Chapter 2

Direct U-series dating of the Apidima C human remains

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Abstract

The site of Apidima, in southern Greece, is one of the most important Paleolithic sites in Greece and southeast Europe. One of the caves belonging to this cave complex, Cave A, has yielded human fossil crania Apidima 1 and 2, showing the presence of an early *Homo sapiens* population followed by a Neanderthal one in the Middle Pleistocene. Less known are the human remains reportedly recovered from Cave C at Apidima. These include a number of isolated elements, but also a partial skeleton interpreted as a female burial, Apidima 3, proposed by Pitsios (e.g., Pitsios 1999) to be associated with Aurignacian lithics and to date to ca. 30 ka. In light of the rarity of the Upper Paleolithic in Greece, and the general scarcity of human remains associated with the Aurignacian, the remains from

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Apidima Cave C are potentially very significant in elucidating the arrival of the early Upper Paleolithic populations in Europe. Here we undertake direct Uranium-series dating of three human samples from Cave C, including the burial, to help clarify their chronology. Results suggest a minimum age of terminal Pleistocene for all three samples.

INTRODUCTION

Apidima is a cave complex situated on the coast of the Mani Peninsula, southern Greece, consisting of five caves (A-E) formed in the Upper Cretaceous–Late Eocene limestone of the coastal cliffs of the inner Mani (Fig. 1). The caves are situated very near the current sea level, Cave A being the lowermost at ca. 4 m above sea level (asl) and Caves C and D the highest (at ca. 19 m and 24 m asl, respectively). The caves were investigated by a team from the Museum of Anthropology of the Medical School of the National and Kapodistrian University of Athens between 1978 and 1985, and several important discoveries were made. These included two human fossil crania of Middle Pleistocene age from Cave A (Pitsios 1985, 1995, 1999; Harvati and Delson 1999; Harvati 2000; Harvati et al. 2009, 2011, 2019), considered among the most important paleoanthropological finds from southeast Europe. Their recent re-investigation showed the presence of an early modern human population, followed by a Neanderthal one, at the site in the Middle Pleistocene, and provided evidence of an early *Homo sapiens* dispersal out of Africa that was both earlier and geographically more widespread than previously thought (Harvati et al. 2019). However, a number of less known, but potentially very important human remains have also been recovered from Cave C. These include a burial hypothesized to be of early Upper Paleolithic age, a find that, if confirmed, would be unique in Greece (Pitsios 1985, 1995, 1999; Mompheratou and Pitsios 1995; Ligoni and Papagrigorakis 1995; Harvati et al. 2009; Tourloukis and Harvati 2018) and in Europe (d'Errico and Vanhaeren 2015).

Human remains reported from Cave C include a partial skeleton, as well as isolated dental remains and skeletal elements likely representing additional individuals (e.g., Mompheratou and Pitsios 1995; personal observation). The skeleton (LAO 1/S3, or Apidima 3) is represented by much of the postcranium, a mandibular fragment preserving the left molar series and possibly isolated teeth. It has been interpreted as a burial of a young woman. Sex was attributed on the basis of the pelvic morphology (Pitsios 1999), whereas age was estimated from dental attrition (Ligoni and Papagrigorakis 1995; Pitsios 1999). More than 40 (41 reported by Pitsios 1985, 43 by Pitsios 1999) pierced shells of *Nassa neritea* (Karali 1995) were reportedly recovered around the upper part of the skeleton (Pitsios 1999) and were considered to represent personal ornaments associated with the burial. A few lithic artifacts reportedly found together with this skeleton were tentatively assigned to the Aurignacian (Darlas 1995). Pitsios (1999) proposed a date of ca. 30 ka for this

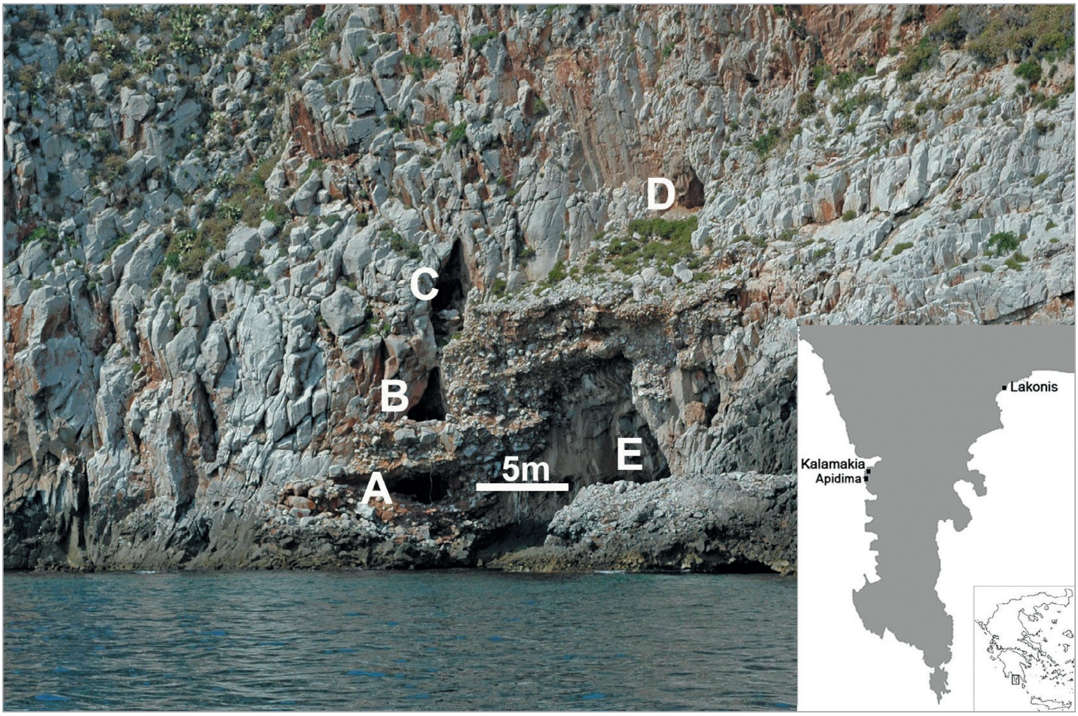

Fig. 1.
The Apidima Cave Complex, showing the position of the five caves, including Cave C. Inlet shows the geographic location of the Apidima, Kalamakia and Lakonis Paleolithic sites on the map of Mani Peninsula, Southern Peloponnese.

burial on the basis of his own stratigraphic observations, the tentative attribution of the lithics to the Aurignacian by Darlas (1995) and on ESR dates from cave sediments by Liritzis and Maniatis (1995).

