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THE METHOD OF COMBINING RADIOCARBON DATES AND OTHER INFORMATION IN APPLICATION TO STUDY THE CHRONOLOGIES OF ARCHAEOLOGICAL SITES

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Abstract: The Bayesian theorem provides mathematical base for probabilistic calibration of radiocarbon dates, but it is also a base for more sophisticated analysis - combining of probability distribution of calibrated radiocarbon dates with information from other sources – for example stratigraphic information or dates obtained by a method differ than radiocarbon dating. This paper presents three examples of using the method of combining radiocarbon and other information to study the chronologies of archaeological sites. The first example concerns the Inca State chronology and is an attempt to define the time intervals of Inca Imperial Phase and Inca Preimperial Phase accurately. The second refers to the settlement in Wolin and allows to assign the chronology to cultural layers excavated in Trench 6, Site 1 located in central part of settlement and to precise obtained results. The last example concerns South American site - Maucallcta and is a case, when application of the method does not give results because of ambiguity of stratigraphic information.

1. INTRODUCTION

Methods of probabilistic interpretation of radiocarbon dates have been developed since eighties, when the first calibration programs were written. The method, which combines radiocarbon dates and other information, derives from this interpretation and, like calibration procedure, is based on Bayesian Theorem. It was proposed in 1991 by Caitlin Buck from Departments of Mathematics, University of Nottingham and her co-workers (Buck *et al.*, 1991). In 1994 Christopher Bronk Ramsey from Oxford University wrote a special computer programme called OxCal, which calibrates radiocarbon dates and performs analysis basing on this method (Bronk Ramsey, 1995). All analysis presented in this paper were realised using version 3.5 of this program.

2. BASIS OF METHOD

The Bayesian Theorem was formulated in 1763 and refers to conditional likelihood. This theorem, with reference to radiocarbon and calendar dates, may be expressed by the following formula:

$$P(T/D) = P(D/T) \cdot P(T) \cdot C \tag{2.1}$$

where:

P(T/D) - probability, that calendar age of sample is equal T on condition that the measured radiocarbon age has value D,

P(D/T) – probability, that measured radiocarbon age is equal D on condition that the calendar age has value T,

P(T) – probability, that calendar age of sample is equal T, which presents our knowledge about the age before radiocarbon dating (probability *a priori*),

C – normalisation constant.

Probability P(D/T) is defined as Gaussian probability distribution

$$P(D/T) = \frac{1}{\sqrt{2\pi}\,\sigma} \cdot \exp\left(-\frac{(D-\mu(T))^2}{2\sigma^2} \right) \tag{2.2}$$

where σ denotes the standard deviation of radiocarbon date and μ(T) is the true radiocarbon age of sample associated with calendar age T by calibration curve.

The method of combining radiocarbon dates and other information is based on appropriate definition of probability *a priori* P(T). In most cases we know nothing or very little about the age of sample before measurement and we should assume the probability *a priori* as approximately constant. This assumption is the basis for calculation of calendar age at calibration programs. However many times we have some information, which refer to the age of dated sample, before measurement - for example: results of dating by other method, stratigraphical data or even some kind of historical data. If we express these data by means of probability distribution we may include them to calculation of probability distribution of calendar age. This procedure enables to obtain more precise calendar age of sample, because takes into consideration both radiocarbon dates and data from other sources.

Incorporation of chronological (stratigraphical or historical) data to analysis distinctly complicates calculations, which should be realised not for single radiocarbon date, but for a group of radiocarbon dates and should include information about chronological sequence of these dates. The simplest method, which allows describing chronological sequence in terms of probability, is to assume that probability *a priori* density function is constant when the values of calendar age satisfy the inequality arising from this sequence and is equal zero otherwise (Buck *et al.,* 1991). For example, if four samples, taken from different strata, have calendar ages: T_1, T_2, T_3, T_4 and it arises from stratigraphical data, that:

$$T_1 > T_2 \geq T_3 > T_4 \qquad (2.3)$$

then the multidimensional probability *a priori* density function takes the form:

$$P(T_1, T_2, T_3, T_4) = \begin{cases} \text{const} & \text{for } T_1 > T_2 \geq T_3 > T_4 \\ 0 & \text{otherwise} \end{cases} \qquad (2.4)$$

It is necessary to emphasise, that the results of recent investigation show, that probability *a priori* density function should be defined in more sophisticated manner (Steier and Rom, 2000; Bronk Ramsey, 2000).

