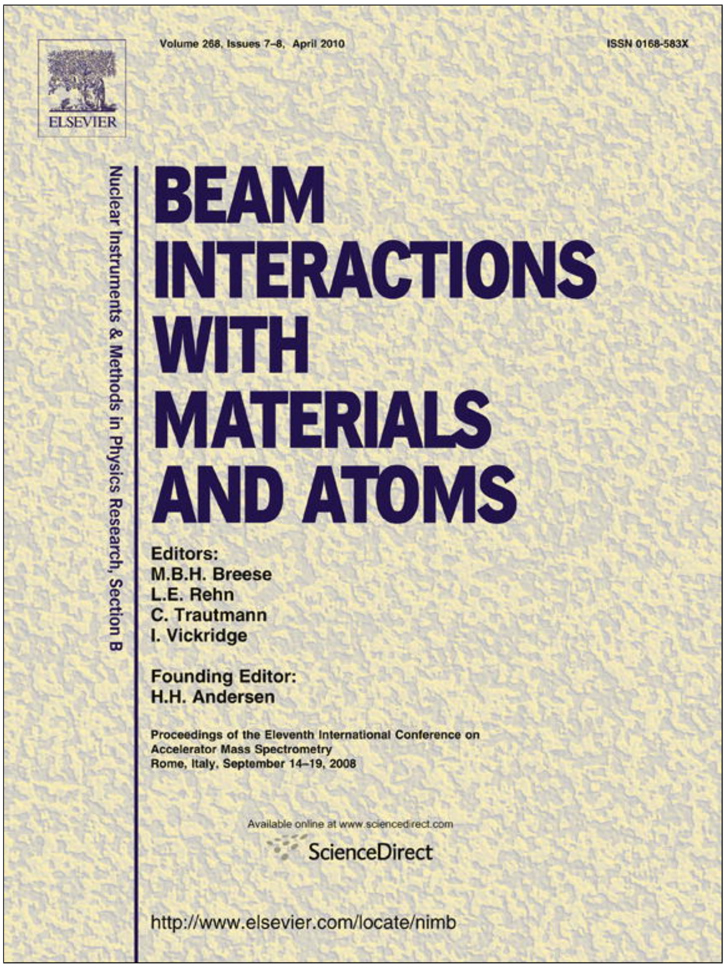
Volume 268, Issues 7–8, April 2010
ISSN 0168-583X
ELSEVIER
Nuclear Instruments & Methods in Physics Research, Section B
BEAM INTERACTIONS WITH MATERIALS AND ATOMS
Editors:
M.B.H. Breese
L.E. Rehn
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Founding Editor:
H.H. Andersen
Proceedings of the Eleventh International Conference on Accelerator Mass Spectrometry
Rome, Italy, September 14–19, 2008
Available online at www.sciencedirect.com
ScienceDirect
http://www.elsevier.com/locate/nimb

Nuclear Instruments and Methods in Physics Research B 268 (2010) 1013–1021

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

^{14}C dating of the Early to Late Bronze Age stratigraphic sequence of Aegina Kolonna, Greece

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ARTICLE INFO

Article history:
Available online 13 October 2009

Keywords:
Radiocarbon dating
Aegina
Aegean Bronze Age
Bayesian sequencing

ABSTRACT

Aegina Kolonna, located in the center of the Saronic Gulf in the Aegean Mediterranean (Greece), is one of the major archaeological sites of the Aegean Bronze Age with a continuous stratigraphic settlement sequence from the Late Neolithic to the Late Bronze Age. Due to its position next to the maritime cross roads between central mainland Greece, the northeast Peloponnese, the Cyclades and Crete, the island played an important role in the trade between these regions. In the course of new excavations, which focused on the exploration of the Early, Middle and Late Bronze Age at Kolonna, several short lived samples from different settlement phases have been ^{14}C-dated with the AMS method at the VERA laboratory. Bayesian sequencing of the ^{14}C data according to the stratigraphic position of the samples in the profile was performed to enable estimates of the transition time between the cultural phases. The Aegina Kolonna ^{14}C sequence is one of the longest existing so far for the Aegean Bronze Age, and therefore of major importance for the absolute Bronze Age chronology in this region. Preliminary results indicate that the Middle Helladic period seems to have started earlier and lasted longer than traditionally assumed. Further, at the present stage of our investigation we can give also a very tentative time frame for the Santorini volcanic eruption which seems to be in agreement with the science derived VDL date.

1. Introduction

The archaeological site at Aegina Kolonna is located on the island of Aegina in the center of the Saronic Gulf (Fig. 1) in the Aegean Mediterranean (Greece). Archaeological excavation work at Kolonna has been performed since the late 19th century by Greek, German and Austrian excavators. Aegina Kolonna is one of the major centres of the Aegean Bronze Age and one of the few archaeological sites in Greece with a continuous stratigraphic settlement sequence from the Late Neolithic to the Late Bronze Age. The importance of the Kolonna site and the entire island may be explained in part because of its location in the centre of the Saronic Gulf, on what seems to have been, at that time, the crossroads between central mainland Greece, the northeast Peloponnese, the Cyclades, and Crete. Impressive fortifications, the earliest known shaft grave in the Aegean, the famous "treasure of Aegina," and a number of additional "prestige" items mainly of Cretan and Cycladic origin mirror the wealth and the key role of ancient Kolonna.

The importance of Kolonna is also shown by the abundant ceramic finds originating from distant cultural regions and by the fact that Kolonna produced high quality pottery, which was exported to the entire Aegean Mediterranean. Thus, Aegina Kolonna is truly significant for the synchronization of cultural phases of the Aegean Bronze Age [1–3].

2. New excavation

Recent excavations since 2002 focused on the exploration of the Early, Middle and Late Bronze Age at Kolonna. Regarding our stratigraphic research a 3.5 m high earth profile (see e.g. Fig. 2) forms the backbone of our stratigraphic work. The oldest layers excavated so far date to the beginning of Early Bronze III, the youngest ones reach Late Bronze II. The excavations unearthed major parts

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0168-583X/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2009.10.086

Fig. 1. Map of the Saronic Gulf and the Island of Aegina in its centre [18].