The Upper Paleolithic is very rare in Greece and is known from only a handful of sites (e.g., Harvati et al. 2009; Harvati 2016; Tourloukis and Harvati 2018). Furthermore, human remains associated with the Aurignacian are very scarce throughout Europe, usually consisting of isolated specimens (most frequently teeth) rather than burials, even though a total absence of Aurignacian burials is not conclusive (Riel-Salvatore and Gravel-Miguel 2013; d'Errico and Vanhaerean 2015). Elaborate inhumations with ornaments, such as beads manufactured from shells, are overall scarce and usually more common in the middle and later parts of the Upper Paleolithic (Riel-Salvatore and Gravel-Miguel 2013). A possible early Upper Paleolithic chronology for Apidima C and the human remains found there is therefore of great interest. However, the age estimate proposed by Pitsios (1999) is largely conjectural. Pitsios (1999) does not specify how his stratigraphic observations can indicate a temporal range. The attribution of the lithics to the Aurignacian is tentative (Darlas 1995) and their association with the skeleton cannot be ascertained from the information published; with the exception of one specimen, a blade, the exact provenance of the lithics is either not specified or reported as probably unrelated to the context of the burial (Mompheratou and Pitsios 1995: 37; but see also Darlas 1995: 59). Finally, while Liritzis and Maniatis (1995) produced two ESR dates of 20–30 ka and 25–45 ka for two travertine samples, these samples were taken from the opening of Cave D and B, respectively, and therefore have no bearing on either Cave C or the burial uncovered there (see also Harvati et al. 2009).

Here we conduct direct dating of the human remains from Apidima C, including the burial as well as two isolated teeth, using U-series dating in order to resolve this question. This effort was undertaken as part of the new research program of the Museum of Anthropology of the Medical School, National and Kapodistrian University of Athens, Greece, in collaboration with the Paleoanthropology group at the University of Tübingen, Germany, and the University of Bergen, Norway.

MATERIALS AND METHODS

Samples were selected from the Museum of Anthropology's collections of human remains excavated at Apidima C in the 1980s (Mompherratou and Pitsios 1995). LAO 1 S5 (Fig. 2A) is an isolated upper molar with extensive crown attrition (advanced stage 2, erosion across the entire dentine layer). It was found in the same context as the second specimen, LAO 1 S6 (Fig. 2B), a likely isolated premolar. Its extreme degree of attrition (stage 3, exposed pulp cavity; see Burns 2015) makes its exact anatomical allocation difficult. Two further specimens were selected from the bones associated with the burial of the female skeleton, Apidima 3: A fragment of the sternum (LAO 1 S3_18; Fig. 2C) and a fragment of a pelvic iliac bone (LAO 1 S3_12; Fig. 2D). Permission for sampling was obtained from the Ministry of Culture and Sports, Athens (ΥΠΠΟΑ/ΓΔΑΠΚ/ΔΣΑΝΜ/ΤΕΕ/Φ77/299995/215105/2663/281). All specimens were 3-d scanned before sampling using a handheld structured-light scanner with a maximum scanning accuracy of 50 microns, and high resolution casts were obtained of the two dental remains so as to create a complete record of their anatomy before the sampling procedure was undertaken. Of the four specimens, the iliac fragment (LAO 1 S3_12) did not preserve an appropriate cross-section for analysis and was therefore not used. The remaining samples were assigned the following laboratory reference numbers: LAO 1 S5 (isolated molar): 3776, LAO 1 S6 (isolated premolar): 3777, LAO 1 S3_12 (sternum fragment from female burial): 3778 (see Fig. 3A).

U-SERIES ANALYSIS

U-series dating is based on the different chemical behavior of uranium (U) and thorium (Th). While uranium is water solvable, thorium is not. As a result, minerals precipitated from water contain uranium isotopes (specifically ^{238}U, ^{234}U and ^{235}U). In a closed system, ^{234}U decays to ^{230}Th. The activity ratio of the two isotopes can be used to determine a U-series age. The ^{230}Th/^{234}U activity ratio starts with zero and grows

over time (about 600,000 years) into equilibrium when the $^{230}Th/^{234}U$ ratio is indistinguishable from unity. However, bones and teeth are not closed systems; they accumulate their uranium while they are buried in the ground. The actual U-uptake history can be highly complex (Grün et al. 2014), but generally leads to age calculations that underestimate the burial age of the specimen. It is possible to address the problem of the unknown U-uptake history with a variety of diffusion models (e.g., through the diffusion-adsorption model described by Pike et al. 2002, or the diffusion-adsorption-decay model of Sambridge et al. 2012). However, all these models are based on continuous diffusion processes and cannot recognize longer initial phases with no or little U-diffusion. This problem can be addressed in teeth by combining U-series and ESR methods (Grün et al. 1988). In the context of this study, ESR analysis was not feasible because of time constraints. To reiterate, the U-series ages reported here are apparent closed system age estimates, which most likely underestimate the burial ages of the specimens.

The U-series analyses were carried out using laser ablation, inductively coupled plasma multi-collector mass spectrometry (LA-ICP-

Fig. 2.
The human remains selected for sampling for dating analysis:
A. LAO 1 S5 (3776) isolated molar;
B. LAO 1 S6 (3777) isolated premolar;
C. LAO 1 S3_12 (3778) sternum fragment from female burial;
D. LAO 1 S3_12, iliac fragment from female burial, not used.

