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CHRONOLOGY OF THE DANISH BRONZE AGE BASED ON ^{14}C DATING OF CREMATED BONE REMAINS

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ABSTRACT. The relative Bronze Age chronology for Scandinavia was established as early as 1885. It is traditionally divided into 6 periods (I–VI). Earlier attempts to make an absolute Bronze Age chronology for southern Scandinavia were derived from burials and settlements and were mainly based on radiocarbon-dated charcoal or carbonized cereals, often with undefined archaeological periods. Here, we present high-precision ^{14}C dating on burials with well-defined associated archaeological periods in order to improve the absolute chronology of the Danish Bronze Age. Our results are in broad agreement with the traditional absolute chronology of the Danish Bronze Age. However, our results do indicate that the onset of period III likely occurred earlier than previously thought.

INTRODUCTION

Radiocarbon dating of collagen from well-preserved human bone has routinely been carried out for decades, but cremated bone samples were always avoided because cremation destroys collagen. However, successful ^{14}C dating of cremated bones based on their content of recrystallized bioapatite was reported by Lanting et al. (2001). As the common burial practice for a number of prehistoric periods was cremation, this method meant a breakthrough for the archaeological community, opening such cultural periods to ^{14}C dating of human bones as demonstrated by the appearance of several studies using cremated bones (e.g. Lanting and Brindlye 1998; Lanting et al. 2001; De Mulder et al. 2007, 2009). This is also the case for the Danish Late Bronze Age. Without ^{14}C dating, the establishment of an absolute chronology of this epoch is difficult and the Danish Bronze Age will be the focus of this study.

The relative Bronze Age chronology for Scandinavia was established in 1885 and is divided into 6 periods (I–VI). This scheme is still largely valid (Montelius 1885, 1986; Randsborg 1996; Vandkilde et al. 1996). Traditionally, the absolute Bronze Age chronology in Scandinavia is related by cross-dates to central Europe, which again depended on a synchronization with the Mediterranean (Vandkilde et al. 1996:183), but in recent decades a large number of radiocarbon dates from especially the Early Bronze Age have become available. Weaknesses are evident in earlier attempts to make an absolute Bronze Age chronology for southern Scandinavia derived from burials and settlements, using mainly ^{14}C-dated charcoal or carbonized cereals (Vandkilde et al. 1996). Only a few dates from period III were represented and few burial dates from the Late Bronze Age seemed to exist. Since then, a large number of dendrochronological dates of oak coffins from a minor segment of the Early Bronze Age have appeared (Christensen 2006), but only a few ^{14}C dates of burials.

This study was inspired by a wish to establish a firm, improved chronology for the Bronze Age with a focus on the Danish area. Because of the uncertainties involved in dating settlements based on charcoal and carbonized cereals, we have chosen to use only burials clearly associated with well-defined archaeological periods. These burials contain artifacts like swords, ornaments, pins, razors, pottery, etc. with a recognizable style, i.e. a distinctive shape or decoration that was used within just one of the periods II–VI. An example is the flange hilted sword (Sprockhoff´s type IIa), an important artifact in burials from period III (Thrane 1964). Our samples include ^{14}C dates of cremated bones

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as well as dendrochronological dates of oak coffins. Here, we present new high-precision ^{14}C results on cremated bones from the Danish Bronze Age (periods II–VI) with the purpose of testing and improving the existing chronology of the Danish Bronze Age using Bayesian models to interpret the available dates.

METHODS

Prior to accelerator mass spectrometry (AMS) dating, cremated bone samples are pretreated as follows (see Olsen et al. 2008). Two grams of unprocessed sample are soaked in a 1.5% sodium hypochlorite solution to dissolve remaining organic material (48 hr, 20 °C). The sample is then washed and submerged in 1M acetic acid to remove postdepositional carbonates as well as less crystalline, soluble fractions of bioapatite (24 hr, 20 °C). Next, the sample is washed and dried (12 hr, 80 °C), generally with a bioapatite yield of ~96%. The pretreated sample is crushed and 1.5 g is treated with 100% dehydrated phosphoric acid (8 hr, 25 °C) to liberate CO_2, from which sulfur impurities are removed using Sulfix® (Baker Hughes, Inc., USA) prior to conversion to graphite for AMS targets (Lanting et al. 2001).

All samples were visually inspected for surface and interior color and burn cracks. Infrared (IR) spectroscopy was performed on powdered pretreated sample material, i.e. bioapatite: The sample material was mixed with KBr and hydraulically pressed into pellets prior to measurement of IR spectra with a PerkinElmer FTIR spectrometer (PARAGON 1000). The spectrum of KBr was automatically subtracted by an online computer. IR spectra on the bioapatite bone fraction provide information on the crystallinity index (CI) and carbon to phosphorus ratio (C/P) (Garvie-Lok et al. 2004; Olsen et al. 2008).

Charcoal and pitch samples for ^{14}C dating were pretreated by the acid-alkali-acid (AAA) method prior to conversion to CO_2 by burning in sealed evacuated ampoules with CuO. The AAA method is as follows: 1M HCl (80 °C, 24 hr) followed by 1M NaOH (80 °C one to several days) and finally 1M HCl (Thomsen 1990).

Part of the resulting CO_2 gas was used for $\delta^{13}C$ analysis on a GV Instruments Isoprime stable isotope mass spectrometer to a precision of 0.15‰, while the rest was converted to graphite for AMS ^{14}C measurements via reduction with H_2 using cobalt as a catalyst (Vogel et al. 1984). All AMS ^{14}C measurements were carried out using the EN tandem accelerator at Aarhus University (Denmark). The dating results are reported as conventional ^{14}C dates in ^{14}C yr BP based on the measured $^{14}C/^{13}C$ ratio corrected for the natural isotopic fractionation by normalizing the result to the standard $\delta^{13}C$ value of –25‰ PDB (Andersen et al. 1989).

LOCALITIES AND SAMPLES

In order to test and improve the Danish Bronze Age chronology, this study includes new ^{14}C dates on cremated human bones as well as previously published dendrochronologically dated oak coffins (Tables 1 and 2). The geographical distribution of the chosen localities is shown in Figure 1.

A total of 31 cremated human bone samples have been dated (Table 1). Of these, 7 samples have previously been measured and compared to context dated material associated with the samples (Olsen et al. 2008). One sample was tested against a dendrochronologically dated oak coffin (AAR-8789, -13976, J Olsen, unpublished data; Olsen et al. 2008), and 6 against pitch sealing material from the cremation urns (AAR-8110, -8111, -8112, -9576, -9571, -9573). Of the total of 37 samples presented here, 28 dated samples were submitted blind (Table 1), i.e. no prior knowledge of inter-sample dependencies was available to the AMS laboratory during analysis.