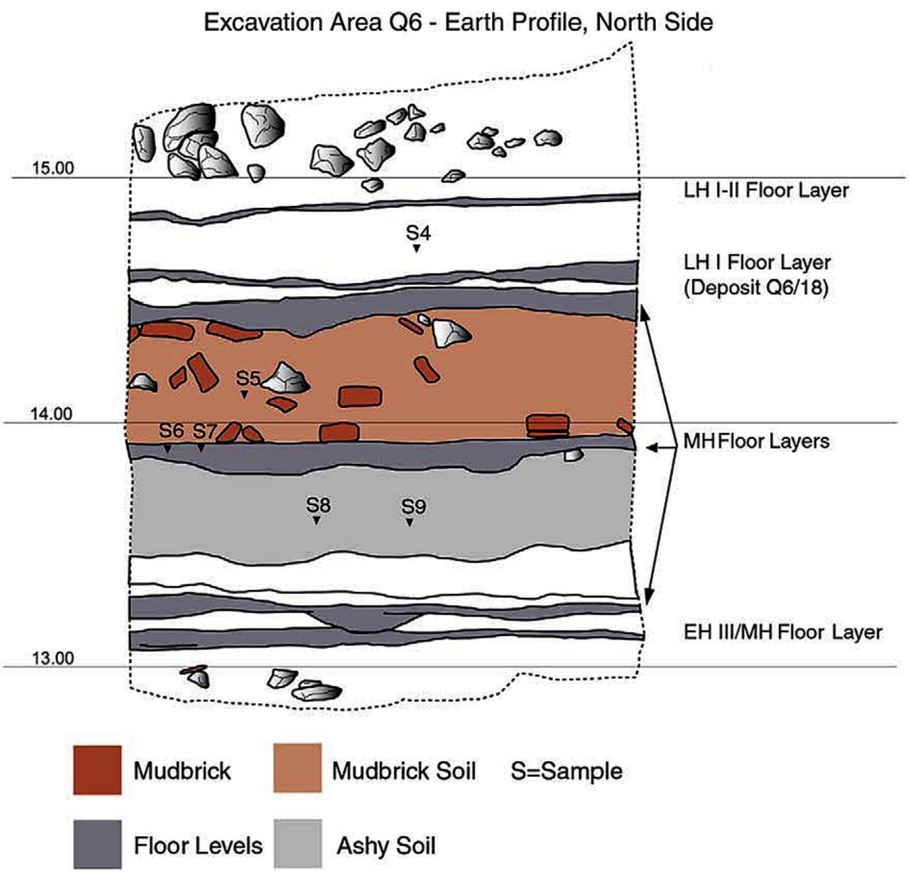

Fig. 2. Vertical stratigraphic sequence at the new excavation area.

Table 1
^{14}C data of all samples from the Aegina Kolonna site determined at the VERA-laboratory.

Laboratory number	Stratigraphic position*	Sample material	Ceramic phase	$\delta^{13}C$ [a,b] [‰]	^{14}C age[b] [BP]	Calibrated age[c]	$\delta^{15}N$ [d] [‰]	%C [d]	C/N [d,e]
VERA-3861HS	Metallofen 2	charcoal (humic acids)	D	-23.6 ± 0.8	4096 ± 27	2860BC (21.0%) 2809BC 2753BC (7.4%) 2721BC 2702BC (65.8%) 2572BC 2513BC (1.2%) 2504BC			
VERA-3863HS	Metallofen 1	charcoal (humic acids)	D	-23.6 ± 0.5	4049 ± 27	2834BC (3.8%) 2818BC 2661BC (1.8%) 2649BC 2635BC (89.7%) 2481BC			
VERA-3864HS	Metallofen 1	charcoal (humic acids)	D	-25.1 ± 0.6	4128 ± 27	2871BC (26.6%) 2802BC 2780BC (63.9%) 2617BC 2611BC (4.9%) 2581BC			
VERA-2678	FG XVIIId	Hordeum vulgare	E	-22.7 ± 1.0	3724 ± 35	2274BC (1.9%) 2257BC 2208BC (93.5%) 2024BC			
VERA-2680	FG XVIIId	Hordeum vulgare	E	-23.5 ± 0.8	3722 ± 35	2272BC (1.4%) 2258BC 2206BC (93.7%) 2024BC 1988BC (0.2%) 1986BC			
VERA-2681	FG XVIIId	Hordeum vulgare	E	-20.1 ± 1.5	3739 ± 35	2279BC (5.4%) 2251BC 2230BC (1.3%) 2221BC 2211BC (88.7%) 2032BC			
VERA-2679	FG XVIIIh	Hordeum vulgare	E	-21.0 ± 0.9	3761 ± 35	2289BC (80.8%) 2121BC 2095BC (14.6%) 2041BC			
VERA-2682	FG XVIIIc	Hordeum vulgare	E	-21.7 ± 1.0	3712 ± 35	2204BC (93.6%) 2018BC 1995BC (1.8%) 1981BC			
VERA-2683	FG XVIIIc	Hordeum vulgare	E	-22.9 ± 0.8	3721 ± 35	2272BC (1.3%) 2259BC 2206BC (93.6%) 2023BC 1991BC (0.6%) 1985BC			
VERA-4641	19/36	bone, Ovis/Capra, metacarpus	E	-15.9 ± 0.8; -19.1[d]	3759 ± 35	2288BC (79.5%) 2121BC 2095BC (15.9%) 2041BC	6.5	35	3.1
VERA-2688	11b2/20	bone, Ovis/Capra, femur	E	-16.6 ± 0.9; -18.0[d]	3698 ± 33	2199BC (9.4%) 2163BC 2152BC (82.4%) 2014BC 1998BC (3.7%) 1979BC	4.5	43	3.2
VERA-2692	19/28	bone (goat)[†]	F	-18.1 ± 1.1; -18.3[d]	3704 ± 36	2201BC (92.2%) 2015BC 1997BC (3.2%) 1979BC	4.7	40	3.1
VERA-4640	19/27	bone, Bos, tibia	G	-16.6 ± 1.2; -19.2[d]	3800 ± 44	2457BC (3.4%) 2418BC 2407BC (3.7%) 2376BC 2367BC (0.7%) 2356BC 2351BC (85.0%) 2132BC 2085BC (2.6%) 2057BC	6.1	38	3.2
VERA-4639	19/23	bone, Bos, ulna[†]	G	-23.0 ± 1.9; -20.7[d]	3809 ± 32	2402BC (2.0%) 2382BC 2348BC (93.4%) 2139BC	4.9	24	3.3
VERA-4638	Q6/056	bone, Ovis/Capra, tibia	G	-20.5 ± 1.1; -19.9[d]	3646 ± 32	2135BC (21.7%) 2078BC 2064BC (73.7%) 1926BC	3.1	41	3.2
VERA-4281	Q3/148	Hordeum vulgare	G	-23.4 ± 0.4	3740 ± 36	2280BC (6.2%) 2249BC 2231BC (1.7%) 2219BC 2213BC (87.5%) 2032BC			
VERA-4282	Q3/149	Hordeum vulgare	G	-24.3 ± 0.5	3711 ± 34	2203BC (93.9%) 2021BC 1994BC (1.5%) 1982BC			
VERA-4283	Q3/150	Hordeum vulgare	G	-23.4 ± 0.4	3780 ± 37	2339BC (1.9%) 2315BC 2310BC (87.0%) 2125BC 2091BC (6.5%) 2043BC			
VERA-4636	Q6/054	bone, Ovis/Capra, coxa	H	-17.6 ± 1.2; -19.9[d]	3628 ± 30	2125BC (7.9%) 2091BC 2044BC (87.5%) 1900BC	4.1	42	3.2
VERA-4637	Q6/055	bone, Bos, long bone	H	-17.5 ± 1.2; -19.5[d]	3643 ± 30	2134BC (18.4%) 2081BC 2061BC (77.0%) 1922BC	6.7	46	3.2