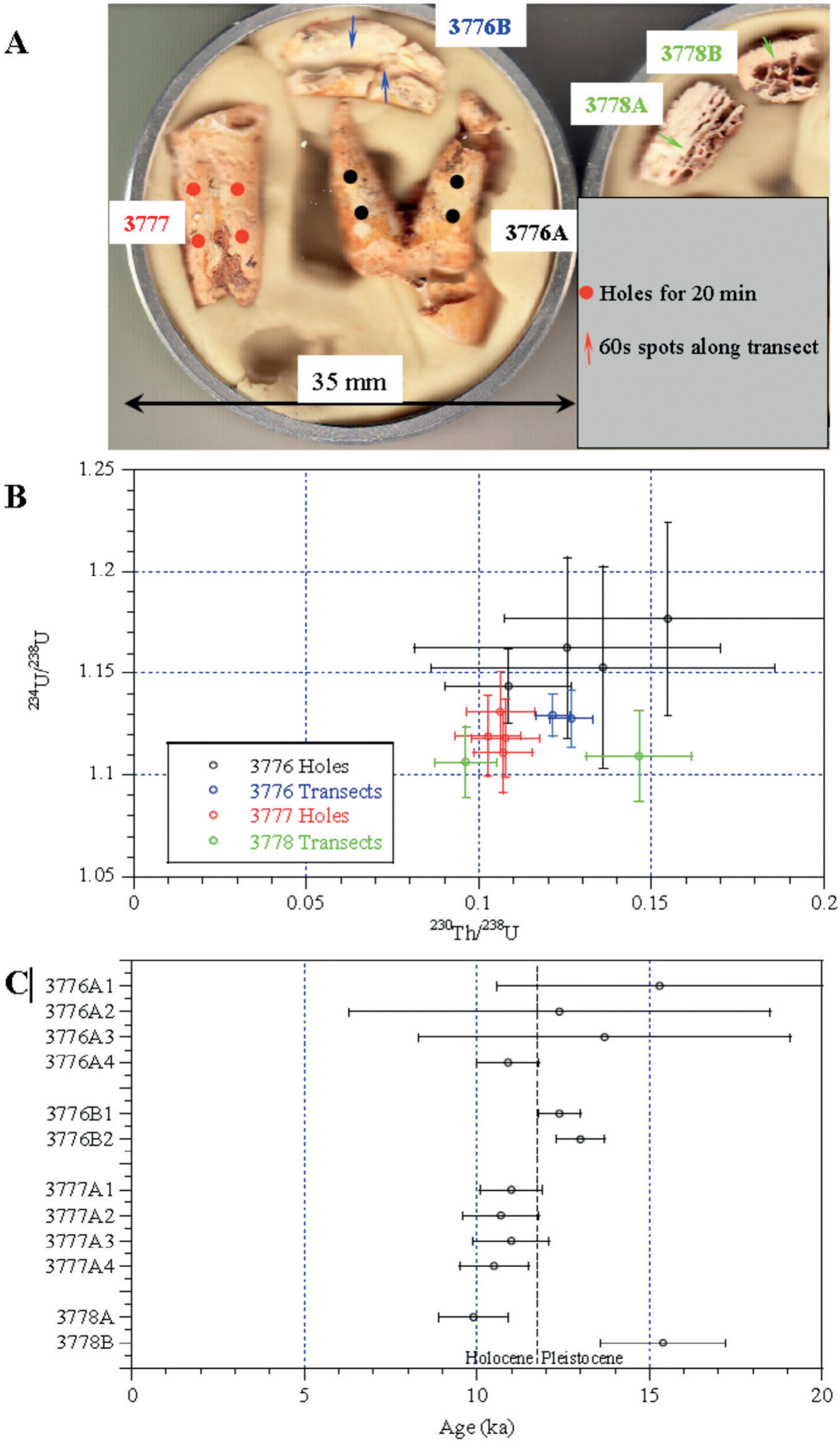

Fig. 3.
Samples and results of U-series analysis:
A. Samples and locations of the laser ablation analyses;
B. $^{230}Th/^{238}U$ vs $^{234}U/^{238}U$ activity ratios;
C. Age results with Pleistocene/Holocene boundary (Walker et al. 2018).

MCMS), which minimizes sample destruction of valuable human fossils (e.g., Groucutt et al. 2018). The analyses followed the procedures that were detailed by Grün et al. (2014). Two different analytical strategies were applied: analyzing spots (each for 60 s) along transects (3776B and 3778) and drilling holes with the laser in stationary position for 20 minutes (3776A and 3777), the latter procedure was applied to minimize sample damage (Benson et al. 2013). Sample 3776 was very fragile and a fragment of one of the roots split off. As a result, this individual tooth was analyzed by drilling four holes into the main part and two transects across the root fragment.

All isotope ratios in this paper are activity ratios with 2-σ errors. Ages were calculated with the Isoplot (Ludwig 2012).

RESULTS

The results of the individual spot analyses are shown in Table 1 and those of the holes in Table 2. The data in Table 2 were binned for 10 cycles (corresponding to approximately 10s ablation). As can be seen from Table 2, the analyses of the first three holes of sample 3776A1 to A3 are associated with large errors due to the low U-concentrations (< 2.3 ppm at the surface). The other holes (3776A4 and 3777-1 to 3777-4) had higher U-concentrations at the surface but the ablation efficiency rapidly decreased with measurement length so that only the data of the first 160 to 200 s were used for age calculations. Samples 3776 and 3777 have extremely high elemental U/Th ratios, indicating that there was no interference from detrital Th. The U/Th ratios for sample 3778 are somewhat higher, particularly for 3778B. All individual LA spots and holes return finite age results, indicating that the teeth have apparently not experienced uranium leaching. This could, however, be only confirmed by combining U-series with ESR data (Grün et al. 1988).

The $^{230}Th/^{238}U$ and $^{234}U/^{238}U$ are shown in Figure 3B. There seems to be an overall trend of slightly increasing $^{234}U/^{238}U$ ratios with increasing $^{230}Th/^{238}U$ ratios, but the large errors (due to low U-concentrations and young ages) prevent any meaningful interpretations. For sample 3776, the results of the transects and holes are compatible. The biggest difference is observed for sample 3778 where the two transects yielded distinctively different $^{230}Th/^{238}U$ results, and subsequently apparent ages. Sample 3778B has also distinctively higher U and Th concentrations, which may indicate some incorporation of detrital U and Th into the sample. However, corrections for detrital Th lead only to slightly younger results (by 0.2 ka). The age differences observed between samples 3778A and B could be simply due to some delayed U-uptake or some more complex processes that we cannot really address with the two transects. The distribution of the U-series ages does not indicate that U-leaching has occurred.

