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Radiocarbon Chronology of Upper Palaeolithic Sites in Eastern Europe at Improved Resolution

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We perform statistical analysis of calibrated radiocarbon age measurements for several key Upper Palaeolithic (UP) sites in East European Plain (Kostenki 1, Layer 1; Kostenki 1, Layer 3; Avdeevo; and Mezhirichi) and isolate a contemporaneous subsample in each set of age measurements. We further estimate the most probable age of the subsample. The confidence interval of the age estimate is significantly less than the standard deviation of the dates in the subsample. Thus, statistical analysis of a data sample allows us to improve considerably the temporal resolution of radiocarbon dating. The dates belonging to a contemporaneous subsample can be considered as pertaining to a momentary event. The screening of the published radiocarbon dates for UP sites in East European Plain has resulted in a new date list, where each site is characterized by a single date. These data indicate a considerable increase in the density of East European UP dates during the Last Glacial Maximum and their total disappearance after 15 ka BP. We argue that this presumable increase in the population had resulted from an influx of groups of anatomically modern humans from the West during the coldest interval of the Last Glacial Maximum.

Keywords: UPPER PALAEOLITHIC, EASTERN EUROPE, RADIOCARBON AGE, STATISTICAL ANALYSIS, PREHISTORIC POPULATION DYNAMICS.

Introduction

The radiocarbon method, with all its strengths and weaknesses, remains the principle instrument for the establishment of precise chronology of Upper Palaeolithic (UP) settlement in Europe. A considerable number of radiocarbon date measurements have become available over the past few decades for UP sites in all parts of Eastern Europe, including East European (or Russian) Plain, Russian North, South Russian and Ukrainian Steppe, Northern Caucasus and the Urals. A substantial part of these measurements have been performed at the laboratories in Russia, those at the Institute for History of Material Culture in St Petersburg and the Institute of Geology in Moscow being particularly active. Several important series were measured at the laboratory in Groningen, Holland. These laboratories used the standard procedure of measurements discussed by Stuiver & Polach (1977). A different technique, Accelerator Mass Spectrometry (Kutschera, 1993) was used in several laboratories, including the Oxford Radiocarbon Unit, U.K., where several important measurements have been obtained for East European UP sites.

A comprehensive synopsis of UP radiocarbon dates for Eastern Europe has been published by Sinitsyn *et al.* (1997). The date list includes practically all the dates of UP sites available for Eastern Europe to date. In certain cases the synopsis contains detailed commentaries, maps and drawings for the most important series.

However, the temporal resolution of these radiocarbon dates yet has not been analysed sufficiently well. Sinitsyn *et al.* (1997: 48) estimated the resolution of the radiocarbon dating as about 5000 years from the apparent age scatter for several key sites. The synopsis of Sinitsyn *et al.* (1997) contains the dates for numerous archaeological complexes whose real lifetime

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(plausibly less than 100 years) is short in comparison to the reported uncertainties which are typically 100–600 years and reach 2000–3000 years in some cases. Yet, careful statistical analysis of large data samples can yield significantly more precise age determinations. The aim of this paper is an attempt at the improvement of the resolution of the radiocarbon dating of UP sites. The resulting uncertainty of radiocarbon age for data samples clustered in space and time can be reduced to a few hundred years.

The Data Set

We analysed the published radiocarbon dates for several UP sites and selected those large data series which were suitable for statistical analysis using a method described later in the paper. This analysis was largely based on the age measurements for the samples from "Palaeolithic dwellings" discussed below. For the remaining UP sites the data are too scarce to justify detailed statistical analysis. These data were screened using the following criteria.

We preferred those dates which have been obtained for objects with adequate stratigraphic and planigraphic evidence. All the dates lacking direct relation to archaeological deposits (e.g., taken from below or above the archaeologic level) were rejected. Whenever possible, we adopted the measurements confirmed by inter-laboratory cross-checking. And finally, controversial results (e.g., those showing considerable discrepancies between the dates obtained in different laboratories) were discarded.

Thus a final data set has been compiled where each UP site selected is characterized by a single date given in Table 5.