(continued on next page)

Table 1 (*continued*)

Laboratory number	Stratigraphic position*	Sample material	Ceramic phase	$\delta^{13}C$ [a,b] [‰]	^{14}C age[b] [BP]	Calibrated age[c]	$\delta^{15}N$ [d] [‰]	%C [d]	C/N [d,e]
VERA-4280	Q3/151	Hordeum vulgare	H	-24.4 ± 0.6	3724 ± 39	2278BC (3.2%) 2251BC 2229BC (0.6%) 2222BC 2211BC (90.4%) 2020BC 1994BC (1.2%) 1982BC			
VERA-4279	Q3/136	Hordeum vulgare	H	-21.7 ± 0.5	3718 ± 38	2274BC (1.7%) 2257BC 2208BC (91.9%) 2016BC 1996BC (1.8%) 1980BC			
VERA-2687	11b1/04	bone, Bos, mandibula	H	-16.8 ± 1.0; -16.0[d]	3694 ± 35	2199BC (8.8%) 2161BC 2153BC (80.8%) 2008BC 2003BC (5.7%) 1977BC	4.7	44	3.1
VERA-4634	Q6/045	bone, Sus, tibia	I	-19.3 ± 1.6; -19.8[d]	3544 ± 37	2009BC (1.0%) 2002BC 1976BC (94.4%) 1756BC	7.8	38	3.2
VERA-4278	Q3/127	indet. cereal	I	-21.9 ± 0.6	3522 ± 38	1947BC (95.4%) 1746BC			
VERA-4277	Q3/126	Hordeum vulgare	I	-25.4 ± 0.6	3368 ± 36	1745BC (85.6%) 1604BC 1587BC (9.8%) 1535BC			
VERA-4038	Q6/41	indet. cereal	I	-24.7 ± 0.9	3506 ± 34	1923BC (95.4%) 1743BC			
VERA-4037	Q6/37	indet. cereal	I	-22.6 ± 0.7	3708 ± 34	2202BC (93.6%) 2020BC 1994BC (1.8%) 1982BC			
VERA-4039HS	Q6/42	indet. cereal (humic acids)	I	-21.9 ± 0.8	3691 ± 37	2198BC (7.9%) 2165BC 2151BC (87.5%) 1965BC			
VERA-4575	Q6/139	bone, Sus, mandibula	I	-19.0 ± 0.5; -18.7[d]	3537 ± 36	1961BC (95.4%) 1751BC	6.5	35	3.1
VERA-4576	Q6/138	bone, Bos, radius	I	-19.9 ± 0.6; -19.1 [d]	3482 ± 37	1899BC (90.3%) 1731BC 1719BC (5.1%) 1692BC	6.2	47	3.2
VERA-4578	Q6/141	bone, Ovis/Capra, mandibula	I	-22.2 ± 0.7; -19.9[d]	3501 ± 39	1931BC (93.9%) 1738BC 1709BC (1.5%) 1697BC	5.7	39	3.1
VERA-4579	Q6/142	bone, Ovis/Capra, tibia	I	-17.8 ± 0.7; -16.8[d]	3526 ± 38	1952BC (95.4%) 1747BC	3.5	43	3.1
VERA-4580	Q6/142	bone, Bos, metatarsus	I	-19.3 ± 0.4; -18.2[d]	3506 ± 33	1919BC (95.4%) 1745BC	6.8	32	3.1
VERA-4276	Q3/100	indet. cereal	I	-22.7 ± 0.6	3506 ± 37	1932BC (95.4%) 1741BC			
VERA-4275	Q3/86	indet. cereal	I	-24.1 ± 0.6	3544 ± 38	2009BC (1.1%) 2002BC 1976BC (94.3%) 1756BC			
VERA-4581	Q3/105	bone, lion, tibia	I	-18.1 ± 1.0; -18.3[d]	3639 ± 36	2135BC (18.2%) 2078BC 2064BC (77.2%) 1907BC	8.3	44	3.2
VERA-4577	Q6/138	bone, Ovis/Capra, metatarsus†	I	-22.8 ± 0.7	3458 ± 39	1887BC (95.4%) 1686BC	nd**	nd	nd
VERA-4571	Q6/80	bone, Ovis/Capra, tibia	J	-18.5 ± 0.7; -18.9[d]	3469 ± 38	1887BC (95.4%) 1691BC	5.5	35	3.2
VERA-4574	Q6/90	bone, Sus, radius	J	-21.5 ± 1.1; -19.4[d]	3430 ± 39	1879BC (13.4%) 1839BC 1830BC (82.0%) 1634BC	7.5	34	3.1
VERA-4573	Q6/92	bone, Ovis/Capra, humerus	J	-21.2 ± 0.6; -19.1[d]	3485 ± 36	1901BC (91.5%) 1733BC 1716BC (3.9%) 1693BC	4.4	39	3.2
VERA-4572	Q5/31	bone, Ovis/Capra, femur	J	-21.0 ± 0.5; -19.4[d]	3407 ± 38	1876BC (5.5%) 1842BC 1821BC (2.4%) 1797BC 1781BC (87.5%) 1612BC	4.6	39	3.2
VERA-4570	Q6/89	bone, Sus, radius	J	-20.9 ± 0.7; -19.2[d]	3428 ± 36	1877BC (11.9%) 1841BC 1826BC (6.7%) 1795BC 1783BC (76.9%) 1635BC	8.5	33	3.0
VERA-4633	Q6/017	bone, Ovis/Capra, metatarsus	K	-16.9 ± 1.5; -18.8[d]	3333 ± 29	1689BC (95.4%) 1527BC	4.3	43	3.2
VERA-4033	Q6/016	indet. cereal	K	-27.8 ± 0.8	3197 ± 45	1607BC (4.3%) 1573BC 1559BC (0.9%) 1549BC 1539BC (90.2%) 1393BC			
VERA-4632	Q6/016	bone, Ovis/Capra, tibia	K	-14.4 ± 1.3	3356 ± 36	1740BC (77.9%) 1600BC 1594BC (17.5%) 1531BC	nd	nd	nd
VERA-4631	Q6/015	bone, Ovis/Capra, radius†	K	-15.7 ± 0.7	3349 ± 36	1737BC (7.5%) 1710BC 1695BC (87.9%) 1529BC	nd	nd	nd