Because of the large associated errors, the apparent U-series ages of the three samples are overall statistically indistinguishable.

3776B1	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	8.22	0.21	38477	0.1136	0.0119	11.332	0.0179	11.376	0.0184	11.5	1.3
2	8.47	n.d.	nd	0.1279	0.0116	11.277	0.0166	11.326	0.0172	13.1	1.3
3	8.42	0.04	212315	0.1223	0.0092	11.292	0.0185	11.338	0.0191	12.5	1.0
4	8.13	0.31	26172	0.1158	0.0116	11.347	0.0174	11.392	0.0180	11.7	1.3
5	8.47	0.92	9222	0.1227	0.0105	11.265	0.0182	11.310	0.0187	12.6	1.2
6	6.64	0.35	19111	0.1269	0.0121	11.260	0.0216	11.307	0.0223	13.0	1.3
AVERAGE VALUES											
	8.06±0.59	0.24±0.43		0.1214	0.0050	11.296	0.0104	11.342	0.0107	12.4	0.6

3776B2	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	7.19	2.36	3042	0.1285	0.0115	11.208	0.0163	11.255	0.0169	13.3	1.3
2	7.23	1.62	4453	0.1310	0.0115	11.221	0.0223	11.269	0.0230	13.5	1.3
3	6.91	0.35	19522	0.1288	0.0142	11.393	0.0223	11.445	0.0231	13.1	1.5
4	5.94	0.66	8974	0.1124	0.0136	11.208	0.0342	11.248	0.0352	11.5	1.5
5	5.84	1.03	5668	0.1315	0.0148	11.373	0.0361	11.426	0.0373	13.4	1.7
AVERAGE VALUES											
	6.62±0.61	1.21±0.80		0.1267	0.0062	11.278	0.0137	11.326	0.0142	13.0	0.7

cont. ⟶

3778A	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	3.86	15.07	256	0.0848	0.0172	11.015	0.0279	11.040	0.0286	8.7	1.9
2	2.97	9.40	316	0.0963	0.0212	10.855	0.0371	10.880	0.0381	10.1	2.4
3	2.87	23.05	125	0.1071	0.0211	10.931	0.0337	10.961	0.0346	11.2	2.4
4	3.42	6.74	507	0.1105	0.0188	11.414	0.0408	11.459	0.0419	11.1	2.0
5	4.03	8.18	492	0.0868	0.0183	11.074	0.0296	11.101	0.0302	8.9	2.0
AVERAGE VALUES											
	3.43±0.45	12.49±6.69		0.0962	0.0089	11.066	0.0173	11.096	0.0177	9.9	1.0

3778B	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	4.21	78.20	54	0.1520	0.0270	11.075	0.0512	11.125	0.0534	16.1	3.2
2	5.03	20.59	244	0.1655	0.0384	10.950	0.0378	10.999	0.0396	17.9	4.5
3	4.26	19.63	217	0.1352	0.0319	11.158	0.0464	11.205	0.0481	14.1	3.6
4	4.71	46.33	102	0.1329	0.0213	11.193	0.0314	11.240	0.0325	13.8	2.4
AVERAGE VALUES											
	4.55±0.39	41.2±27.6	111	0.1463	0.0153	11.094	0.0223	11.143	0.0231	15.4	1.8

Table 1. (left and above)
U-series results on cross section 1 (indicated by arrows on Fig. 3A). All errors are 2-σ. n.d.: not determined; Th concentration below background. Ages calculated with Isoplot (Ludwig 2012). To avoid correlated errors, individual age errors do not include errors from standard. Average age errors result from the combination of the errors of the mean and the standard.

3776A1	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	2.23	1.63	1364	0.1373	0.0816	11.750	0.0859	11.818	0.0888	13.5	8.5
2	1.91	n.d.	n.d.	0.1271	0.1096	11.736	0.0676	11.798	0.0698	12.5	11.4
3	1.76	0.58	3012	0.1153	0.0897	12.042	0.0927	12.106	0.0952	11.0	9.0
4	1.66	1.20	1381	0.1947	0.0769	11.490	0.0801	11.577	0.0841	20.2	8.9
5	1.42	n.d.	n.d.	0.1464	0.1398	11.766	0.1842	11.840	0.1907	14.5	14.9
6	1.21	n.d.	n.d.	0.2358	0.1555	12.578	0.1864	12.747	0.1961	22.5	16.8
7	1.02	n.d.	n.d.	0.1632	0.1495	10.907	0.2187	10.953	0.2289	17.7	18.0
AVERAGE VALUES											
				0.1547	0.0441	11.769	0.0474	11.847	0.0492	15.3	4.7

3776A2	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	2.06	4.08	505	0.1833	0.1064	12.185	0.0811	12.297	0.0847	17.7	11.2
2	1.95	2.78	700	0.1174	0.0403	12.111	0.1160	12.178	0.1191	11.1	4.2
3	1.81	n.d.	n.d.	0.0802	0.0995	11.516	0.1025	11.550	0.1046	7.9	10.1
4	1.66	1.68	989	0.1395	0.0780	11.466	0.0753	11.526	0.0780	14.1	8.5
5	1.50	n.d.	n.d.	0.0809	0.1252	10.953	0.1054	10.976	0.1077	8.4	13.5
6	1.35	2.18	620	0.1894	0.1993	10.955	0.1449	11.012	0.1529	20.7	24.1
7	1.13	0.72	1556	0.1911	0.1070	11.757	0.2063	11.856	0.2159	19.3	12.4
8	1.04	1.33	781	0.0774	0.1285	12.244	0.1379	12.290	0.1404	7.1	12.2
9	0.84	n.d.	n.d.	0.0602	0.2926	11.055	0.2565	11.073	0.2607	6.1	30.6
10	0.74	n.d.	n.d.	0.1336	0.2599	12.220	0.2173	12.300	0.2243	12.6	26.0
AVERAGE VALUES											
				0.1255	0.0583	11.627	0.0443	11.685	0.0458	12.4	6.1