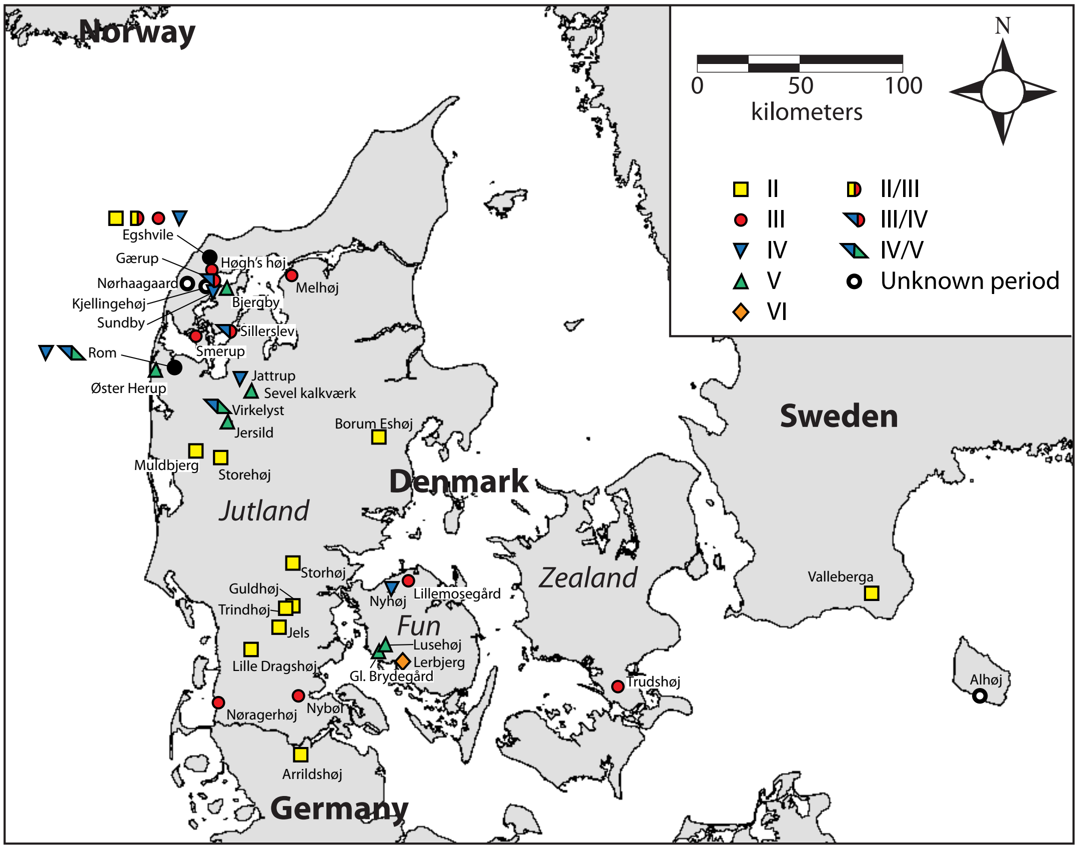


Figure 1 Map showing the geographical distribution of localities of samples used in this study

As revealed by χ^2 tests, there is a good agreement between the dated cremated human bone samples and their associated pitch samples (Table 1). All except the pair AAR-9571 and AAR-9568 yield acceptable χ^2 statistics. The age difference between the cremated bone sample AAR-9571 and its associated pitch sample AAR-9568 amounts to 8 standard deviations and is excluded in the statistical analysis. Unlike the bone date, the pitch date is incompatible with the archaeological date, pointing to an erroneous identification of the pitch sample. For the remaining samples, the weighted average age difference between cremated bone samples and pitch is +26 ± 25 ^{14}C yr (χ^2_{meas}: 1.7 ≤ 9.5), i.e. the bones are insignificantly older than the pitch. This observation fits well with the concept of a limited "old wood" CO_2 effect as discussed below.

Stratigraphic information from the excavations showed that a few samples represent the same event, while for other samples only the chronological order is known. The samples from the locality Rom D1 and D2 (Table 1) were found close to each other on a flat stone and were surrounded by a shared packing of round stones. From an archaeological point of view, they are assumed to be contemporaneous. The ^{14}C ages from Rom D1 and D2 yield a combined age of 2821 ± 22 ^{14}C yr BP (Table 1). Stratigraphic evidence from the excavation of the Egshvile location shows that AAR-8826 is older than AAR-8827, which in turn is older than AAR-8828, and AAR-8828 is older than AAR-8788 (Table 1). Also, in the Lerbjerg location, AAR-9568, -9571 are older than AAR-9569, -9573 (Table 1). A thorough presentation of the localities and single finds as well as archaeological dates is beyond the scope of the present paper and will be presented elsewhere.

Table 1 Human cremated bone and pitch samples measured in this and previous study (Olsen et al. 2008). C/P is the carbon to phosphate rate. CI the crystallinity index. Lab numbers with BP indicates blind test. Periods refer to the traditional Bronze Age Chronology. n/a = not available.