VERA-4630	Q6/013	bone, Ovis/Capra, tibia†	L	-16.1 ± 0.7; -19.5[d]	3313 ± 48	1736BC (2.9%) 1712BC 1695BC (92.5%) 1494BC	5.1	37	3.2
VERA-4284	Q3/115	Hordeum vulgare	M	-24.5 ± 0.5	3044 ± 35	1411BC (95.4%) 1212BC			
VERA-4582	Q3/156	charred wood (twig)	M	-26.3 ± 0.6	2986 ± 33	1375BC (4.7%) 1340BC 1320BC (90.7%) 1118BC			
VERA-4285	Q3/159	legumes	M	-20.9 ± 0.6	3040 ± 37	1411BC (94.3%) 1208BC 1202BC (0.6%) 1196BC 1139BC (0.5%) 1135BC			

* Stratigraphic position: general excavation area / actual layer.
** Not determined
[a] Determined with the AMS system, the $\delta^{13}C$ value reflects mass dependent isotope fractionation in nature and in the laboratory. For most bone samples $\delta^{13}C$ values of the extracted gelatin determined with an EA-IRMS system are also given
[b] I sigma uncertainty
[c] 95.4% probability, determined with OxCal 4.0 and the IntCal04 calibration curve
[d] Determined for subsamples of the dated gelatin with an EA-IRMS system (elemental analyzer-isotope ratio mass spectrometer), for VERA- 2692 gelatin was extracted from a subsample of the bone for this measurements; long time precision of a repeatedly measured standard material: 0.1‰ for $\delta^{15}N$ and $\delta^{13}C$.
[e] Atom-% ratio
† Indicates samples with a collagen yield between 1% and 0.5% (see text)

of a very large-scaled, presumably at least two storied building, erected of massive undressed stone blocks in its lowest lines. The building technique, its dimensions and the rich finds unearthed inside the building indicate that it was the mansion of the Middle Bronze and Late Bronze Age settlement at Kolonna. Judging from present archaeological evidence, the building was constructed at the beginning of the Middle Bronze Age, perhaps at the same time as the first palaces in Minoan Crete. Within its existence the building was remodelled several times and until now three major architectural phases are distinguishable. At the beginning of the Late Bronze Age the building went out of use. It was partly destroyed first by a Late Bronze Age (LH IIIA) potters' kiln and later by the constructions of the later Greek sanctuary of the first millenium, when remains of the earlier habitations at Kolonna were levelled and cleared away in order to build the sanctuary.

The most interesting finds recovered inside the large building are high-quality Cretan drinking vessels, as well as locally produced imitations of Cretan pottery. The latter is a clear indication of the strong Cretan influence at Aegina Kolonna. Other imported and locally produced pottery of high quality furthermore indicate the importance and high social status of the people living inside the building [2,3].

The long stratigraphic sequence at Kolonna with rich finds of its material culture is perfectly suitable for an intensive diachronic ^{14}C analysis, which is at present one of the major exigencies in the Aegean Bronze Age absolute chronology, in particular for the Early and Middle Bronze Age [1,4]. The absolute terms for these periods in the Aegean presently relate to a few and often old ^{14}C data from various sites but so far no continuous stratigraphic sequence of a length comparable to the Kolonna site has been ^{14}C dated systematically. In spite of intensive ^{14}C analysis throughout the Aegean, the problem of the discrepancy between the absolute chronology and the historical chronology particularly for the end of the Middle Bronze Age and the beginning of the Late Bronze Age is still unsolved [4].

3. Radiocarbon dating

3.1. Materials and methods

In the course of the new excavations several samples from the different settlement phases corresponding also to different cultural periods were collected for radiocarbon dating. In the sample selection main attention was put on a – as far as possible – secure context between the sample and the archaeological layers which were assigned to the respective cultural phases according to characteristic pottery assemblages. A further criterion in the selection was that the samples comprise short-lived terrestrial material as e.g. charred seeds and animal bones. Also one charcoal sample from a twig with preserved bark was acquired for dating. The plant remains were identified by an archaeobotanist and the animal bones by an archaeozoologist. In order to exclude a marine diet component, bones from herbivores (Capra/Ovis and Bos) were used but also four bones from *Sus scrofa domesticus* (omnivore). The ^{14}C samples were mainly taken from compact long bones.