3776A3	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	2.03	May-88	346	0.2456	0.0762	13.168	0.1082	13.374	0.1135	22.4	7.9
2	1.91	0.52	3703	0.0946	0.1000	11.411	0.0958	11.449	0.0981	9.4	10.4
3	1.76	n.d.	n.d.	0.1289	0.0605	11.491	0.1512	11.547	0.1560	13.0	6.7
4	1.61	n.d.	n.d.	0.2235	0.1092	11.959	0.1102	12.087	0.1163	22.5	12.3
5	1.47	n.d.	n.d.	0.0610	0.0508	11.504	0.1358	11.529	0.1378	5.9	5.1
6	1.31	n.d.	n.d.	0.1031	0.1428	11.620	0.1181	11.667	0.1212	10.1	14.7
7	1.19	0.86	1388	0.1574	0.3060	10.665	0.1456	10.698	0.1526	17.4	36.7
8	1.06	n.d.	n.d.	0.2171	0.1442	11.192	0.1551	11.274	0.1645	23.5	17.7
9	0.91	n.d.	n.d.	0.1055	0.2293	12.340	0.2265	12.406	0.2320	9.7	22.1
10	0.79	n.d.	n.d.	0.1080	0.1365	10.990	0.2990	11.023	0.3078	11.3	15.3
AVERAGE VALUES											
				0.1359	0.0506	11.531	0.0497	11.591	0.0515	13.7	5.4

cont. →

Table 2. (left, above and the following 5 pages)
U-series results from continuous laser drilling (filled circles on Fig. 3A). Apparent U and Th concentrations partly indicate the declining ablation yield with depth 1. All errors are 2-σ. n.d.: not determined; Th concentration below background. Ages calculated with Isoplot (Ludwig 2012)). To avoid correlated errors, individual age errors do not include errors from standard. Average age errors result from the combination of the errors of the mean and the standard.

3776A4	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	^{234}U/ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	7.76	4.24	1831	0.1269	0.0182	13.214	0.0583	13.316	0.0597	11.0	1.7
2	7.25	2.57	2821	0.1048	0.0143	11.522	0.0572	11.567	0.0586	10.4	1.6
3	6.75	1.35	5014	0.0856	0.0045	11.315	0.0307	11.347	0.0314	8.6	0.5
4	6.39	1.07	5955	0.1131	0.0241	11.569	0.0518	11.619	0.0532	11.2	2.6
5	5.83	0.18	32711	0.1294	0.0271	11.474	0.0383	11.529	0.0396	13.0	2.9
6	5.14	1.13	4533	0.1117	0.0427	11.674	0.0485	11.726	0.0498	11.0	4.4
7	4.89	0.72	6788	0.0938	0.0319	11.847	0.0584	11.895	0.0596	9.0	3.2
8	4.38	1.89	2317	0.1319	0.0282	11.440	0.0548	11.496	0.0566	13.3	3.1
9	3.79	1.05	3605	0.1008	0.0313	11.242	0.0680	11.279	0.0698	10.2	3.4
10	3.37	1.22	2762	0.1186	0.0517	11.280	0.0651	11.325	0.0671	12.1	5.6
11	2.99	n.d.	n.d.	0.1226	0.0534	11.101	0.0510	11.142	0.0527	12.8	5.9
12	2.74	n.d.	n.d.	0.1285	0.0743	11.010	0.0560	11.049	0.0580	13.5	8.3
13	2.56	0.06	41499	0.1416	0.0323	11.172	0.0658	11.222	0.0683	14.8	3.7
14	2.36	0.02	106695	0.0993	0.0371	11.119	0.0795	11.152	0.0816	10.2	4.1
15	2.21	0.65	3412	0.0974	0.0488	11.634	0.0834	11.679	0.0853	9.5	5.0
16	2.12	0.22	9616	0.1086	0.0582	11.242	0.1414	11.281	0.1454	11.1	6.4
17	1.94	n.d.	n.d.	0.0676	0.0319	10.944	0.1366	10.963	0.1391	7.0	3.5
18	1.80	1.52	1186	0.0972	0.0365	10.974	0.1145	11.002	0.1175	10.1	4.1
19	1.59	n.d.	n.d.	0.0399	0.0538	11.741	0.0630	11.759	0.0636	3.8	5.2
20	1.55	n.d.	n.d.	0.0910	0.0677	11.271	0.0597	11.304	0.0611	9.2	7.1
21	1.44	n.d.	n.d.	0.1308	0.0987	11.664	0.1297	11.726	0.1339	13.0	10.5
22	1.32	2.61	505	0.1255	0.0422	11.640	0.1551	11.698	0.1598	12.4	4.8
AVERAGE VALUES											
				0.1085	0.0088	11.438	0.0183	11.483	0.0188	10.9	0.9

3777-1	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U$i error	Age (ka)	Age error (ka)
1	8.36	17.20	486	0.1418	0.0225	11.084	0.0538	11.131	0.0559	14.9	2.6
2	7.73	5.40	1432	0.1319	0.0157	10.908	0.0614	10.945	0.0636	14.1	2.0
3	7.31	1.98	3687	0.1108	0.0265	11.343	0.0269	11.386	0.0277	11.2	2.8
4	6.93	0.83	8315	0.0949	0.0286	10.952	0.0848	10.979	0.0870	9.9	3.2
5	6.27	0.48	13099	0.0946	0.0289	11.254	0.0724	11.288	0.0741	9.6	3.1
6	5.61	2.55	2198	0.1298	0.0295	11.046	0.0486	11.087	0.0503	13.6	3.4
7	5.03	0.41	12155	0.1097	0.0198	11.230	0.0496	11.269	0.0511	11.2	2.2
8	4.37	3.50	1247	0.1057	0.0216	11.275	0.0714	11.314	0.0733	10.7	2.4
9	3.80	n.d.	n.d.	0.0959	0.0376	11.177	0.0364	11.210	0.0373	9.8	4.0
10	3.41	n.d.	n.d.	0.0854	0.0336	10.919	0.0615	10.942	0.0629	8.9	3.7
11	3.04	n.d.	n.d.	0.0990	0.0452	10.962	0.0639	10.991	0.0656	10.3	5.0
12	2.81	n.d.	n.d.	0.1124	0.0438	10.883	0.0974	10.913	0.1004	11.9	5.0
13	2.56	n.d.	n.d.	0.0825	0.0550	11.015	0.0631	11.039	0.0646	8.5	5.9
14	2.52	0.16	16029	0.0907	0.0517	11.197	0.0454	11.229	0.0465	9.2	5.5
15	2.36	n.d.	n.d.	0.0910	0.0291	11.497	0.0800	11.536	0.0818	9.0	3.1
16	2.17	0.80	2726	0.0585	0.0250	11.108	0.0986	11.127	0.1001	5.9	2.6
AVERAGE VALUES											
				0.1070	0.0085	11.113	0.0200	11.148	0.0206	11.0	0.9