Lab nr (Blind test ID)	Location	Material	Prep. yield	C wt%	C/P	CI	$\delta^{13}C$ ‰ VPDB	^{14}C age BP	Color: Surface	Color: Interior	Visible burn cracks
Period II (1500–1300 BC)											
AAR-8789 (PB7)	Egtved	Bone	98.6%	0.09	0.09	5.3	–23.05	3128 ± 28	Yellow	White	No
AAR-13976	Egtved	Bone	96.9%	0.12	n/a	n/a	–23.69	3126 ± 29	Yellow	White	No
Combined (AAR-8789, -13976)								*3127 ± 20 (0.0 ≤ 3.8)*[a]			
AAR-8826 (PB15)	Egshvile N6	Bone	97.3%	0.16	0.05	5.8	–27.17	3052 ± 46	White	White	Yes
Transition period II–III											
AAR-8827 (PB16)	Egshvile N5	Bone	87.8%	0.23	0.12	4.9	–22.89	3049 ± 27	White	White	Yes
Period III (1300–1100 BC)											
AAR-13975	Lillemosegård	Bone	97.2%	0.12	n/a	n/a	–23.45	3045 ± 32	White	White	Yes
AAR-8825 (PB14)	Skallerup	Bone	96.4%	0.18	0.14	5.0	–16.60	3071 ± 35	Gray/White	Gray/White	Yes
AAR-8828 (PB17)	Egshvile N1	Bone	96.7%	0.31	n/a	4.2	–22.74	3097 ± 27	White	White	Yes
AAR-9517 (PB21)	Høgh`s høj	Bone	97.0%	0.08	n/a	3.9	–22.70	3092 ± 42	Gray/White	Gray/White	Yes
AAR-9523 (PB27)	Smerup	Bone	98.0%	0.09	0.10	6.0	–22.80	3059 ± 38	Gray/White	White	Yes
Transition period III/IV											
AAR-9516 (PB 20)	Gærup, Stagstrup	Bone	95.5%	0.06	0.17	4.4	–23.30	2938 ± 41	Gray/White	Gray/White	Yes
AAR-9519 (PB 23)	Sillerslev	Bone	97.0%	0.05	0.24	4.3	–25.50	2910 ± 44	Gray/White	Gray/White	No
Period IV (1100–950/920 BC)											
AAR-8788 (PB6)	Egshvile N7	Bone	97.9%	0.32	0.15	4.4	–24.54	2882 ± 24	White	White	Yes
AAR-9514 (PB18)	Sundby	Bone	96.0%	0.05	0.11	5.2	–24.10	2805 ± 43	White	White	Yes
AAR-9515 (PB19)	Jattrup	Bone	98.7%	0.07	0.17	4.6	–24.50	2837 ± 39	Gray/White	Gray/White	Yes
AAR-9524 (PB28)	Rom D3	Bone	97.8%	0.09	0.17	4.9	–23.80	2886 ± 34	Gray/White	White	Yes
AAR-9574 (PB36)	Nyhøj, Kattebjerg	Bone	94.6%	0.16	0.08	4.4	–23.40	2867 ± 33	White	White	Yes
Transition period IV/V											
AAR-4681	Rom D2	Pitch	44.8%	80.5	n/a	n/a	–28.50	2790 ± 45			
AAR-8110	Rom D2	Bone	92.3%	0.10	0.09	6.2	–26.10	2882 ± 47	White	White	Yes
Combined (AAR-4681, -8110)								*2834 ± 33 (2.0 ≤ 3.8)*			
AAR-4682	Rom D1	Pitch	46.4%	80.1	n/a	n/a	–29.50	2815 ± 40			
AAR-8111	Rom D1	Bone	94.6%	0.20	0.15	5.0	–23.50	2805 ± 45	White	White	Yes
Combined (AAR-4682, -8111)								*2811 ± 30 (0.0 ≤ 3.8)*			
Combined (AAR-4681, -8110, -4682, -8111)								*2821 ± 22 (2.3 ≤ 7.8)*			

Table 1 Human cremated bone and pitch samples measured in this and previous study (Olsen et al. 2008). C/P is the carbon to phosphate rate. CI the crystallinity index. Lab numbers with BP indicates blind test. Periods refer to the traditional Bronze Age Chronology. n/a = not available. *(Continued)*

Lab nr (Blind test ID)	Location	Material	Prep. yield	C wt%	C/P	CI	$\delta^{13}C$ ‰ VPDB	^{14}C age BP	Color: Surface	Color: Interior	Visible burn cracks
AAR-6097	Virkelyst	Pitch	63.8%	48.8	n/a	n/a	–28.40	2815 ± 40			
AAR-8112	Virkelyst	Bone	96.2%	0.10	0.10	6.2	–24.60	2829 ± 39	White	White	Yes
Combined (AAR-6097, -8112)								*2822 ± 28 (0.1 ≤ 3.8)*			
Period V (950/920–800 BC)											
AAR-8786(PB4)	Ø. Herup	Bone	95.3%	0.12	0.04	5.9	–23.26	2722 ± 25	Gray/White	White	Yes
AAR-8787 (PB5)	Sevel Kalkværk	Bone	98.0%	0.23	0.17	5.3	–25.62	2650 ± 25	Gray/White	White	Yes
AAR-9518 (PB22)	Bjergby	Bone	97.9%	0.01	0.18	4.7	–22.50	2583 ± 34	Gray/White	White	Yes
AAR-9520 (PB24)	Jersild	Bone	98.2%	0.09	0.12	5.6	–22.20	2683 ± 36	Yellow	White	Yes
AAR-9522 (PB26)	Tilsted	Bone	95.9%	0.07	0.09	6.1	–20.60	2206 ± 37[b]	White	White	Yes
AAR-9570 (PB32)	Gl. Brydegård	Pitch	64.8%	73.6	n/a	n/a	–27.20	2706 ± 35	White	White	Yes
AAR-9576 (PB38)	Gl. Brydegård	Bone	98.7%	0.21	0.04	6.2	–21.60	2714 ± 34	White	White	Yes
Combined (AAR-9570, -9576)								*2710 ± 24 (0.0 ≤ 3.8)*			
AAR-9575 (PB37)	Lusehøj GX	Bone	98.8%	0.21	0.09	5.5	–23.50	2611 ± 33	Gray/White	White	Yes
Period VI (800–530/520 BC)											
AAR-9568 (PB30)[c]	Lerbjerg I	Pitch	52.1%	76.5	n/a	n/a	–29.90	2851 ± 24[b]			
AAR-9571 (PB33)	Lerbjerg I	Bone	96.0%	0.08	0.06	6.5	–22.90	2486 ± 25	White	White	Yes
Combined (AAR-9568, -9571)								*2676 ± 17 (110 ≤ 3.8)*[b]			
AAR-9569 (PB31)	Lerbjerg II	Pitch	50.3%	74.9	n/a	n/a	–29.50	2459 ± 41			
AAR-9573 (PB35)	Lerbjerg II	Bone	96.8%	0.17	0.07	5.6	–24.60	2502 ± 39	White	White	Yes
Combined (AAR-9569, -9573)								*2482 ± 28 (0.6 ≤ 3.8)*			
Unknown archaeological date											
AAR-13974	Alhøj	Bone	92.3%	0.18	n/a	n/a	–23.65	3008 ± 28	White	White	Yes
AAR-9521 (PB25)	Nørhaagaard	Bone	97.2%	0.22	0.02	6.4	–23.00	2697 ± 42	White	White	Yes
AAR-9525 (PB29)	Kjellingehøj IV	Bone	95.3%	0.04	0.18	4.7	–21.70	2823 ± 41	White	White	Yes

[a]The context of sample AAR-8789 and AAR-13976 is dendrochronologically dated to 1370 BC (Christensen 2006) and the ^{14}C date is therefore not used in the model.

[b]Outliers not used.

[c]For AAR-9568, see discussion in Olsen et al. (2008).

Table 2 Supplementary material. Both ^{14}C and dendrochronological dates are provided. Where a dendrochronological date is available, this age has been used in the model.