Apart from the shortlived samples, three charcoals were also among the selected ^{14}C samples. The latter were inspected by a dendrochronologist and pieces which according to the bending of the tree rings may originate from the outer part of a trunk or from a twig were used for dating. In total approx. fifty samples were ^{14}C-dated with the AMS method at the VERA laboratory.

The standard ABA method (1 M HCl – 0.1 M NaOH – 1 M HCl at 60 °C) of the VERA lab was applied for the pre-treatment of the carbonized samples (see e.g. Wild et al. [5]). The three charcoals and one charred seed sample completely dissolved during the alkaline

Table 2
^{14}C ages of samples from Aegina Kolonna determined earlier with the radiometric method.

Laboratory number	Stratighraphic position*	Sample material	Ceramic phase	^{14}C age[a] (BP)	Calibrated age[b]
HV 5843	FG IX (floor of corridor house)	indet. plant remains	C	3755 ± 105	2470BC (95.4%) 1905BC
HV 5842	Metallofen 1	charcoal	D	4130 ± 45	2873BC (95.4%) 2580BC
HV 5841	FG XVIII	charcoal	E	3625 ± 65	2198BC (2.6%) 2166BC 2150BC (87.7%) 1871BC 1846BC (2.9%) 1812BC 1804BC (2.2%) 1776BC
HV 5840	FG XVIII	charcoal	E	3820 ± 65	2468BC (91.9%) 2131BC 2086BC (3.5%) 2050BC
VRI 0395	FG XVIII	charcoal	E	3670 ± 90	2337BC (0.5%) 2323BC 2308BC (90.8%) 1865BC 1850BC (4.1%) 1773BC

* stratigraphic position: general excavation area/actual layer.
[a] 1 sigma uncertainty.
[b] 95.4% probability, determined with OxCal 4.0 and the IntCal04 calibration curve.

step. From these samples only humic acids precipitated from the alkaline solution could be used for ^{14}C dating.

Collagen from the animal bones was extracted and purified with a "modified Longin" method, i.e. the Longin procedure [6] was extended by a NaOH and a subsequent HCl treatment before gelatinisation, and the extraction yield determined. In several ^{14}C laboratories a collagen yield > 1% of the initial sample amount is used as an indication for bones yielding reliable ^{14}C dates. In addition some other parameters, e.g. the δ^{13}C- and δ^{15}N-values, the C-content in the gelatin (%C) and the C/N ratio may be used to characterize the extracted collagen [7]. These parameters are usually determined with an elemental analyser coupled to an isotope ratio mass spectrometer (EA-IRMS) operated in the continuous flow mode. At VERA the EA-IRMS measurement was performed with a *CE Instruments* NC 2500 elemental analyser – *Micromass Optima* mass spectrometer system for subsamples of the ^{14}C dated gelatine samples.

After the chemical pre-treatment the samples were further processed as described in Wild et al. [8,5] and the ^{14}C measurements were performed following the VERA protocol for routine measurements [9].

The VERA ^{14}C data (Table 1) plus three ^{14}C dates (ceramic phase E) determined earlier with the conventional ^{14}C method in Hannover and Vienna (Table 2) were combined with the stratigraphic information by Bayesian sequencing using the OxCal 4.0 program [10,11] to improve the uncertainty of the calibrated sample ages and the resulting time spans of the individual ceramic phases.

3.2. Results and discussion

The ^{14}C data of all samples measured at VERA are given in Table 1 together with the δ^{13}C values determined with the AMS system and the information about the sample location in the excavation area. Five bones with collagen yields between 1% and 0.5% are indicated in the table. For all other bones collagen yields above the 1% limit were determined. The quality parameters determined by EA-IRMS measurement are listed in Table 1 as well. All values lie in the range of bones assessed to yield reliable ^{14}C dating results [7]. Only one low-collagen sample (VERA-4639) showed a lower C-content which may be caused by the presence of some inorganic material, the other parameters of this sample are in the accepted range.

Among the dated bones were four samples from omnivores (*Sus scrofa domesticus*), where a marine component (fish residues) in the diet could be possible. A marine portion in the feed would lead to a shift of the ^{14}C data to older ages (reservoir effect). By comparison of the omnivore dates with data of coeval not-affected samples no age offsets and thus no indication for a marine influence could be detected, e.g. the weighted mean value (3510 ± 14 years BP) of the unaffected dates and the single *Sus scrofa domesticus* age of 3537 ± 36 years BP (VERA 4575) from the so called "Minoan layer" in ceramic phase I agree within 1 σ uncertainty. This conclusion is also corroborated by the measured δ^{13}C and δ^{15}N values, which do not indicate the consumption of a considerable amount of marine food. Marine diet should increase both the δ^{13}C and δ^{15}N values (see e.g. Schwarcz and Schoeninger [12]). The δ^{13}C values of the pigs are in the range of the values determined for the majority of the herbivores and the slightly higher δ^{15}N values may reflect the omnivore diet. Unexpected δ^{13}C values of -16‰ and -16.8‰ were determined for the herbivore samples VERA-2687 and VERA-4579. Whether these values indicate a C4 component in the feeding remains unclear but seems to be supported by the concordance of the sample ages with the ^{14}C data of the other samples (animal and plant remains) from the same ceramic phases. For clarification a more detailed stable isotope study would be required.

The ^{14}C data determined earlier with the radiometric method in Hanover and Vienna are given in Table 2 together with the information on the stratigraphic position of the dated samples and the sample material.

Fig. 3 shows an OxCal 4.0 plot with the results of the Bayesian sequencing of the ^{14}C data. From the entire ^{14}C data set presently available for the Aegina Kolonna Bronze Age period some few dates were not incorporated into the sequence due to either sample quality reasons, e.g. only humic acids could be dated or due to a poor agreement index (<20%).