cont. ⟶

3777-2	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	6.92	21.27	326	0.1216	0.0336	11.204	0.0538	11.247	0.0556	12.5	3.7
2	6.82	3.25	2101	0.1108	0.0358	11.271	0.0485	11.312	0.0499	11.3	3.9
3	6.56	0.90	7286	0.1134	0.0319	11.200	0.0504	11.240	0.0519	11.6	3.5
4	5.99	n.d.	n.d.	0.1029	0.0254	11.243	0.0581	11.280	0.0596	10.5	2.8
5	5.18	0.56	9178	0.1217	0.0387	11.033	0.0698	11.071	0.0722	12.7	4.4
6	4.47	1.86	2407	0.1068	0.0162	11.416	0.0536	11.459	0.0550	10.7	1.8
7	3.95	n.d.	n.d.	0.1103	0.0289	12.051	0.0583	12.112	0.0598	10.5	2.9
8	3.57	1.85	1933	0.0796	0.0334	10.823	0.0652	10.843	0.0666	8.3	3.7
9	3.21	n.d.	n.d.	0.1014	0.0454	11.537	0.0495	11.581	0.0507	10.0	4.7
10	2.93	0.92	3192	0.0801	0.0370	11.002	0.0711	11.025	0.0726	8.2	4.0
11	2.66	1.15	2314	0.1055	0.0633	12.124	0.0516	12.184	0.0529	9.9	6.2
12	2.55	0.94	2720	0.1253	0.0664	11.089	0.1051	11.130	0.1086	13.1	7.5
13	2.28	n.d.	n.d.	0.0790	0.0451	11.782	0.0823	11.820	0.0839	7.6	4.5
14	2.22	n.d.	n.d.	0.1195	0.0437	11.629	0.1207	11.684	0.1242	11.8	4.7
15	1.86	n.d.	n.d.	0.1435	0.0689	11.664	0.0819	11.733	0.0848	14.3	7.4
16	1.48	n.d.	n.d.	0.1071	0.0677	11.609	0.1092	11.657	0.1121	10.5	7.1
17	1.43	n.d.	n.d.	0.0506	0.0363	11.246	0.1048	11.264	0.1062	5.0	3.7
18	1.35	n.d.	n.d.	0.0730	0.0461	10.779	0.1136	10.796	0.1159	7.7	5.1
19	1.29	n.d.	n.d.	0.0770	0.0682	10.135	0.1451	10.139	0.1486	8.6	8.1
AVERAGE VALUES											
				0.1062	0.0098	11.311	0.0197	11.352	0.0202	10.7	1.1

3777-3	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	7.03	18.27	385	0.1409	0.0228	11.139	0.0589	11.187	0.0611	14.7	2.7
2	6.73	5.32	1266	0.1133	0.0242	10.868	0.0260	10.898	0.0269	12.0	2.7
3	6.34	0.37	17266	0.1115	0.0291	11.167	0.0612	11.206	0.0630	11.5	3.2
4	5.76	1.80	3205	0.0868	0.0301	11.674	0.0512	11.714	0.0522	8.4	3.1
5	4.97	0.25	19934	0.0911	0.0300	11.283	0.0611	11.317	0.0625	9.2	3.2
6	4.38	n.d.	n.d.	0.1407	0.0318	11.151	0.0674	11.200	0.0699	14.7	3.7
7	3.86	0.92	4189	0.0961	0.0287	11.004	0.0605	11.032	0.0620	10.0	3.2
8	3.47	0.88	3933	0.0978	0.0418	11.101	0.0615	11.132	0.0631	10.1	4.5
9	3.13	n.d.	n.d.	0.1534	0.0460	11.518	0.0652	11.587	0.0677	15.6	5.1
10	2.72	0.59	4598	0.1165	0.0460	10.789	0.0808	10.817	0.0835	12.5	5.3
11	2.52	n.d.	n.d.	0.0989	0.0323	11.211	0.0569	11.246	0.0583	10.1	3.5
12	2.27	n.d.	n.d.	0.1034	0.0376	11.473	0.0761	11.517	0.0781	10.3	4.0
13	2.29	0.02	99403	0.0860	0.0669	11.888	0.0969	11.932	0.0989	8.2	6.6
14	2.11	n.d.	n.d.	0.0968	0.0310	11.033	0.0923	11.063	0.0947	10.0	3.5
15	1.83	2.06	884	0.1119	0.0436	10.643	0.0771	10.665	0.0796	12.1	5.1
16	1.62	1.46	1111	0.1028	0.0744	11.148	0.0836	11.183	0.0859	10.6	8.0
17	1.49	n.d.	n.d.	0.0615	0.0465	10.710	0.1119	10.723	0.1138	6.5	5.1
18	1.36	n.d.	n.d.	0.0566	0.0775	10.715	0.1135	10.727	0.1153	5.9	8.4
19	1.23	n.d.	n.d.	0.0748	0.0670	10.856	0.0995	10.875	0.1015	7.8	7.3
20	1.13	0.56	2024	0.0680	0.0953	12.158	0.1115	12.197	0.1133	6.3	9.1
AVERAGE VALUES											
				0.1077	0.0099	11.183	0.0190	11.220	0.0196	11.0	1.1

