50–500 km (Pyle, 1989, 1990). The rate of thinning of the Y5 ash layer from marine core data is towards the upper end of this range (305 km). Given an assumed fallout area of 1.5–3×10^6 km^2 and a range of plausible values for b_t we can constrain both the extrapolated maximum ash deposit thickness at source, and total deposit volume (Table 5, Fig. 9). Given that the thickest ash layer in marine cores is of the order of 10–20 cm, it is most likely that the total bulk ash volume associated with the eruption was in the range 74–120 km^3 (31–50 km^3 DRE). Thus, there is a consistent and fairly narrow range of likely solutions which together place important limits on the scale of the distal ash fall deposit.

This distal ash would have been derived by the elutriation of tephra from the ignimbrites that were deposited across the Campanian Plains. The volume of these ignimbrites is estimated at 80–180 km^3 (Table 3) corresponding to a dense rock equivalent volume of 70–150 km^3 of magma. The best estimate of the total (ignimbrite + Plinian pumice fall + distal tephra) volume

Table 5
Estimated bulk volume and maximum source thickness of distal fallout tephra

Thickness half-distance b_t (km)	Maximum deposit thickness T_0 (m)	Area of 1 mm isopach (km^2)	Bulk deposit volume (km^3)	Erupted magma volume (DRE) (km^3)
150	0.4	5.3×10^6	117	49
200	0.16	6.7×10^6	83	35
300	0.06	9.9×10^6	74	31
500	0.03	1.9×10^7	99	41

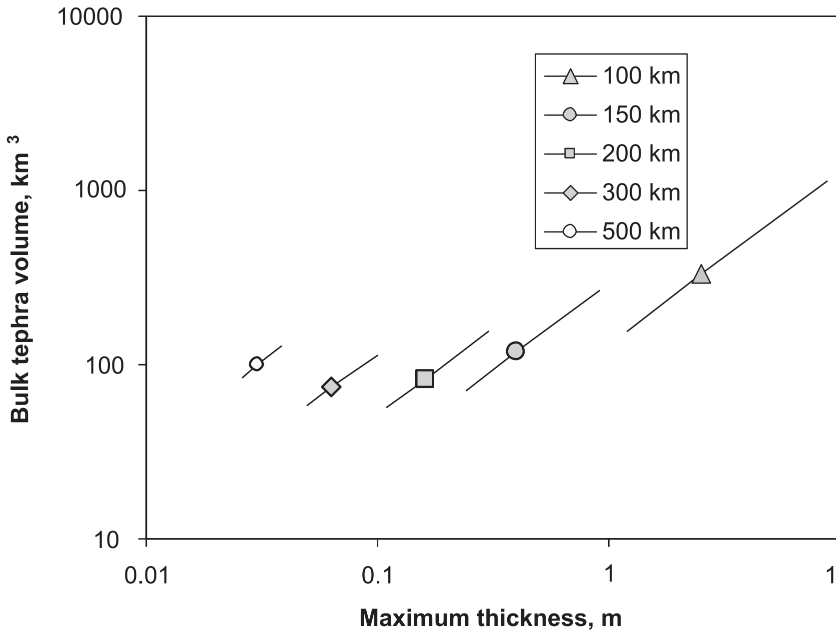

Fig. 9. Constraints on the bulk tephra volume of the Y5 distal ash layer. The y-axis shows the estimated volume, the x-axis shows the extrapolated maximum ash fall deposit thickness. Points show solutions assuming a 'best estimate' of the 1 cm isopach area of 2×10^6 km^2 and a range of rates of exponential thinning of the distal deposit (b_t, the thickness half-distance, range between 100 and 500 km). The range of possible solutions is indicated by 'error bars', assuming lower and upper limits to the 1 cm isopach area of 1.5×10^6 and 3×10^6 km^2. It is likely that the total bulk volume of the distal Y5 ash layer is of the order of 75–120 km^3, and the maximum thickness is of the order of 10–50 cm.

and mass of the eruption is therefore 105–210 km^3 of dense magma, or $(2.5–5) \times 10^{14}$ kg of tephra. This is considerably larger than the 3.5 ka BP Minoan eruption of Santorini (Greece), for example, (ca 28 km^3 or 7×10^{13} kg; Pyle, 1990), and ranks as the largest European eruption known from the last 100,000 yr.