Three obviously too old ^{14}C ages of humic acids from the charcoals (VERA-3861HS, VERA-3863HS and VERA-3864HS) from the earliest stages of the EBA III (ceramic phase D), which completely dissolved during the ABA treatment, were not incorporated into the sequence, as these ages may be affected by a re-use or an "old wood" effect or a contamination with "old" humic acids. These dates are in agreement with a ^{14}C date of a sample (HV-5842) from the same layer determined earlier with the conventional method in Hanover but are inconsistent with the ^{14}C date of a sample (HV-5843) from the underlying horizon (ceramic phase C, end of the EBA II period) determined by the same lab. Therefore we do not consider this part of the stratigraphy in the Aegina Kolonna sequence at the moment.

The ^{14}C date of a lion's bone (VERA-4581) which was probably affected by a contamination with a cast material, and a ^{14}C date determined for humic acids from a seeds sample (VERA-4039HS) which completely dissolved in the alkaline step of the pre-treatment were also not included into the sequence. Further, three ^{14}C dates (VERA-4277, VERA-4037 and VERA-4033) which yielded a very poor agreement index (<20%) in a first run were excluded

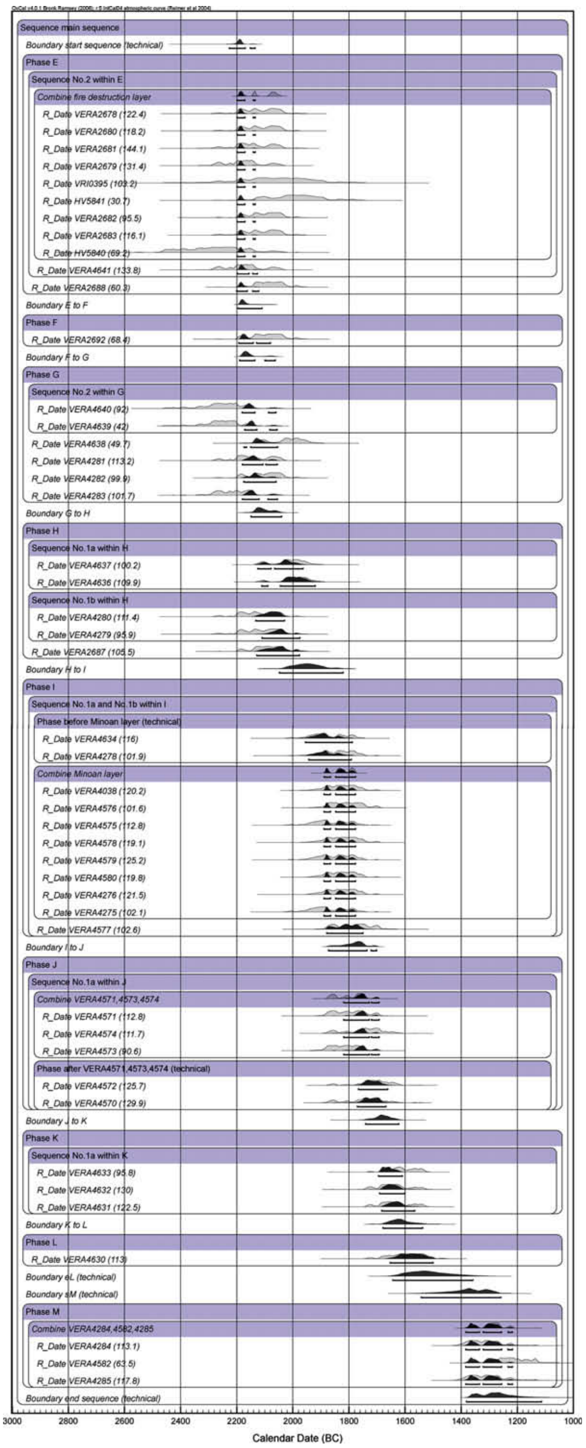

Fig. 3. OxCal plot of the Bayesian sequence of the ^{14}C data from Aegina showing the ceramic phases (E to M) and the transitions (boundaries) between them. Note that there is a hiatus between phase L and M. The probability distribution for the individual calendar ages resulting from the Bayesian model are displayed in dark grey, the results of single sample calibrations are indicated in light grey. Concerning the stratigraphy three types of information are used in the model: (a) grouping into ceramic phases, (b) local continuous sample sequences (1a, 1b and 2) and (c) well defined layers or contexts representing a short time span, e.g. 'fire destruction layer', 'Minoan layer'. In the latter case the analysed samples were treated as coeval (technical remark: we used the 'Combine' command of OxCal in order to show the consistency of all single sample calibrations in the plot. This result differs only marginally from the values calculated with the alternative 'R_Combine' command, because by using 'Combine' the individual sample calibrations are treated as independent, ignoring the shared use of the calibration data and their uncertainties. R_combine would allow to show only a single distribution for combined samples).

from the present sequence as well. Interestingly these three outliers were small single seeds, which may have been mobile in the sediment.

The ^{14}C data of the five low-collagen bones were not excluded from the sequence. ^{14}C data of bone samples with such a relatively low preservation state should be treated with caution (see e.g. van Klinken [7]), but the agreement indices of all but one of these bone data were above 60% and show the compatibility of these dates with the entire data set. A lower agreement index of 42% was only determined for sample VERA-4639 which is assigned to the ceramic phase G at the beginning of the Middle Bronze Age. Removing this sample and samples VERA-2687 and VERA-4579 from the sequence would not change the presented picture of the chronology of cultural periods from the EH/MH transition to the LH period. The only significant effect would be a $\sim$50 yr extension to younger ages of the time range for the ceramic phase E/F transition within the EH III period caused by the removal of sample VERA-4639.

Presently the sequence comprises 46 ^{14}C dates, which are distributed over almost the entire time span covered by the excavation. An overall agreement index of 100.2% was calculated for the sequence. This value indicates the consistency of the model with the input data (for details of the agreement indices see e.g. Rhodes et al. [13]).