cont. ⟶

3777-4	U (ppm)	Th (ppb)	U/Th	$^{230}Th/^{238}U$	$^{230}Th/^{238}U$ error	$^{234}U/^{238}U$	$^{234}U/^{238}U$ error	initial $^{234}U/^{238}U$	$^{234}U/^{238}U_i$ error	Age (ka)	Age error (ka)
1	7.12	15.09	472	0.1312	0.0277	11.337	0.0351	11.388	0.0363	13.4	3.0
2	6.77	0.29	23626	0.0971	0.0263	11.018	0.0503	11.048	0.0517	10.1	2.9
3	6.26	n.d.	n.d.	0.1106	0.0264	11.200	0.0445	11.239	0.0458	11.3	2.9
4	5.94	0.32	18482	0.1009	0.0245	10.729	0.0661	10.751	0.0680	10.8	2.8
5	5.52	0.48	11405	0.1074	0.0226	11.011	0.0468	11.044	0.0482	11.2	2.5
6	4.72	0.74	6383	0.1021	0.0374	11.339	0.0829	11.379	0.0850	10.3	4.0
7	4.21	n.d.	n.d.	0.0931	0.0344	11.326	0.0922	11.362	0.0944	9.4	3.7
8	3.64	n.d.	n.d.	0.0891	0.0290	11.651	0.0738	11.692	0.0754	8.7	3.0
9	3.30	n.d.	n.d.	0.0883	0.0664	11.386	0.0680	11.421	0.0695	8.8	6.9
10	3.02	0.10	30743	0.0995	0.0371	11.942	0.0641	11.995	0.0655	9.5	3.7
11	2.91	n.d.	n.d.	0.0957	0.0361	10.737	0.0627	10.758	0.0644	10.2	4.1
12	2.82	n.d.	n.d.	0.0750	0.0253	10.843	0.0602	10.862	0.0615	7.8	2.8
13	2.53	n.d.	n.d.	0.1015	0.0389	11.164	0.0875	11.198	0.0898	10.4	4.3
14	2.32	n.d.	n.d.	0.1270	0.0568	10.786	0.0622	10.817	0.0645	13.7l	6.6
15	2.13	0.68	3122	0.0818	0.0507	11.859	0.0900	11.901	0.0917	7.8	5.0
16	1.90	n.d.	n.d.	0.0755	0.0740	11.032	0.0748	11.055	0.0764	7.7	7.9
17	1.81	n.d.	n.d.	0.1289	0.0406	10.514	0.1326	10.535	0.1377	14.3	5.2
18	1.64	n.d.	n.d.	0.1710	0.0679	0.9917	0.0782	0.9912	0.0829	20.7	9.2
AVERAGE VALUES											
				0.1026	0.0094	11.193	0.0199	11.229	0.0205	10.5	1.0

DISCUSSION AND CONCLUSIONS

Our age results imply that all samples have experienced a U-uptake event that corresponds to the Pleistocene/Holocene transition at 11.7 ka b2k (before the year 2000; Walker et al. 2018). Considering that the samples were most likely an open system for some time, particularly in view of the young apparent ages, it can be reasonably envisaged that the U-uptake took place during the terminal Pleistocene. However, it is important to consider that our dates represent minimum age constraints for the samples, and therefore do not exclude an earlier Upper Paleolithic age for the human remains and burial. Nevertheless, in light of these findings, the association of the Apidima 3 skeleton with the Aurignacian lithics, as well as the attribution of the lithics to the Aurignacian, should be re-evaluated. A better understanding of the chronology of the human samples would be gained by ESR analyses on samples 3776 and 3777 (e.g., Brumm et al. 2016). Unfortunately, radiocarbon dating of these samples (e.g., Higham at al. 2014) was not possible due to poor collagen preservation (Higham pers. comm.). However, it might be possible to apply that method to the pierced shell remains associated with Apidima 3 (Douka 2017). Finally, the question of association of the human remains with the material cultural remains recovered at the site can only be resolved through renewed fieldwork and excavation aiming to resolve the stratigraphy, depositional context and site formation processes at Apidima C. In summary, our results confirm a Pleistocene age for the Apidima C human remains, but further research is necessary to assess their association with the early Upper Paleolithic assemblages described for this site.

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REFERENCES

Benson, A., L. Kinsley, A. Defleur, H. Kokkonen, M. Mussi, and R. Grün. 2013. Laser ablation depth profiling of U-series and Sr isotopes in human fossils. *Journal of Archaeological Science* 40: 2991–3000.

Brumm, A., G. van den Bergh, M. Storey, I. Kurniawan, B. V. Alloway, R. Setiawan, E. Setiyabudi, R. Grün, M. W. Moore, D. Yurnaldi, M. R. Puspaningrum, U. P. Wibowo, H. Insani, I. Sutisna, J. A. Westgate, N. J. G. Pearce, M. Duval, H. J. M. Meijer, F. Aziz, T. Sutikna, S. van der Kaars, and M. J. Morwood. 2016. Age and context of the oldest known hominin fossils from Flores. *Nature* 534: 249–253.

Burns, R. K. 2015. *Forensic anthropology training manual*. Routdlege: New York.

Darlas, A. 1995. Τα λίθινα εργαλεία του σκελετού ΛΑΟ 1/Σ 3 (Απήδημα – Μάνη). *Acta Anthropologica* 1: 59–62.

d'Errico, F., and M. Vanhaeren. 2015. Upper Palaeolithic mortuary practices: Reflection of ethnic affiliation, social complexity, and cultural turnover. In *Death Rituals, Social Order and the Archaeology of Immortality in the Ancient World: 'Death Shall Have No Dominion'*, ed. by C. Renfrew, M. Boyd and I. Morley, pp. 45–62. Cambridge: Cambridge University Press.

Douka, K. 2017. Radiocarbon dating of marine and terrestrial shell. In Molluscs in Archaeology: methods, approaches and applications, ed. by M. J. Allen, pp. 381–389. Studying Scientific Archaeology 3. Oxbow Books.