The Upper Palaeolithic Dwellings

The dwellings first recognized as UP sites in Russia in the 1920s form an outstanding feature with large potentialities for absolute dating. These dwellings (*zemlyanka*) usually consisted of lense-like clusters of splitted stone and fragmented animal bones, often with the hearths consisting of small-size concentrations of charred bone. They were located within artificially dug-out hollows and included regularly arranged large mammoth bones (Rogachev & Anikovich, 1984; Grigor'ev, 1993). The first such dwellings recognized in Russia was that of the Layer 1 of the Kostenki 1 site (Figure 1). Originally Efimenko (1932) interpreted it as a long house (40 m by 20 m), inhabited by a "band of hunters". Later, Grigor'ev (1967) saw it as a row of small rounded dwellings each inhabited by a core family. The dwellings identified so far in Russia vary by their size, shape and other attributes, such as the presence or absence of hearths, storage pits, etc. (Soffer, 1985).

One of the most important issues in relation to the UP dwellings is the duration of their occupation (Soffer, 1985: 386). Taking into account the complexity of these dwellings and considerable investment of labour required for their construction, the great majority of Russian scholars (Abramova & Grigor'eva, 1997; Abramova, 1999) consider them as long-time habitations, indicative of sedentary mode of life. Leonova (1993: 151) argues that a "long-time occupation" of the sites with dwellings may vary, "from a few months . . . to a decade-long sedentaryness". According to Ukrainian archaeologists (Stanko, Gladkikh & Segeda, 1999: 143), even the largest UP dwelling sites in that area (Mezin and Dobranichevka) existed for no longer than 20–23 years.

Even if one accepts Leonova's (1993) arguments that parts of the settlements could have been abandoned and later reused, one can reasonably suggest than any of the dwellings, for which substantial series of radiocarbon dates are available, were in use for less than 100 years.

Calibration

In contrast to the radiocarbon dates of the Holocene period, where the dendrochronological calibration is widely in use, there is no universally accepted calibration curve for radiocarbon measurements of Pleistocene age (van der Plicht, 1998). Several attempts to calibrate the radiocarbon dates older than 10 ka have recently been made. One of these is based on the estimation of the temporal variations in the intensity of the earth's magnetic field, as recorded in the cores of marine and lacustrine sediments as well as volcanic rocks. Using these records, the calibration diagrams have been obtained, showing the deviation of the "old" radiocarbon dates from the calendar date (Laj *et al.*, 1996; van Andel, 1997). The difference between the radiocarbon and calendar ages reaches 3000–3400 years in the timespan between 20 and 30 ka BP. In the present study we used these results to calibrate the dates shown in Tables 1–5. In accordance with the recommendations of Laj *et al.* (1996) and van Andel (1997), the calibration error was adopted as 900 years for the dates between 15 and 30 ka BP, and 700 years for more recent dates.

A Statistical Criterion of Contemporaneity

Consider N radiocarbon datings t_i, $i=1, \ldots, N$, all belonging to a certain archaeological complex. Let σ_i be the uncertainty of a date t_i. Suppose that the lifetime of this complex is $T \pm \sigma_T$ with σ_T being the real scatter in the lifetimes of the objects belonging to the complex. All the objects of the complex must be considered as coeval if $\sigma_T \ll \sigma_i$. Here T is unknown and should be determined from the datings available.

Table 1. Radiocarbon datings of the Kostenki 1/1 group and their uncertainties

No.	t_i [years BP]	$\sigma_i^{(0)}$ [years]	t_i [years BP]	σ_i [years]
1	18,230	620	21,430	1438
2	18,400	3300	21,600	3421
3	19,010	120	22,260	1438
4	19,540	580	22,790	1438
5	19,620	460	22,510	1438
6	19,860	200	23,110	1438
7	20,100	680	23,400	1438
8	20,310	200	23,610	1438
9	20,855	260	24,155	1438
10	20,800	300	24,100	1438
11	**21,150**	**200**	**24,500**	**1438**
12	21,180	100	24,530	1438
13	21,300	400	24,650	1438
14	21,680	700	25,030	1438
15	21,800	200	25,110	1438
16	21,800	300	25,110	1438
17	21,800	300	25,110	1438
18	21,950	250	25,300	1438
18a	22,000	300	25,350	1438
19	22,020	310	25,370	1438
20	22,060	500	25,410	1438
21	22,200	300	25,510	1438
22	**22,200**	**500**	**25,510**	**1438**
23	22,300	200	25,610	1438
24	22,300	230	25,610	1438
25	22,330	150	25,680	1438
26	22,600	300	25,950	1438
27	22,600	300	25,950	1438
28	22,700	250	26,050	1438
29	22,760	250	26,160	1438
30	22,800	200	26,200	1438
31	22,800	300	26,200	1438
32	23,000	500	26,400	1438
33	23,010	300	26,410	1438
34	**23,260**	**680**	**26,660**	**1438**
35	**23,490**	**420**	**26,890**	**1438**
36	23,500	200	26,900	1438
37	23,600	400	27,000	1438
38	23,640	320	27,040	1438
39	**23,770**	**200**	**27,110**	**1438**
40	24,030	410	27,430	1438
41	24,100	500	27,500	1438
42	24,570	3930	28,070	4032