Compared to the un-modelled data our ^{14}C sequence of Aegina Kolonna, which should presently be treated as preliminary (some refinements are planned) allows a more precise estimate for the transition dates between the individual phases. A time frame within which the transition occurred with a certain probability (boundary time range) can be derived from the Bayesian model. The thus determined time ranges for the individual cultural transitions detected in the Aeginetan profiles throughout the Bronze Age period are given in Table 3 together with archaeological information as cultural (Bronze Age) period, settlement and ceramic phases and first appearances of ceramic styles. These transitions exhibit a framework for the absolute chronology of the Early to the Late Bronze Age of Mainland Greece and the Islands.

A relative sharp time interval for the important transition from EH to MH period can be deduced from the Kolonna sequence. Date ranges for the EH/MH transition of 2191 BC to 2064 BC (2σ) and the MH/LH transition of 1742 BC to 1623BC (2σ) indicate that the MH period may have lasted a bit longer, respectively began a bit earlier than suggested initially [1]. Our results seem to be in agreement with the historical chronology, which suggests a start of the Middle Minoan IA period (equivalent to MH I on the Greek Mainland and the Islands) in Crete in the First Intermediate period in Egypt within 2160 BC – 2025 BC [4]. A calibrated ^{14}C age of 2280 BC to 2130 BC (2σ) determined by Manning [14] for a short lived sample from the coeval early Middle Cycladic period also supports our finding.

A further result derived from the sequence is a – at the moment very tentative – time frame for the Santorini volcanic eruption, which occurred during the time period of ceramic phase K. Time spans of 1742 BC to 1623 BC (2σ) within which the transition from ceramic phase J to phase K (transition from MH III to LH I, see above) occurred and 1679 BC to 1538 BC (2σ) for the transition from ceramic phase K to L (LH I to LH II) were determined. However, it must be noted that the latter boundary is weakly defined due to the fact that only one ^{14}C date from an herbivore bone with poor collagen preservation is available from phase L at the moment. Clearly more ^{14}C data from samples near the K/L boundary are needed to verify this value. But although very preliminary at the present stage of our investigation, these results seem to be in agreement with the science based date of the Thera VDL (Volcanic Destruction Layer) [15,16]. Regarding the latter the ongoing

Table 3
Chronological chart of Aegina Kolonna.

Cultural period, conventional (high) (a) and historical chronology (b)	Settlement Phase	Ceramic Phase	Research Areas 1 2 3 4	Imports First Appearance	Boundary between Ceramic Phases	modeled calibrated date 68.2% probability (d)	modeled calibrated date 95.4% probability (d)
Neol to EH I	I	Phase A (c)					
EH II a: EBA II Late: 2450/2350 to 2200/2150 BC	II	Phase B					
	III	Phase C					
	III (Rebuild.)	Phase C					
EH III a: EBA III: 2200/2150 to 2050/2000 BC b: EBA III/MBA transition: 2160 to 2025 BC	IV	Phase D		Peloponnese			
					beginning of E	earlier than 2181 BC (e)	earlier than 2136 BC (e)
	V (Destr.)	Phase E					
	V (Reconstr.)	Phase E		Central Greece			
					boundary E / F	2191 to 2169 BC	2196 to 2111 BC
	VI	Phase F		Cycladic (schist fabric) Local Cycladic Imitations			
MH I a: MBA I: 2050/2000 to 1950/1900 BC b: MBA I: 2160/2025 to before 1800 BC	VI	Phase G			boundary F / G	2183 to 2154 BC	2191 to 2064 BC
	VII	Phase G		Lustrous Decorated			
					boundary G / H	2139 to 2061 BC	2150 to 2041 BC
	VIII	Phase H		Minoan, Cycladic (Melos/Thera)			
	VIIIA	Phase H					
MH II a: MBA II: 1950/1900 to 1750/1720 BC b: MBA II: before 1800 to 1700 BC					boundary H / I	2007 to 1904 BC	2049 to 1822 BC
	IX	Phase I		Local Minoan Imitations			
MH III a: MBA III: 1750/1720 to 1680 BC b: MBA III: 1700 to 1600/1580 BC					boundary I / J	1811 to 1745 BC	1873 to 1702 BC
	X	Phase J					
LH I a: LBA I: 1680 to 1600/1580 BC b: LBA I: 1600/1580 to 1510/1485 BC					boundary J / K	1707 to 1648 BC	1742 to 1623 BC
	X	Phase K		SE-Aegean			
LH II a: LBA II:1600/1580 to 1445/1415 BC b: LBA II:1510/1485 to 1400/1390 BC					boundary K / L	1661 to 1591 BC	1679 to 1538 BC
		Phase L					
					end of L	later than 1610 BC (e)	later than 1644 BC (e)
	Hiatus						
LH IIIA a: LBA IIIA: 1445/1415 to 1340/1330 BC b: LBA IIIA: 1400/1390 to 1340/1330 BC					beginning of M	earlier than 1285 BC (e)	earlier than 1259 BC (e)
		Phase M		Cypriote			
					end of M	later than 1367 BC (e)	later than 1382 BC (e)

Research Areas
1) Fortification Wall
2) "Inner Settlement" (Innenstadt)
3) South Slope, Q-trenches (Südhügel)
4) Well Deposit

—— vertical stratigraphic sequence
····· existing deposits, but not in vertical stratigraphic sequence

Notes:
(a) long absolute chronology for the the Aegean Bronze Age based on the few presently published ^{14}C dates [1,2,19];
(b) historical chronology based on the Egyptian Chronology and its relations to the Aegean (according to Refs. [4,20–22]);
(c) with subphases (A1, A2, etc.);
(d) time range for the respective confidence level (1σ and 2σ);
(e) no time range is given for boundaries at the beginning or the end of the sequence or hiatus.

discussion about the discrepancy between the date derived from the synchronisation with the Egyptian historical chronology and the science based date is worth to note [17].

4. Conclusion

The ^{14}C sequence from Aegina is one of the longest sequences existing so far for the Aegean Bronze Age, and therefore of major importance for the absolute Bronze Age chronology in this region. We report here preliminary results of this sequence which allow us – at the present state of our investigation – a fairly precise estimate for the EH/MH and MH/LH transitions. Less precise and secure appears the end of the sequence, i.e. the LH I–LH II part. In these time periods definitely more data are needed to verify the present appearance of a time frame for the Thera eruption.