3. APPLICATION TO CHRONOLOGIES OF ARCHAEOLOGICAL SITES

The Inca State chronology

The first example of application presents an attempt to find out the time intervals of two phases of the Inca State - Imperial and Pre-imperial. The widely accepted Inca State chronology is still an object of controversies, though it was established on the grounds of the historical sources – the Chronicles. There are two reasons of these controversies:

1st – the Inca did not leave any written sources. The Chronicles were written down by Spaniards after the Inca State had fallen.

2nd – the significance of information contained in the Chronicles is not clear and univocal (Adamska, Michczyński, 1996).

The main aim of study was to assign length of the Inca Imperial and Pre-imperial Phase basing on composite probability distribution of radiocarbon dates. The probability distributions obtained for radiocarbon dates, which represent Pre-imperial and Imperial Phase are shown in **Fig. 1** by thin line. Dashed area presents time intervals of these phases estimated on the basis of Chronicles. We can notice that distribution for Pre-Imperial Phase corresponds very well with the estimated interval. On the other hand cumulative probability distribution for 24 samples, which represent Imperial Phase shows three, almost separated peaks with maxima at about 1325 AD, 1450 AD and 1600 AD. This shape of probability distribution is caused by wiggles of calibration curve. We know from reliable historical sources, that the last bastion of the Inca State – Vilcabamba – fell in 1572, so the third peak falls in Colonial period. The method, which combines radiocarbon dates and other information give us possibility to include information about the date of fall of Inca State in statistical analysis. Results of this analysis are presented in **Fig. 1** by thick lines, which show probability distribution obtained with assumption that samples from Pre-imperial Phase are older than samples from Imperial Phase and that all dates should be older than 1572 AD. We can notice that only central peak of previous distribution may be treated as a measure of Imperial Phase time-interval.

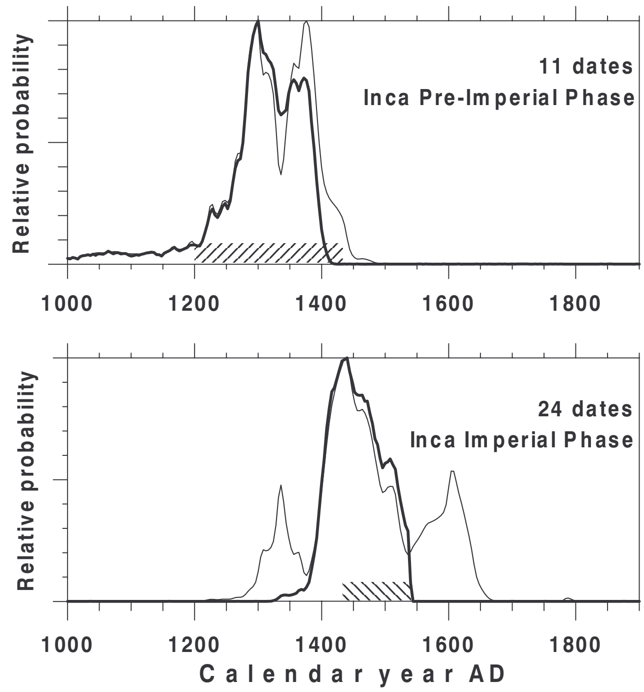

Fig. 1. *Composite probability distributions of calibrated radiocarbon dates for Inca Preimperial and Inca Imperial Phase. Dashed area shows limits of phases established on the basis of the chronicles. Thin lines present probability distributions obtained from radiocarbon dates without additional data; thick lines show probability distributions obtained as a result of combining information.*