Groucutt, H. S., R. Grün, I. S.A. Zalmout, N. A. Drake, S. J. Armitage, I. Candy, R. Clark-Wilson, J. Louys, P. S. Breeze, M. Duval, L. T. Buck, et al. 2018. Homo sapiens in Arabia by 85,000 years ago. *Nature Ecology & Evolution* 2: 800–809. DOI: 10.1038/s41559-018-0518-2.

Grün, R., S. Eggins, L. Kinsley, H. Mosely, and M. Sambridge. 2014. Laser ablation U-series analysis of fossil bones and teeth. *Palaeogeography, Palaeoclimatology, Palaeoecology* 416: 150–167.

Grün, R., H. P. Schwarcz, and J. M. Chadam. 1988. ESR dating of tooth enamel: Coupled correction for U-uptake and U-series disequilibrium. *Nuclear Tracks and Radiation Measurements* 14: 237–241.

Harvati, K. 2000. Apidima. In *Encyclopedia of Human Evolution and Prehistory*, ed. by E. Delson, I. Tattersall, J. A. van Couvering and A. S. Brooks, pp. 141–2. 2nd edition. New York: Garland Publishing.

Harvati, K. 2016. Paleoanthropology in Greece: Recent findings and interpretations. In *Paleoanthropology of the Balkans and Anatolia: Human Evolution and its Context*, ed. by K. Harvati and M. Roksandic, pp. 3–14. Vertebrate Paleobiology and Paleoanthropology Series. Dordrecht: Springer.

Harvati, K., and E. Delson. 1999. Conference report: Paleoanthropology of the Mani Peninsula (Greece). *Journal of Human Evolution* 36: 343–348.

Harvati, K., E. Panagopoulou, and C. Runnels. 2009. The paleoanthropology of Greece. *Evolutionary Anthropology* 18: 131–43.

Harvati, K., C. Stringer, and P. Karkanas. 2011. Multivariate analysis and classification of the Apidima 2 cranium from Mani, Southern Greece. *Journal of Human Evolution* 60: 246–250.

Harvati, K., C. Röding, A. Bosman, F. A. Karakostis, C. Stringer, P. Karkanas, N. Thompson, V. Koutoulidis, L. A. Moutopoulos, V. Gorgoullis, and M. Kouloukoussa. 2019. Apidima cave fossils provide earliest evidence of Homo sapiens in Eurasia. *Nature* 571: 502–504.

Higham, T., K. Douka, R. Wood, C. Bronk Ramsey, F. Brock, L. Basell, M. Marta Camps, A. Arrizabalaga, J. Baena, C. Barroso-Ruiz, C. Bergman, C. Boitard, P. Boscato, M. Caparros, N. J. Conard, C. Draily, A. Froment, B. Galvan, P. Paolo Gambassini, A. Garcia-Moreno, S. Grimaldi, P. Haesaerts, B. Holt, M. J. Iriarte-Chiapusso, A. Jelinek, J. F. Jorda Pardo, J. M. Maillo-Fernandez, A. Marom, J. Maroto, M. Menendez, L. Metz, E. Morin, A. Moroni, F. Negrino, E. Panagopoulou, M. Peresani, S. Pirson, M. de la Rasilla, J. Riel-Salvatore, A. Ronchitelli, D. Santamaria, P. Semal, L. Slimak, J. Soler, N. Soler, A. Villaluenga, R. Pinhasi, and R. Jacobi. 2014. The timing and spatiotemporal patterning of Neanderthal disappearance. *Nature* 512: 306–309.

Karali, L. 1995. Preliminary report on malacological material found in Apidima cave in Laconia. *Acta Anthropologica* 1: 159–162.

Ligoni, E., and M. Papagrigorakis. 1995. Odontological examination of skeleton LAO 1 / S3. *Acta Anthropologica* 1: 53–58.

Liritzis, Y., and Y. Maniatis. 1995. ESR experiments on calcites and bones for dating purposes. *Acta Anthropologica* 1: 65–98.

Ludwig, K. R. 2012. Isoplot. Excel package version 3.76.12.02.24 http://www.bgc.org/isoplot_etc/isoplot.html

Mompheratou, E., and T. K. Pitsios. 1995. Apidima, cave Gamma (Γ): The burial of female skeleton LAO 1 /S3. *Acta Anthropologica* 1: 27–51.

Pike, A. W. G., R. E. M. Hedges, and P. Van Calsteren. 2002. U-series dating of bone using the diffusion-adsorption model. *Geochimica et Cosmochimica Acta* 66: 4273–4286.

Pitsios, T. K. 1985. Παλαιοανθρωπολογικές έρευνες στη θέση «Απήδημα» της Μέσα Μάνης. Αρχαιολογία 15: 26–33.

Pitsios, T. K. 1995. Paleoanthropological Research at the cave site of Apidima, Laconia, Greece. *Acta Anthropologica* 1: 1–180.

Pitsios, T. 1999. Paleoanthropological research at the cave site of Apidima and the surrounding region (South Peloponnese, Greece). *Anthropologischer Anzeiger* 57: 1–11.

Riel-Salvatore, J., and C. Gravel-Miguel. 2013. Upper Palaeolithic mortuary practices in Eurasia: A critical look at the burial record. In *The Oxford handbook of the archaeology of death and burial*, ed. by L. Nilsson Stutz and S. Tarlow, pp. 303–46. Oxford: Oxford University Press.

Sambridge, M., R. Grün, and S. Eggins. 2012. U-series dating of bone in an open system: The diffusion-adsorption-decay model. *Quaternary Geochronology* 9: 42–53.

Tourloukis, V., and K. Harvati. 2018. The Palaeolithic record of Greece: A synthesis of the evidence and a research agenda for the future. *Quaternary International* 466: 48–65.

Walker, M., M. J. Head, M. Berkelhammer, S. Björck, H. Cheng, L. Cwynar, D. Fisher, V. Gkinis, A. J. Long., J. Lowe, R. Newnham, S. O. Rasmussen, and H. Weiss. 2018. Formal ratification of the subdivision of the Holocene Series/Epoch (Quaternary System/Period): Two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stage/subseries. *Episodes* 41: 213–223.