Lab nr	Location	Material	Description	Arch. date	^{14}C age BP	Dendrochronological age	Reference
Ke 2878B	Lille Dragshøj (Sb. 210104-52), Højrup sogn, Hviding herred, Tønder amt	Wood (*Quercus* sp.)	From oak coffin	II	3050 ± 50	1375–1370 BC (3323 ± 3 BP)	Aner and Kersten 1981; Christensen 2006:195ff, nr 3
Ke 3820C	Guldhøj (Sb. 190109-05), Vamdrup sogn, Andst herred, Ribe amt	Wood (*Quercus* sp.)	From oak coffin, grave C	II	3130 ± 80	1389 BC (3339 ± 0.5 BP)	Aner and Kersten 1986; Christensen 2006:197ff, nr 5
Ke 3817B	Trindhøj (Sb. 190109-26), Vamdrup sogn, Anst herred, Ribe amt	Wood (*Quercus* sp.)	From oak coffin B	II	3060 ± 70	1340–1308 BC (3274 ± 16 BP)	Aner and Kersten 1986; Christensen 2006:227ff, nr 21
Ke 3817A	Trindhøj (Sb. 190109-26), Vamdrup sogn, Andst herred, Ribe amt	Wood (*Quercus* sp.)	From oak coffin A	II	3080 ± 80	1364–1337 BC (3301 ± 14 BP)	Aner and Kersten 1986; Christensen 2006:227ff, nr 21
Ke 4620	Storehøj (Sb. 180113-96A), Vorgod sogn, Bølling herred, Ringkøbing amt	Wood (*Quercus* sp.)	From oak coffin	II	3190 ± 85	1373 BC (3323 ± 0.5 BP)	Aner and Kersten 1986; Christensen 2006:219ff, nr 17
NMB 1404	Borum Eshøj (Sb. 150101-12), Borum sogn, Framlev herred, Århus amt	Wood (*Quercus* sp.)	From oak coffin, grave B	II	2930 ± 65	1353–1326 BC (3290 ± 14 BP)	Jensen 1998:83ff; Christensen 2006:193ff, nr 2
Ke 2243	Kong Arrildshøj, Harrislee Kirchspiel, Kreis Schleswig-Flensburg	Wood (*Quercus* sp.)	From oak coffin	II		1361–1329 BC (3295 ± 16 BP)	Aner and Kersten 1978; Christensen 2006:190ff, nr 1
Ke 3820A	Guldhøj (Sb. 190109-05), Vamdrup sogn, Andst herred, Ribe amt	Wood (*Quercus* sp.)	From oak coffin, grave A	II		1389 BC (3339 ± 0.5 BP)	Aner and Kersten 1986; Christensen 2006:197ff, nr 5
Ke 3443	Jels (Sb. 200204-83), Jels sogn, Gram herred, Haderslev amt	Wood (*Quercus* sp.)	From oak coffin	II		1348 BC (3298 ± 0.5 BP)	Aner and Kersten 1984; Christensen 2006:202ff, nr 7
Ke 4740A	Muldbjerg (Sb. 180405-59), Hover sogn, Hind herred, Ringkøbing amt	Wood (*Quercus* sp.)	From oak coffin	II		1365 BC (3315 ± 0.5 BP)	Aner and Kersten 1995; Christensen 2006:207ff, nr 10
Lu-804	Mound, Valleberga 6[7] Valleberga s., Scania	Collagen (human)	Human bone from coffin	II	3170 ± 55		Håkansson 1974; Strömberg 1974
Lu-803	Mound, Valleberga 6[7] Valleberga s., Scania	Wood (*Quercus* sp.)	From oak coffin	II	3190 ± 55		Håkansson 1974; Strömberg 1974
Combined (Lu-804, Lu803)					*3180 ± 39 (0.1 ≤3.8)*		
Ke 2909	Nøragerhøj (Sb. 210202-39) Emmerlev sogn, Højer herred, Tønder amt	Wood (*Quercus* sp.)	From oak coffin	III	3030 ± 70	1301–1272 BC (3237 ± 15 BP)	Aner and Kersten 1981; Christensen 2006:212ff, nr 13
K-3874	Melhøj (Sb. 120705-15), Mjallerup, Løgsted sogn, Slet herred, Ålborg amt	Wool	From stone cist grave	III	2930 ± 80		Jørgensen et al. 1984:43
Ke 3022	Nybøl (Sb. 220202-64), Hjordkær sogn, Rise herred, Åbenrå amt	Wood (*Quercus* sp.)	From oak coffin	III		1277–1246 BC (3212 ± 16 BP)	Aner and Kersten 1981; Christensen 2006:211ff, nr 12
AAR-13138	Lusehøj (Sb. 080205-16) Flemløse sogn, Båg herred, Odense amt	Textile stinging nettle	From stone cist grave	V	2650 ± 60		^{14}C date made available by Ulla Mannering, U. of Copenhagen (Thrane 2004:79ff)

Supplementary Material

Of considerable importance for the Danish absolute chronology are a number of dendrochronological dates of oak coffins from the Early Bronze Age (Table 2). The 28 oak coffins all date within the interval 1391–1266 BC, i.e. period II and the beginning of period III, and 25 of the 28 dates within a period of <50 yr, from ~1391 to ~1344 BC (Christensen 2006). Apart from the dendrochronological dates, sporadic ^{14}C dates of graves are available, but practically all of them are finds without any archaeologically datable objects (Vandkilde et al. 1996). Here, supplementary samples are selected based on the criterion that the samples are archaeologically datable to a single period within periods II–VI or may be placed in the transition between 2 periods (Table 2).

CHRONOLOGICAL MODEL FOR THE DANISH BRONZE AGE

Based on the typology of grave goods, the Danish Bronze Age is subdivided into 6 periods (I–VI). Here, we concentrate on the periods II to VI and consensus ages of each period are presented in Tables 1 and 4. Cremated human bones samples deriving from graves with positive typological identifiers are archaeologically associated with one of the periods II–VI (Tables 1 and 2). However, some of the samples have typological identifiers associated with 2 periods and are therefore archaeologically associated with transition periods. Two samples (AAR-9521, AAR-9525) are from burials containing interesting, but rare, grave goods and urns. AAR-13974 is a burial without grave goods. These 3 burials are exceptions to the rule of a positive archaeological date to a particular period and therefore not included in the chronological model (Table 1). For reasons unknown (it is suggested that a mistake of some kind has taken place from excavation to store), the calibrated age of sample AAR-9522 ranges from 383 to 186 BC (i.e. in the Iron Age) and is therefore inconsistent with the archaeological date (period V). AAR-9522 is thus regarded as an outlier (Table 1).

To obtain a chronology of the Danish Bronze Age, a conceptual model for the Bronze Age periods II to VI is developed (Figure 2). It is presumed that periods may overlap in time with the condition that periods not directly adjacent to each other have no overlap (Figure 2). Thus, period II is older than period IV, which again is older than period VI and period III is older than period V (Figure 2). For the transitions, it is assumed that the transition II–III is older than the transition III–IV, which again is older than the transition IV–V (Figure 2). Thus, the chronological model is constructed as 3 sequences where each period or transition is given as phases. The first sequence consists of periods II, IV, and VI, the second of period III and V, and the third of transitions II–III, III–IV, and IV–V. The boundaries of each phase denote onset and termination of each period or transition phase. As an additional constraint on the model, the start and end of each period must be chronologically ordered (Figure 2). The stratigraphic evidence from the Egshvile and Lerbjerg locations provide further constrains on the chronological model and are thus included.