The chronology of settlement in Wolin

The settlement in Wolin was recognised as one of the most important and the largest fortified early-medieval harbour cities at the Western Pomerania, Poland. Archaeological investigations of this settlement were carried out since early fifties by Professor Władysław Filipowiak from National Museum in Szczecin (Filipowiak, 1973, 1994). The subject of analysis was to assign chronology to cultural layers excavated in Trench 6, Site 1, which was located in central part of settlement. Southern stratigraphic profile of this trench is presented in **Fig. 2**. The profile was divided into following stratigraphic units: cultural layers X-XV, which were sub-divided afterwards into two units - layers X-XIII and layers XIV-XV, cultural layer XVI and two half-dugouts - number 2 and 3. The most important from archaeological point of view is layer XVI, because it marks the beginning of intensive early-mediaeval colonisation. **Table 1** shows radiocarbon dates of 17 samples collected from the profile. Three of them were excluded from further analysis because of their incompatibility with the rest of dates (we assume that they are not representative for layers they were collected from). Basing on these dates we calculate cumulative probability distribution for each unit without any additional information and with information concerns stratigraphy. We assume that the both half-dugouts have the same age and they are older than Layer XVI, which is then older than Layers XV-XIV and Layers X-XIII. The results are presented in **Fig. 3**: thin lines show cumulative probability distribution obtained from radiocarbon dates without any additional information, thick lines show results of combining radiocarbon and stratigraphic information. When

Table 1. *Radiocarbon dates of 17 samples collected from the profile in Trench 6, Site 1, Wolin. Three dates excluded from further analysis are printed in italic.*

Sample	Laboratory code and number	$\delta^{13}C$ (‰,PDB)	Radiocarbon ^{14}C Age (BP)	Material
Layers X-XIII				
I/72	Gd-1779	-30.9	1030 ± 40	Moss
II/73	Gd-2253	-30.4	1040 ± 60	Moss
III/73	*Gd-2334*	*-30.0*	*1440 ± 60*	*Moss*
IV/73	Gd-1850	-28.5	1040 ± 50	Moss
Layers XIV-XV				
V/73	Gd-2335	-29.0	1190 ± 60	Moss
VI/73	Gd-2267	-27.8	1200 ± 60	Moss
Layer XVI				
9/74	Gd-1711	-26.2	1340 ± 50	Charcoal
8/74a	Gd-3039	-25.2	1290 ± 35	Charcoal
8/74b	Gd-1714	-25.2	1340 ± 60	Charcoal
843/74	*Gd-3048*	*-28.0*	*1150 ± 35*	*Hasel-nuts*
896/74	Gd-2216	-27.8	1290 ± 70	Hasel-nuts + moss
Half-dugout 3				
878/74	Gd-2217	-13.1	1460 ± 70	Charred millet seeds
13/74	Gd-1709	-11.3	1390 ± 40	Charred millet seeds
6/74	Gd-3040	-25.7	1290 ± 35	Charcoal
10/74	Gd-1710	-12.4	1370 ± 50	Charred millet seeds
Half-dugout 2				
7/74	*Gd-1666*	*(-25)*	*1570 ± 50*	*Charcoal*
908/74	Gd-2218	(-25)	1310 ± 110	Moss