5.5. Potential environmental impact of the Campanian Ignimbrite/Y5 eruption?

While the Campanian Ignimbrite/Y5 eruption was of considerable scale, it remains difficult to infer the potential scale of the environmental impact of either the tephra deposition, or of the associated emissions. In terms of dispersal area, and amount of magma erupted, the Campanian Ignimbrite/Y5 eruption was still an order of magnitude smaller than the largest known eruptions of the Pleistocene (e.g. The Younger Toba Tuff; see Mason et al., 2004). Nonetheless, the area affected by ash deposition corresponds closely to the areas of eastern Europe that were most vegetated during MIS 3 (e.g. Huntley and Allen, 2003), and it is likely that the consequential impact on vegetation would have contributed substantially to levels of 'climatic stress' (cf. Stringer et al., 2003). Deposition of fine ash across such a large continental area would have substantially enhanced the regional albedo, with important (but as yet unknown) consequences for regional climate, at least in the short term. The scale of volatile emissions from the eruption remains poorly constrained (Signorelli et al., 2001; Webster et al., 2003), due in part to an absence of experimental data on the solubility of volatile species of S in trachytic melts, and in part due to the difficulties of fully reconstructing the pre-eruptive conditions. Nonetheless, the very high Cl contents of the glasses determined here is consistent with experimental observations on the proximal Campanian Ignimbrite which show that the uppermost and most evolved trachytic layer in the magma chamber coexisted with a Cl-rich brine just prior to eruption

(Signorelli et al., 2001; Signorelli and Carroll, 2002). Vapourisation of this brine during eruption would have strongly enriched the gaseous emissions in Cl, which would have contributed, along with outgassed SO_2, to a strongly acidic aerosol and which may have been deposited along with the distal tephra.

6. Conclusions

A trachytic volcanic ash layer that is widely distributed across south-western Russia is confirmed as a distal equivalent of the deposits of the ca 39.3 ka Campanian Ignimbrite eruption of the Phlegrean Fields, Italy, and is correlated with the Y5 ash layer in marine cores in the south-eastern Mediterranean. This work confirms that coarse (60–90 μm) ash particles can be dispersed over considerable distances (>2500 km) during large magnitude explosive eruptions, and confirms the Campanian Ignimbrite/Y5 eruption as the most significant volcanic eruption in Europe of the past 100 ka. This correlation places tight constraints on the absolute ages of a number of important archaeological horizons in southern Russia.

While no macroscopic tephra deposits of Y5 age have as yet been reported from the western Caucasus mountains or the Black Sea, both regions preserve contexts of this age where discrete or dispersed tephra may be present. The extent of dispersal of ash during the Campanian Ignimbrite eruption confirms this event as the largest known volcanic eruption in Europe of the past 100,000 yr.

Acknowledgements

We thank the McDonald Institute for Archaeological Research for a Fieldwork Grant (to TvA, DMP); the Russian Academy of Sciences and the Russian Humanitarian Science Fund for Grant RFFI 05-05-6485 (to AAS), and Queens' College, Cambridge, for an undergraduate travel fund (to GDR). We gratefully acknowledge technical support and assistance from Jason Day (ICP MS), Chris Hayward (Electron microprobe), Chris Rolfe and Steve Boreham (Physical Geography Laboratories) for technical assistance, and Julie Miller for soil thin sections. DMP thanks Tamsin Mather, Oli Bazeley and Rupert Housley for discussion and comment, and Siwan Davies and Simon Blockley for perceptive reviews.

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