Table 3 Calibrated age intervals of unmodeled and modeled data. Samples are from Tables 1 and 2. The "type" column denotes whether a ^{14}C date (C14) or dendrochronological (D) date has been used in the model. The column "A" denotes the agreement index between the sample and the applied model. Generally, A values below 60% are considered as poor agreement. Periods refer to the traditional Bronze Age Chronology.

Lab nr/Sample ID	Type	Unmodeled conf. interval	Modeled conf. interval	A
Period II (1500–1300 BC)				
Combined (Lu-804, Lu-803)	C14	1525–1389 BC (95.4%)	1495–1373 BC (92.8%) 1338–1323 BC (2.6%)	80.1%
Ke 3820C	D	1389–1387 BC (95.4%)	1389–1387 BC (95.4%)	100.8%
Ke 3820A	D	1389–1387 BC (95.4%)	1389–1387 BC (95.4%)	100.6%
Ke 2878B	D	1378–1368 BC (95.4%)	1378–1367 BC (95.4%)	99.8%
Ke 4620	D	1373–1371 BC (95.4%)	1374–1372 BC (95.4%)	99.9%

Table 3 Calibrated age intervals of unmodeled and modeled data. Samples are from Tables 1 and 2. The "type" column denotes whether a ^{14}C date (C14) or dendrochronological (D) date has been used in the model. The column "A" denotes the agreement index between the sample and the applied model. Generally, A values below 60% are considered as poor agreement. Periods refer to the traditional Bronze Age Chronology. *(Continued)*

Lab nr/Sample ID	Type	Unmodeled conf. interval	Modeled conf. interval	A
Ke 4740A	D	1365–1363 BC (95.4%)	1366–1364 BC (95.4%)	99.9%
Ke 3817A	D	1377–1323 BC (95.4%)	1378–1335 BC (95.4%)	108.1%
Ke 3443	D	1348–1346 BC (95.4%)	1349–1347 BC (95.4%)	100.0%
Ke 2243	D	1376–1312 BC (95.4%)	1379–1332 BC (95.4%)	104.9%
NM B 1404	D	1366–1312 BC (95.4%)	1370–1331 BC (95.4%)	96.0%
Ke 3817B	D	1355–1291 BC (95.4%)	1367–1327 BC (95.4%)	54.3%
AAR-8826 (PB15)	C14	1425–1192 BC (94.5%) 1140–1132 BC (0.9%)	1422–1321 BC (95.4%)	110.4%
Transition period II–III				
AAR-8827 (PB16)	C14	1404–1258 BC (94.1%) 1227–1219 BC (1.3%)	1379–1282 BC (95.4%)	112.3%
Period III (1300–1100 BC)				
AAR-8828 (PB17)	C14	1430–1304 BC (95.4%)	1339–1263 BC (95.4%)	45.3%
AAR-9517 (PB 21)	C14	1447–1259 BC (95.4%)	1354–1258 BC (95.4%)	69.7%
AAR-8825 (PB14)	C14	1423–1259 BC (95.4%)	1354–1258 BC (95.4%)	80.2%
AAR-9523 (PB27)	C14	1419–1253 BC (91.4%) 1238–1213 BC (4.0%)	1358–1255 BC (95.4%)	95.7%
AAR-13975	C14	1408–1252 BC (89.9%) 1239–1212 BC (5.5%)	1357–1254 BC (95.4%)	106.2%
Ke 2909	D	1316–1258 BC (95.4%)	1304–1260 BC (95.4%)	105.7%
Ke 3022	D	1292–1230 BC (95.4%)	1300–1254 BC (95.4%)	83.6%
K-3874	C14	1378–1334 BC (4.4%) 1321–924 BC (91%)	1352–1220 BC (95.4%)	73.6%
Transition period III/IV				
AAR-9516 (PB 20)	C14	1290–1278 BC (1.2%) 1269–1010 BC (94.2%)	1249–1049 BC (95.4%)	112.6%
AAR-9519 (PB 23)	C14	1260–977 BC (95.4%)	1252–1230 BC (3.4%) 1219–1041 BC (92.0%)	106.5%
Period IV (1100–950/920 BC)				
AAR-8788 (PB6)	C14	1188–1179 BC (0.9%) 1155–1144 BC (1.1%) 1129–977 BC (93.3%)	1111–995 BC (95.4%)	109.9%
AAR-9524 (PB28)	C14	1206–1201 BC (0.6%) 1194–1139 BC (10.2%) 1133–972 BC (82.6%) 955–939 BC (2%)	1112–984 BC (95.4%)	115.1%
AAR-9574 (PB36)	C14	1187–1180 BC (0.7%) 1153–1145 BC (0.9%) 1129–924 BC (93.9%)	1108–975 BC (95.4%)	124.6%
AAR-9515 (PB 19)	C14	1120–903 BC (95.4%)	1108–962 BC (95.4%)	103.9%
AAR-9514 (PB 18)	C14	1109–1102 BC (0.6%) 1081–1063 BC (1.5%) 1055–836 BC (93.3%)	1093–947 BC (95.4%)	72.6%
Transition period IV/V				
Combined (AAR-6097, -8112)	C14	1050–903 BC (95.4%)	1016–915 BC (95.4%)	113.4%
Combined (AAR-4681, -8110, -4682, -8111)	C14	1040–910 BC (95.4%)	1012–919 BC (95.4%)	107.9%
Period V (950/920–800 BC)				
AAR-8786(PB4)	C14	911–814 BC (95.4%)	887–805 BC (95.4%)	86.4%
Combined (AAR-9570, -9570)	C14	904–810 BC (95.4%)	885–805 BC (95.4%)	97.7%

Table 3 Calibrated age intervals of unmodeled and modeled data. Samples are from Tables 1 and 2. The "type" column denotes whether a ^{14}C date (C14) or dendrochronological (D) date has been used in the model. The column "A" denotes the agreement index between the sample and the applied model. Generally, A values below 60% are considered as poor agreement. Periods refer to the traditional Bronze Age Chronology. *(Continued)*