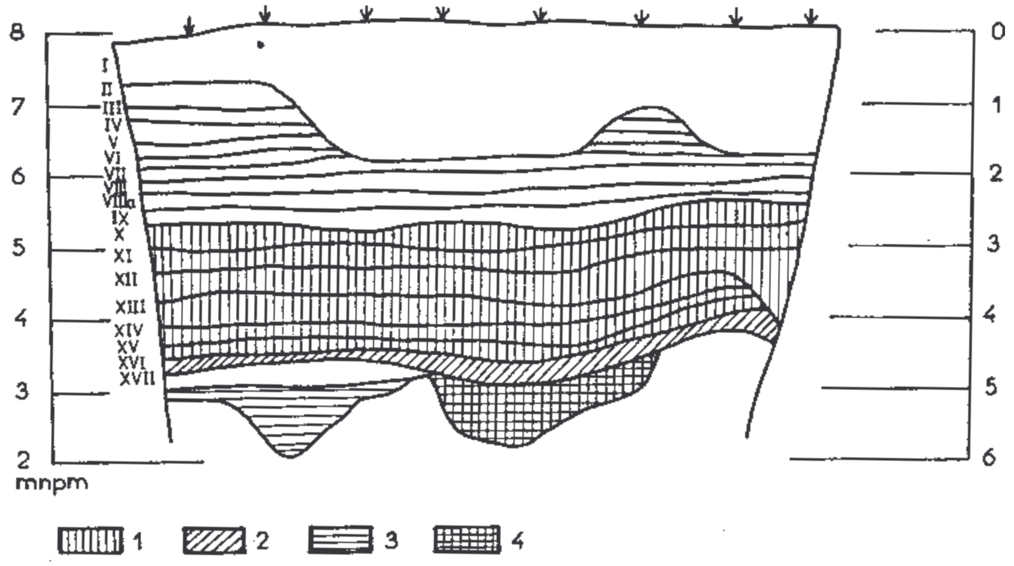

Fig. 2. *Stratigraphic profile of Trench 6, Site 1, Wolin settlement: 1 - half-dugout 3, 2 - half-dugout 2, 3 - cultural layer XVI, 4 - cultural layers X-XV (Pazdur et al., 1994). Left-hand side vertical scale shows altitude above sea level; right-hand side vertical scale shows depth below surface.*

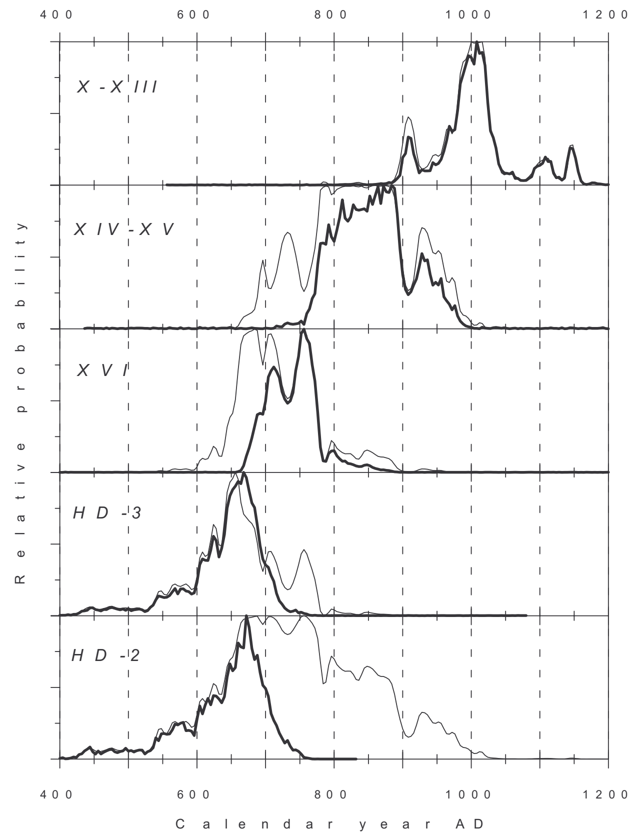

Fig. 3. *Cumulative probability distributions of calibrated radiocarbon dates from Trench 6, Site 1, Wolin settlement Thin lines presents probability distributions obtained from radiocarbon dates without any additional information, thick lines show results of combining radiocarbon and stratigraphic information.*

we compare these distributions with the archaeological estimation of the age of stratigraphic units, which were done basing on typology of ceramic remains (see **Table 2**), we may notice that distributions obtained from radiocarbon dates only (thin lines) confirm archaeological estimation. However distributions obtained as a result of combining radiocarbon and stratigrapic data (thick lines) make estimation of time intervals of stratigraphic units more precise. It is clearly visible in **Table 3**, which contains the highest likelihood 68% confidence intervals calculated for probability distribution obtained from radiocarbon dates only and from radiocarbon dates with stratigraphic data. The results show that taking into consideration stratigraphic data allows to obtain more accurate calendar ages of particular stratigraphic units, especially Half-dugout 2 and the most important for archaeology Layer XVI.