$X^2(T_0)=43{\cdot}4$, $\chi^2_{42}(0{\cdot}95)=58{\cdot}1$

Table 2. Radiocarbon datings of the Kostenki 1/3 site and their uncertainties

No.	t_i [years BP]	$\sigma_i^{(0)}$ [years]	t_i [years BP]	σ_i [years]
101	20,900	1600	24,200	1600
103	**24,500**	**1300**	**27,950**	**1300**
104	**25,400**	**400**	**28,900**	**400**
105	**25,600**	**1000**	**29,100**	**1000**
106	**25,700**	**600**	**29,200**	**600**
107	25,730	1800	29,230	1800
108	25,900	2200	29,400	2200
109	25,820	400	29,320	400
110	26,200	1500	29,700	1500
111	*32,600*	*400*	*35,500*	*400*
112	*32,600*	*1100*	*35,500*	*1100*
113	38,080	5460	40,680	5460

$X^2(T_0)=12{\cdot}0$, $\chi^2_9(0{\cdot}95)=16{\cdot}9$

Table 3. Radiocarbon datings of the Avdeevo site and their uncertainties

No.	t_i [years BP]	$\sigma_i^{(0)}$ [years]	t_i [years BP]	σ_i [years]
176	*11,950*	*310*	*13,350*	*766*
177	*13,900*	*200*	*15,600*	*728*
178	*16,565*	*270*	*19,265*	*940*
179	16,960	420	19,860	993
180	18,500	2100	21,450	2285
181	19,500	500	22,800	1030
182	19,800	1200	23,100	1500
183	20,100	200	23,400	922
184	20,100	300	23,400	949
185	20,100	400	23,400	985
186	**20,100**	**500**	**23,400**	**1030**
187	**20,800**	**200**	**24,100**	922
188	21,000	200	24,300	922
189	21,000	800	24,300	1204
190	21,200	200	24,500	922
191	22,400	600	25,700	1082
192	**22,400**	**600**	**25,700**	1082
193	22,200	700	25,700	1140
194	22,700	700	26,050	1140
196	23,400	700	26,800	1140

$X^2(T_0)=20{\cdot}3$, $\chi^2_6(0{\cdot}95)=26{\cdot}3$

Since the lifetime of the complex is assumed to be negligible in comparison with the measurement uncertainties σ_i, the scatter of the dates t_i about T represents a Gaussian random noise, that is

$$t_i = T + \xi_i \sigma_i, \qquad (1)$$

where ξ_i, $i=1, \ldots, N$, are independent Gaussian random variables with zero mean and unit dispersion. In other words, the scatter of the age measurements is assumed to arise from the dating uncertainties alone, whereas the real scatter in the ages is assumed to be negligible.

Provided σ_i, $i=1, \ldots, N$, are known, we can check whether there is any unique value of T for which the statistical hypothesis (1) is compatible with the available datings and then we can estimate both the age T and its uncertainty. For this purpose we consider the Gaussian variables

$$\xi_i = \frac{t_i - T}{\sigma_i}$$

and define the quantity X via

$$X^2 = \sum_{i=1}^{N} \xi_i^2 = \sum_{i=1}^{N} \frac{(t_i - T)^2}{\sigma_i^2}. \qquad (2)$$

Table 4. Radiocarbon datings of the Mezhirichi site and their uncertainties

No.	t_i [years BP]	$\sigma_i^{(0)}$ [years]	t_i [years BP]	σ_i [years]
266	**14,700**	**500**	**16,600**	**860**
267	**14,530**	**300**	**16,330**	**762**
268	14,300	300	16,000	762
269	11,700	800	13,100	1063
270	12,900	200	14,400	743
271	**14,400**	**250**	**16,100**	**743**
272	14,320	270	16,020	750
273	15,245	1080	17,545	1287
274	*17,855*	*950*	*20,855*	*1180*
275	*18,020*	*600*	*21,120*	*1082*
276	*18,470*	*550*	*21,670*	*1055*
277	*19,100*	*500*	*22,400*	*1030*
278	*19,280*	*600*	*22,580*	*1082*
279	14,420	190	16,320	934