Lab nr/Sample ID	Type	Unmodeled conf. interval	Modeled conf. interval	A
AAR-9520 (PB24)	C14	901–798 BC (95.4%)	881–795 BC (95.4%)	118.5%
AAR-13138	C14	973–955 BC (1%) 939–748 BC (89.7%) 686–665 BC (2.2%) 640–591 BC (2.5%)	879–777 BC (95.4%)	137.8%
AAR-8787 (PB5)	C14	889–878 BC (1.9%) 841–790 BC (93.5%)	834–792 BC (95.4%)	104.3%
AAR-9575 (PB37)	C14	834–760 BC (93.3%) 681–670 BC (2.1%)	830–775 BC (95.4%)	106.3%
AAR-9518 (PB22)	C14	815–747 BC (76.3%) 687–665 BC (10%) 641–590 BC (7.9%) 577–565 BC (1.2%)	822–769 BC (95.4%)	109.7%
Period VI (800–530/520 BC)				
AAR-9571 (PB33)	C14	770–509 BC (95.2%) 431–428 BC (0.2%)	760–536 BC (95.4%)	102.9%
Combined (AAR-9569, -9573)	C14	769–505 BC (92.2%) 460–449 BC (1%) 439–416 BC (2.2%)	770–559 BC (95.4%)	104.7%
Unknown samples				
AAR-13975	C14	1410–1214 BC (95.4%)		
AAR-9525 (PB29)	C14	1119–855 BC (95.4%)		
AAR-9521 (PB25)	C14	924–797 BC (95.4%)		

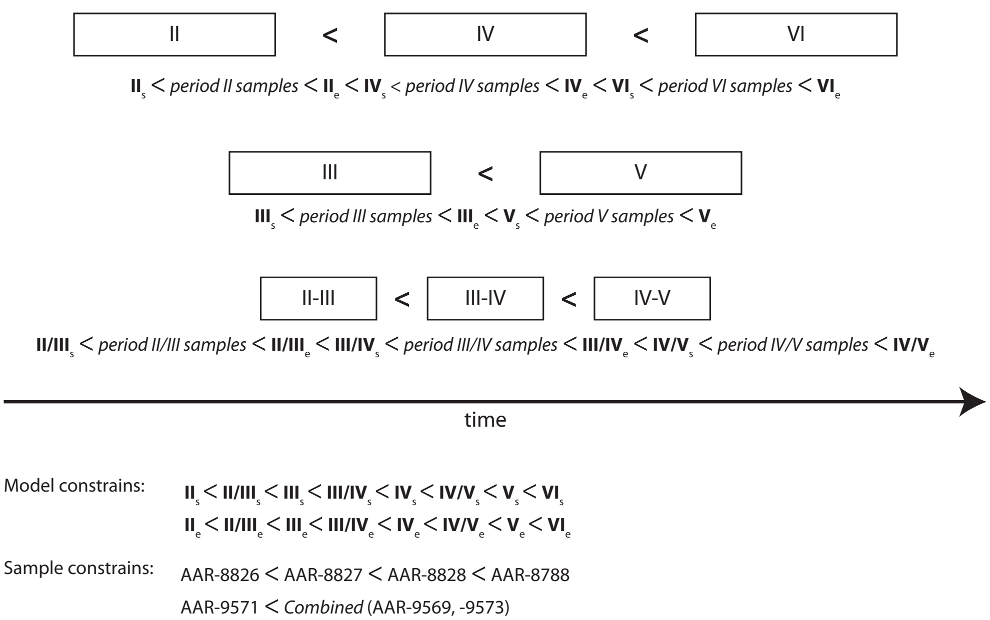


Figure 2 Conceptual schematic of the constructed chronological model for the Danish Bronze Age. Constraints from stratigraphical information are also shown. Subscripts *s* and *e* denote start and end, respectively.

Using the data from this study (Table 1) combined with the supplementary data (Table 2), the chronological model for the Danish Bronze Age is translated into a Bayesian statistical model using OxCal v 4.1 (Bronk Ramsey 2009) and the IntCal09 calibration curve data (Reimer et al. 2009). Running the model, it turned out that the 10 high-precision dendrochronological dates included in period II constrained period II to a very limited time interval and resulted in very low agreement index for the sample Combined (Lu-804, Lu-803). To avoid this problem, the dendrochronological dates of period II and III were included in the model as subphases in their respective periods as otherwise OxCal presupposes a more or less uniform distribution of samples across the main phase, which in turn puts too much weight on the very precise and narrowly distributed dendrochronological dates. In total, 39 ^{14}C and dendrochronological dates are used in the chronological model and the results are summarized in Tables 3 and 4 and Figure 3.

RESULTS AND DISCUSSION

The success of ^{14}C dating of burned or cremated bones depends on the exposed temperature during burning and the degree of recrystallization of the inorganic bone matrix (Van Strydonck et al. 2005, 2009; Olsen et al. 2008). The degree of recrystallization can be characterized by visual inspection, infrared spectrometry, and carbon stable isotope analysis. The carbon content and carbon to phosphorus ratio (C/P) on the bioapatite fraction of cremated bones can also be characterized (Olsen et al. 2008). The presented samples all show low C/P ratios and $\delta^{13}C$ values as well as high crystallinity index (CI) values, indicating that these bones are likely to have been exposed to high-temperature cremation (Table 1). Only sample AAR-8825 shows an outlying $\delta^{13}C$ value as high as –16.6‰ (Table 1). Furthermore, the CI and C wt% values of the period III samples AAR-8825, -8828, and -9517 may suggest that these samples have not been exposed to high-temperature cremation (Table 1). Hence, this opens the possibility of exchange reactions with soil carbonate and thereby the ^{14}C ages being offset. However, bicarbonate exchange reactions with fossil bones commonly result in ^{14}C ages too young (Tamers and Pearson 1965; Hassan et al. 1977; Hedges and Millard 1995; Surovell 2000), which, if true, pushes the start of period III further back in time. Recent results suggest that the carbon isotope composition of cremated bones probably reflects the CO_2 of the burning atmosphere (Hüls et al. 2010; van Strydonck et al. 2010). This indicates the possibility of cremated bone samples being affected in a similar fashion as charcoal samples by the "old wood" effect. Nevertheless, the good age consistency within all the period III ^{14}C dates speaks against possible ^{14}C contamination of these samples, and we believe these dates are reliable (Tables 1, 2, and Figure 4). As a final remark, we note that bioapatite derives from blood bicarbonate originating from the energy production in cells (Lee-Thorp et al. 1989; Sandford 1993; Wright and Schwarcz 1996; Munro et al. 2007). The bioapatite fraction thus reflects total energy intake, and therefore should not be as prone to possible reservoir effects caused by either a predominantly marine or freshwater diet as would be the case for bone collagen (e.g. Richards and Hedges 1999; Fischer et al. 2007; Olsen et al. 2010).

The outcome of the constructed Bayesian model is shown in Figure 3. The overall agreement of the model (A_{model}) is 90.7%. Posterior probability distribution can be difficult to interpret in terms of single dates. Here, we adopt the weighted mean value of the period posterior probability distributions to define the onset and termination of each period (Figure 3, Table 4). For comparison, the modes (most frequent value) of the posterior probability distributions are also included in Table 4, and with 1 exception (IV_e), both the weighted mean estimate and the mode agrees with ±40 yr; the mean difference is 1 yr. VI_e shows a large deviation between the weighted mean estimate and the mode of 123 yr (Table 4). Only 2 samples show agreement index values (A) lower than 60%, i.e. the lower limit for good agreement with the constructed model. Sample Ke 3817B shows an A value of

54.3% and sample AAR-8828 gives an A value of 45.3%. The low A value of AAR-8828 is a result of the stratigraphic information attached to this sample as it is to be younger than AAR-8827 (Figure 3, Table 3).