Table 2. *Estimated archaeological dating of stratigraphic units.*

Sstratigraphic unit	Estimated age
Levels X-XV	700 – 1100 AD
Level XVI	600 – 800 AD
Half-dugout 3	500 – 800 AD
Half-dugout 2	500 – 800 AD

Table 3. *Highest likelihood 68% confidence intervals calculated for probability distributions obtained from radiocarbon dates only and from radiocarbon dates with stratigraphic data.*

Layer	Highest likelihood 68.3% confidence intervals	
	radiocarbon dates only	with stratigraphic data
X-XIII	900-920 AD (8.4%) 960-1040 AD (59.8%)	900–920 AD (3.8%) 960-1040 AD (64.4%)
XIV-XV	720-750 AD (4.9%) 770-900 AD (57.6%) 920-940 AD (5.6%)	780-900 AD
XVI	650-780 AD	700-775 AD
HD3	600-720 AD 740-770 AD	605-700 AD
HD2	640-880 AD	600-710 AD

The chronology of Maucallacta site

The last example concerns South American site - Maucallcta and is a case, when application of the method, which combines radiocarbon and other information does not give results. The archaeological site of Maucallacta is located in the Department of Arequipa in Peru, at the altitude of 3600-3800 meters a.s.l. Archaeological investigations of this site are carried out since 1996 by the Polish-Peruvian Archaeological Project „Condesuyos” directed by Professor Mariusz S. Ziółkowski from the University of Warsaw, Poland, and Dr. Luis Augusto Belan Franco from the Catholic University „Santa Maria” in Arequipa, Peru. According to the present state of investigations, Maucallacta was most probably the main Inca religious and administrative centre in this part of the Andes, associated with the cult of the Holy Mountain Coropuna. An important dump was encountered among stone constructions to the south of the pyramidal platform on the slope of the hill. In general, two kinds of strata were identified in the dump: earth layers and ash layers. Interestingly enough, their superposition discloses a curious pattern of deposition: one or several ash units changed regularly with different earthen strata. The archaeological context suggests two possible ways of deposition. First of them would be purely „stratigraphic” with subsequent layers being deposited regularly in the association with periodic ceremonies of purificatory functions, attested in ethnohistorical sources. Another possibility was single deposition of accumulated material, which should have resulted in total reversal of strata (Ziółkowski *et al.,* 1999; Michczyński *et al*., 2000).

The main aim of analysis was to test, which of the possible ways of deposition appear and to precise dating of individual strata. Dates included in the analysis are presented in **Table 4**. We built two models - the first, which assumes that strata were deposited in stratigraphic order (the lowest stratum is the oldest) and the second, which assumes that site has reversal stratigraphy. Both models assume, that terminus ante quem of sequence is equal 1540 (The Inca presence in this area can be dated till 1540 AD). The results of analysis are presented in **Fig. 4** by thick line. **Fig. 4A** shows the probability distribution obtained from combining radiocarbon dates and stratigraphic information if we assumed that strata were deposited one after the other, **Fig. 4B** presents the probability distribution obtained from combining radiocarbon dates and stratigraphic information with assumption that site has reversed startigraphy. The results of calibration of pure radiocarbon data, presented on this Figure by thin lines, show, that strata B, C and G have practically the same age (Stratum B seems to be somewhat older than stratum C, and C somewhat older than G), but the ages of stratum K and stratum L shift each other in opposite directions. Therefore the date Gds-108 (stratum K) fits very well on hypothesis, that strata were deposited one after the other („startigraphic"), but the date Gds-120 (stratum L) is not coherent with it. On the other hand the date Gds-120 fits the hypothesis, that deposition was reversal. Unfortunately both models are not coherent and we do not know as before which of them is correct. In our opinion the main reason of this was simply imperfect sampling strategy - the greater amount of samples for radiocarbon dating should be taken from the uppermost and lowermost stratum in order to better estimation of date which begins sequence of strata and date which ends it.

CONCLUSIONS

The presented examples clearly show, that the method, which combines radiocarbon dates and other information may considerably increase precision of chronologies and makes powerful tool for statistical inference based on various types of information. On the other hand it should be emphasised, that the method may be apply only at that time, when information we want to include are well defined.