Acknowledgements

This work was supported by the Special Research Program (SFB) SCIEM2000 of the Austrian Academy of Sciences and the Austrian Science Fund. SCIEM2000 is under Patronage of the UNESCO. The excavations at Aegina Kolonna are supported by the Salzburg University and the Institute of Aegean Prehistory (INSTAP). We thank the Greek Antiquities Service for the permission to undertake the ^{14}C analysis. We thank Michael Grabner (University of Natural Resources and Applied Life Sciences, Vienna) for inspecting the charcoal pieces. We wish to thank Stefan Lehr for his help in the sample preparation and Kerstin Rumpelmayr for her assistance in the EA-IRMS measurements.

References

[1] J.B. Rutter, The Prepalatial Bronze Age of the Southern and Central Greek Mainland, in: T. Cullen (Hrsg.), Aegean Prehistory, A Review, American Journal of Archaeology Supplement 1 (2001) 95–155 (Boston 2001).
[2] W. Gauß, R. Smetana, Early and Middle Bronze Age Stratigraphy and Pottery from Aegina Kolonna, in: M. Bietak, E. Czerny (Hrsg.), The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millennium B.C. III, Proceedings of the SCIEM 2000 – 2nd EuroConferenceVienna, 28th of May–1st June 2003,Vienna 2007, pp. 451–472.
[3] W. Gauß, R. Smetana, Aegina Kolonna, The stratigraphic sequence of the SCIEM 2000 project, in: F. Felten,W. Gauß, R. Smetana (Hrsg.), Middle Helladic

Potttery and Synchronisms, Proceedings of the International Workshop held at Salzburg, October 31st–November 2nd 2004, Vienna 2007, pp. 57–80.
[4] P. Warren, V. Hankey, Aegean Bronze Age Chronology, Bristol 1989.
[5] E.M. Wild, Chr. Neugebauer-Maresch, Th. Einwögerer, P. Stadler, P. Steier, F. Brock, ^{14}C-dating of the Upper Paleolithic Site at Krems-Hundssteig in Lower Austria, Radiocarbon 50 (1) (2008).
[6] R. Longin, New method of collagen extraction for radiocarbon dating, Nature 230 (1971) 241–242.
[7] G.J. Van Klinken, Bone quality indicators for palaeodietary and radiocarbon measurements, J. Archaeological Sci. 26 (1999) 687–695.
[8] E. Wild, R. Golser, P. Hille, W. Kutschera, A. Priller, S. Puchegger, W. Rom, P. Steier, W. Vycudilik, First ^{14}C results from archaeological and forensic studies at the Vienna Environmental Research Accelerator, Radiocarbon 40/1 (1998) 273–281.
[9] P. Steier, F. Dellinger, W. Kutschera, W. Rom, EM. Wild, Pushing the precision of ^{14}C measurements with AMS, Radiocarbon 46/1 (2004) 5–16.
[10] C. Bronk Ramsey, Development of the radiocarbon calibration program OxCal, Radiocarbon 43/2A (2001) 355–363.
[11] C. Bronk Ramsey, Radiocarbon calibration and analysis of stratigraphy: the OxCal program, Radiocarbon 37/2 (1995) 425–430.
[12] H.P. Schwarcz, M.J. Schoeninger, Stable isotope analyses in human nutritional ecology, Yearbook Phys. Anthropology 34 (1991) 283–321.
[13] E.J. Rhodes, C. Bronk Ramsey, Z. Outram, C. Batt, L. Willis, S. Dockrill, J. Bond, Bayesian methods applied to the interpretation of multiple OSL dates: high precision sediment ages from Old Scatness Broch excavations, Shetland Isles, Quater. Sci. Rev. 22 (2003) 1231–1244.
[14] S.W. Manning, Some initial wobbly steps towards a late neolithic to early Bronze III radiocarbon chronology for the cyclades, in: N. Brodie, J. Doole, G. Gavalas, C. Renfrew (Hrsg.), Horizon. A Colloquim on the Prehistory of the Cyclades, 25–28 March 2004, McDonald Institute of Archaeological Research, Cambridge, 2008, pp. 55–59.
[15] S.W. Manning, C. Bronk Ramsey, W. Kutschera, Th. Higham, B. Kromer, P. Steier, E.M. Wild, Chronology for the Aegean Late Bronze Age 1700-1400 B.C. Science 28 April 2006 312(5773) (2006) 565–569. doi: 10.1126/science.1125682.
[16] W.L. Friedrich, B. Kromer, M. Friedrich, J. Heinemeier, T. Pfeiffer, S. Talamo, Santorini Eruption Radiocarbon dated to 1627-1600 B.C. Science 312 (2006) 548. doi: 10.1126/science.1125087 (in Brevia).
[17] M. Balter, New Carbon Dates Support Revised History of Ancient Mediterranean Science 312 (2006) 508.
[18] H. Walter, F. Felten, F. Die vorgeschichtliche Stadt, Alt-Ägina III 1 Mainz, 1981.
[19] S.W. Manning, The Absolute Chronology of the Aegean Early Bronze Age, Archaeology, Radiocarbon and History, Monographs in Mediterranean Archaeology 1, Sheffield, 1995.
[20] P. Warren, The date of the Thera eruption in relation to Aegean-Egyptian Interconnections and the Egyptian Historical Chronology, in: E. Czerny et al. (Hrsg.), Timelines. Studies in Honour of Manfred Bietak, OLA 149.2, Leuven 2006, pp. 305–321.
[21] P.M. Warren, A new pumice analysis from Knossos and the end of Late Minoan IA, in: M. Bietak, E. Czerny (Hrsg.), The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millenium B.C. III, Proceedings of the SCIEM 2000 – 2nd EuroConference, Vienna 28th of May to 1st of June 2003, Vienna, 2007, pp. 495–499.
[22] M. Bietak, F. Höfelmayer, Introduction: High and low chronology, in: M. Bietak, E. Czerny (Hrsg.), The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millenium B.C. III. Proceedings of the SCIEM 2000 – 2nd EuroConference, Vienna, 28th of May to 1st of June 2003, Vienna, 2007, pp. 13–23.