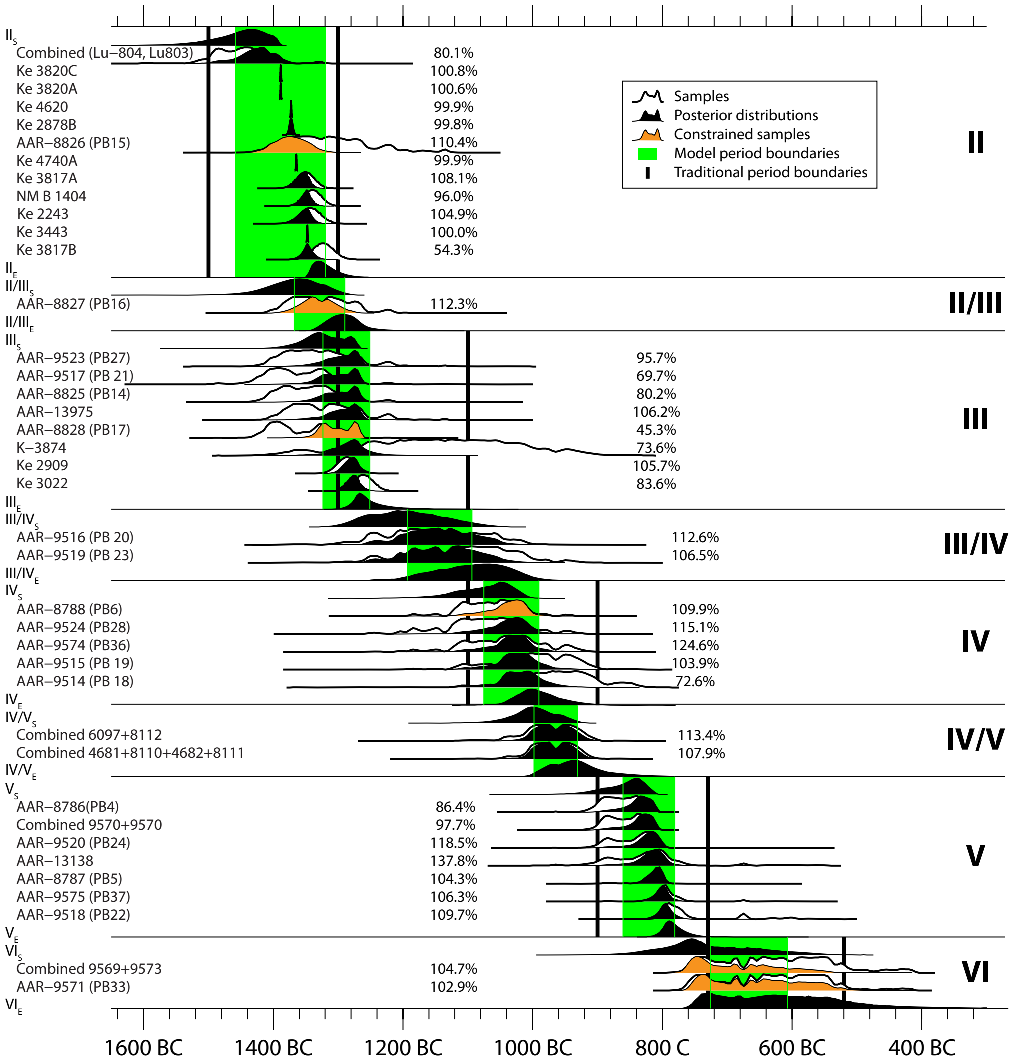


Figure 3 Modeled and unmodeled calibrated age probability distributions grouped by period (II–VI) and transition between periods (II/III, III/IV and IV/V). Solid vertical lines indicate the traditional ages of each of the periods (II–VI), and green areas indicate the model output dates for each of the periods. Numbers refer to the OxCal 4.1 agreement index of each sample with the model.

In general, the outcome of the chronological model for the Bronze Age is in good agreement with traditional Bronze Age periods (Figure 3, Table 4). The modeled boundaries of periods are all compatible with the traditional Danish chronology as the periods II, IV, V, and VI all fall within the age ranges of the traditional chronology (Table 4, Figure 3). An exception is period III, which is suggested to start some 30 yr earlier, ~1330 BC, than the traditional onset of period III (1300 BC). According to Randsborg (2006), the start of period III is ~1330 BC (1344–1319 BC) based solely on the Danish dendrochronological dates, which are in good agreement with the result obtained by the modeled data. Further, the periods III to VI, including the transition periods III/IV and IV/V, all appear in successive chronological order with no overlaps even though this has been allowed in the model construction. The transition period II/III does, however, show an overlap with period II and III. In contrast, both III/IV and IV/V appear as a further subdivision of the traditional periods III and IV (Figure 3, Table 4). The transition period III/IV is a well-defined Danish archaeological phase, named subperiod III, corresponding to the central European phase Ha A2 (Randsborg 1972). Future chronological studies may show whether the transition period IV/V is an archaeological phase as well. All periods II to VI show significantly decreased spans in comparison to the traditional periods (Figure 4, Table 4). The main reason is the small number of samples included in each period, which is particularly true for periods II/III, III/IV, IV/V, and VI consisting of only 1 to 2 samples. Another reason may be that the samples originate from a small geographical region and as such do not represent the whole of the Danish region. However, periods II, IV, and V are represented with samples from both Jutland and Funen and in addition period III includes Zealand (Figure 1). Hence, the Danish region as a whole is represented and the result therefore points towards a likely more confined span of each period than previously thought. Interestingly, the southern Swedish period II find dates (Lu-803, Lu-804, Table 2) are significantly earlier than the period II finds from Jutland and northern Germany (Figure 3, Table 3), perhaps suggesting regional differences in the timing of each period. However, this difference may also signal a warning against drawing too firm a conclusion on a limited geographical data set.

Table 4 Bronze Age periods (model output). μ refers to the weighted mean of the calibrated probability distribution (95.4% confidence interval) and mode refers to most frequent value (Dates ranges BC).