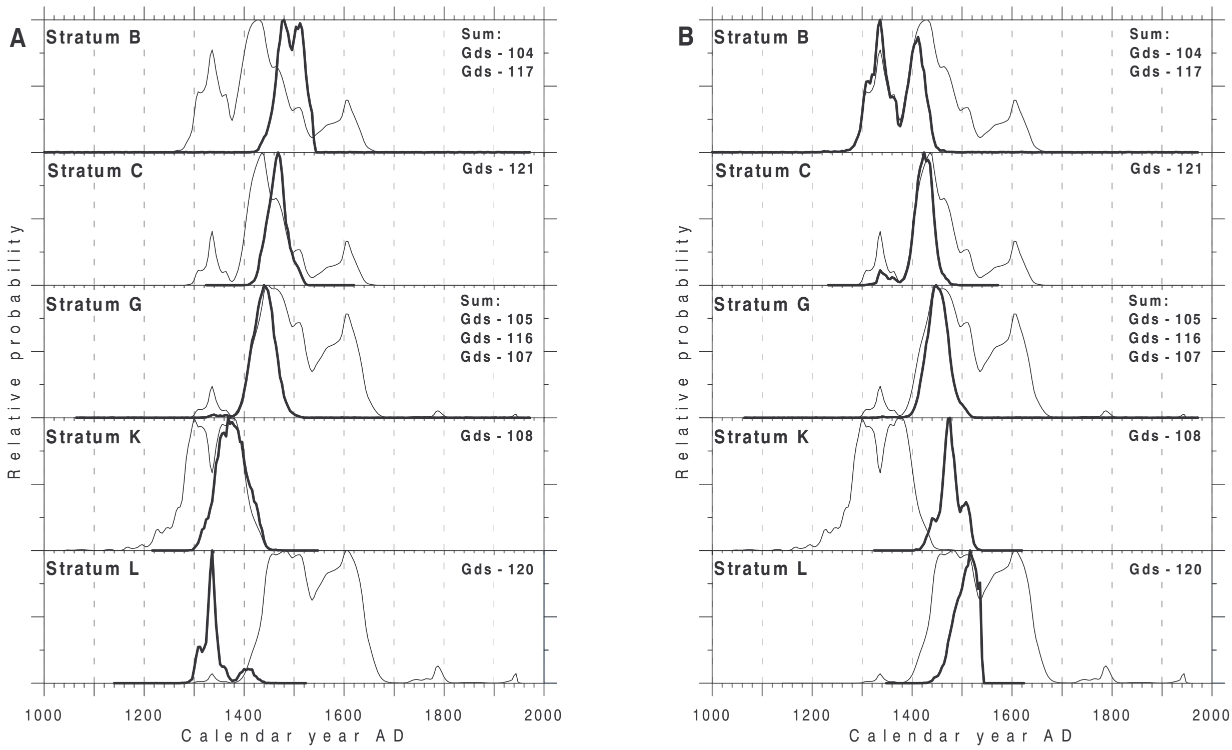

Fig. 4. *Probability distributions obtained from combining calibrated radiocarbon dates and prior stratigraphic information (thick line). Moreover the figure shows the probability density functions obtained from radiocarbon data only (thin lines). In our analysis we assume that strata were deposited one after the other (A) or that the site has reversed stratigraphy (B).*

Table 4*. Radiocarbon dates of the samples collected from the investigated midden (Maucallacta site).*

Stratum	Sample	Laboratory code and number	^{14}C Age (BP)
B	Maucallacta 7/98	Gds-104	540 ± 85
	Maucallacta 1/98	Gds-117	450 ± 80
C	Maucallacta 6/98	Gds-121	470 ± 70
G	Maucallacta 8/98	Gds-105	380 ± 80
	Maucallacta 2/98	Gds-116	420 ± 75
	Maucallacta 3/98	Gds-107	460 ± 75
K	Maucallacta 5/98	Gds-108	650 ± 80
L	Maucallacta 4/98	Gds-120	380 ± 80

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