$X^2(T_0)=13{\cdot}8$, $\chi_8^2(0{\cdot}95)=15{\cdot}5$

The random variable X^2 is a sum of Gaussian random variables squared, so it has a standard probability distribution known as the χ^2-distribution with $N-k$ degrees of freedom, where N is the number of independent measurements and k is the number of parameters to be estimated (e.g., Cramér, 1946); in our case, $k=1$ since we use the data to estimate their most probable common age T alone. If, with a probability p (known as the confidence level and often chosen to be 95%), the hypotheses (1) is compatible with the available measurements, then X^2 must be smaller, with the probability P, than a certain critical value denoted $\chi^2_{N-k}(P)$, a known function of P and $N-k$.

The most probable value of T is that which provides a minimum value to $X^2(T)$; we denote the best estimate of T as T_0. Thus,

$$X^2(T_0)=\min X^2(T) \tag{3}$$

(the weighted least squares method). The hypothesis (1) is compatible with the data and acceptable if

$$X^2(T_0)\leq\chi^2_{N-k}(P). \tag{4}$$

The mean age and the confidence interval

The mean age T_0 can be easily obtained from Eqs (2) and (3): since $dX^2/dT|_{T=T_0}=0$, we obtain

$$T_0=\frac{\Sigma_{i=1}^N t_i/\sigma_i^2}{\Sigma_{i=1}^N 1/\sigma_i^2}. \tag{5}$$

The age interval $T_0-\Delta\leq T\leq T_0+\Delta$ for which the hypothesis (1) is acceptable (called the *confidence interval* for T) is given by the range of T in which the following inequality is satisfied:

$$X^2(T)\leq\chi^2_{N-1}(P). \tag{6}$$

The centre of the confidence interval is T_0. The width of the confidence interval 2Δ can be estimated as follows. We have from Eqs (2) and (5):

$$X^2(T)=X^2(T_0)+N\frac{(T-T_0)^2}{\sigma^2},$$

where

$$\frac{1}{\sigma^2}=\frac{1}{N}\sum_{i=1}^N\frac{1}{\sigma_i^2}$$

Therefore, the confidence interval, defined by the extreme values of T that still satisfy Eq. (6), results as

$$\Delta=\frac{\sigma}{\sqrt{N}}\sqrt{\chi^2_{N-1}(P)-X^2(T_0)}. \tag{7}$$

Summarizing, we conclude that the hypothesis (1) can be accepted if $\min X^2(T)=X^2(T_0)\leq\chi^2_{N-1}(P)$; then the temporal resolution of the method is Δ, and the age can be estimated as

$$T=T_0\pm\Delta. \tag{8}$$

The true value of T is restricted to this range with the probability P. For $P=95\%$, Δ is equal to two standard deviations of a Gaussian random variable.

A statistical criterion similar to (4) has been employed by Zajtseva *et al.* (1996) to identify coeval Sayan–Altai barrows using tree-ring chronology and radiocarbon age measurements. Statistical criteria similar to (4) have been used in isotope geochronology (e.g., Vinogradov & Sokoloff, 1988).

The empirical uncertainty

Successful application of the criterion (4) crucially depends on the reliability of the uncertainty estimates σ_i for an individual dating. Usually the values of σ_i are taken to be equal to the instrumental uncertainties $\sigma_i^{(0)}$ determined by the measurement procedure. However, the true uncertainties σ_i can, and most probably do depend on the archaeological context and carbon contamination from later loss (or influx) of ^{14}C (Taylor, 1987: 67). Then the true uncertainty of the measurements, that includes all sources of statistical noise rather than the instrumental error alone, should exceed the measurement errors, $\sigma_i>\sigma_i^{(0)}$. We stress that t_i and $\sigma_i^{(0)}$ may represent a perfectly reliable estimate of the radiocarbon age and its instrumental error, and nevertheless the scatter of the datings in a contemporaneous subsample can be greater than $\sigma_i^{(0)}$ due to various additional sources of errors. As shown below, the scatter of the radiocarbon ages of objects that have firm archaeological evidence of contemporaneity often exceeds $\sigma_i^{(0)}$ significantly.