			Model start (BC)		Model end (BC)		Period span		
Period	Traditional (BC)	*n*	μ	Mode	μ	Mode	Trad.	Year	Mode
II	1500–1300	12	1459 (1558–1387)[a]	1435	1320 (1348–1284)	1330	200	140 (52–252)	116
II/III		1	1368 (1450–1289)	1360	1290 (1337–1241)	1290		78 (–1–174)	52
III	1300–1100	8	1323 (1381–1268)	1330	1251 (1296–1184)	1267	200	72 (–3–171)	5
III/IV		2	1193 (1294–1084)	1210	1094 (1201–996)	1057		99 (–1–223)	53
IV	1100–950/920	5	1075 (1163–1007)	1050	990 (1053–911)	1000	165	119 (–3–344)	5
IV/V		2	998 (1065–931)	1002	931 (1004–837)	935		67 (–3–177)	10
V	950/920–800	7	861 (925–811)	842	781 (816–740)	790	135	80 (1–168)	55
VI	800–530/520	2	726 (853–572)	755	607 (762–411)[b]	730	275	85 (–3–201)	40

[a] *Terminus ante quem*.
[b] *Terminus post quem*.

An archaeological classification for the 3 samples, AAR-13974, -9525, and -9521, has not been possible (Figure 5, Tables 1 and 3). Here, we apply the constructed Bronze Age chronology to try to connect these samples to a certain period by calculating the percentage of the calibrated probability distribution that falls within each period (Figure 5). Sample AAR-13974 has most of its area falling within period II/III (27.8%) and III (44.8%). Sample AAR-9525 falls within the traditional period IV, with 32.8% of its area in period IV and 46.8% in period IV/V. Sample AAR-9521 has 56.5% of its area within period V, but also a large fraction between period IV/V and V (Figure 5).

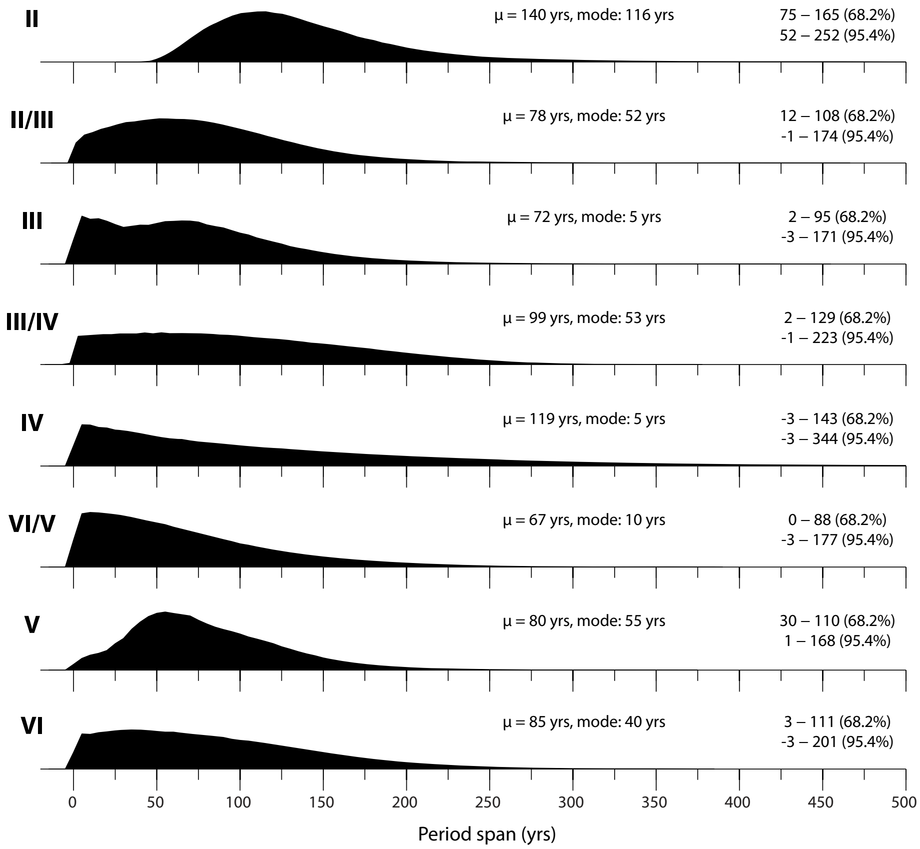
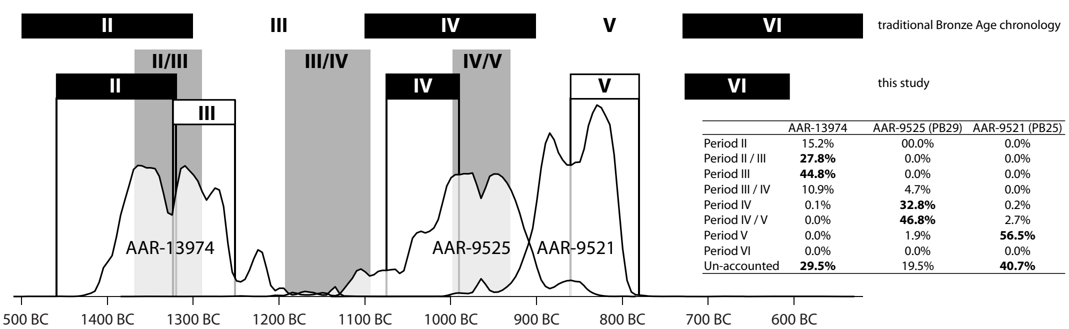


Figure 4 The probability distribution for the duration of each modeled period. μ refers to the weighed mean of the calibrated probability distribution and mode refers to most frequent value.



	AAR-13974	AAR-9525 (PB29)	AAR-9521 (PB25)
Period II	15.2%	00.0%	0.0%
Period II / III	**27.8%**	0.0%	0.0%
Period III	**44.8%**	0.0%	0.0%
Period III / IV	10.9%	4.7%	0.0%
Period IV	0.1%	**32.8%**	0.2%
Period IV / V	0.0%	**46.8%**	2.7%
Period V	0.0%	1.9%	**56.5%**
Period VI	0.0%	0.0%	0.0%
Un-accounted	**29.5%**	19.5%	**40.7%**

Figure 5 Calibrated age probability distributions of unknown Bronze Age period samples. The table indicates the percentage areas of each unknown sample within each modeled period. "Un-accounted" refers to the area of the calibrated age probability distributions falling outside the modeled period spans.

CONCLUSION

In this study, ^{14}C dating of cremated bones has been used to improve the traditional chronology of the Danish Bronze Age. The careful selection of samples from burials with positive archaeological classification to a single period or a transition phase has resulted in a satisfactory absolute model for

Denmark. The model is almost in agreement with the proposed chronology, which relates to the central European chronology. The model raises an interesting question concerning the early beginning of period III, which only future work may fully explore. In the previous work by Vandkilde et al. (1996), the Danish Late Bronze Age was almost absent due to the lack of ^{14}C dates from period IV and VI burials. Based on 20 new high-precision ^{14}C dates, we are now able to define the Late Bronze Age periods IV to VI.

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