Many effects can lead to systematic deviations of the radiocarbon age of an object from its true age (the calibration of radiocarbon age estimates removes just one of the systematic effects). Nevertheless, we assume that σ_i are Gaussian errors. The justification is as follows. If the systematic errors are independent for distinct objects, they merely produce a random Gaussian scatter of the dates in the sample and σ_i, as estimated below, is a reliable estimate of the associated error. Datings having exceptionally large systematic error will be discarded by the procedure described later. If, otherwise, *all* the measurements in the sample were plagued by the same systematic error, any statistical method would not be able to reveal that fact and the only remedy would be a more careful analysis of the archaeological context.

An alternative approach could be based on non-parametric statistics which is free of the assumption of Gaussian noise and where mean values and quartiles are used to characterize a random variable. This approach would preclude any statistical hypothesis testing, so one would have to presume that a given (sub)sample is contemporaneous. Non-parametric statistics provides an estimate of the mean age and its error for a contemporaneous subsample, but one must use non-statistical arguments to select the subsample itself. In this paper we employ an alternative statistical approach and isolate a contemporaneous subsample using the χ^2 criterion, but this involves additional assumptions about the statistical nature of the data, most importantly that their errors represent a Gaussian random variable.

In some cases one can estimate σ_i from the datings themselves. Suppose that an archaeological complex includes several subcomplexes, e.g., the remains of a residential site may consist of several structures (dwellings and their elements). Then it is highly plausible that the materials collected within a single dwelling structure are contemporaneous. Hence we can use the scatter of age measurements for this single dwelling σ_0 (the empirical uncertainty) as a reliable estimate of the typical uncertainty of the datings belonging to the whole site.

For the sake of simplicity, consider the case of a single subcomplex, with datings $t_1, \ldots, t_M$ belonging to this subcomplex, and $M<N$. Then we can estimate σ_0 as a scatter of the measurements belonging to the subcomplex:

$$\sigma_0 = \sqrt{\frac{1}{M-1}\sum_{k=1}^{M}(t_k - \tilde{T})^2}, \qquad (9)$$

where $\tilde{T} = M^{-1}\sum_{k=1}^{M} t_k$ is the mean value of t_k for the subcomplex. The accuracy of this determination of σ can be also determined, but this is hardly useful for our purposes.

If there are several subcomplexes which can be used to estimate the empirical standard deviation, the simplest (and conservative) option is to adopt the maximum empirical uncertainty among the subcomplexes as σ_0. If a more elaborate procedure is justified, an average value of individual σ_0 estimates can be adopted if their scatter does not exceed the accuracy of their estimation.

The use of σ_0 thus defined instead of $\sigma_i^{(0)}$ is justified only when $\sigma_0>\sigma_i^{(0)}$. Otherwise, the measurement error remains a better estimate of the true uncertainty. (We note that $\sigma_0>\sigma_i^{(0)}$ in most cases discussed in this paper.) Thus, the uncertainty of an individual measurement is

$$\sigma_i = \max(\sigma_i^{(0)}, \sigma_0),\ i=1, \ldots, N.$$

With allowance for an independent error due to calibration, the dating uncertainties were adopted as

$$\sigma_i = \sqrt{\sigma_i^2 + \sigma_c^2}, \qquad (10)$$

where σ_c is the calibration error discussed above, $\sigma_c=900$ year for $15<t_i<30$ kyear BP and 700 year for $t_i<15$ ka BP.

This method can be applied to those complexes where a certain subcomplex can be isolated confidently and where there is a sufficient number M of measurements originating in the subcomplex. Strictly speaking, this requires $M\geq 30$, but the results are often reasonable even for $M\geq 5$.

Statistical Analysis and Results

In this section we describe the application of the above approach to several UP sites. Our results are compiled in Tables 1–4 where we show the dating number as given by Sinitsyn *et al.* (1997) (Column 1), the published uncalibrated age estimate (Column 2), its measurement error (Column 3), the calibrated age (Column 4), and its error obtained from Equation (10) (Column 5). The entries shown boldfaced are for the measurements known *a priori* to be contemporaneous and used to determine σ_0. The entries printed in italics are those shown not to belong to a contemporaneous subsample and so discarded when estimating T_0.

Our analysis started with the determination of empirical dispersions σ_0 for data subsets which can be confidently considered to be contemporaneous, as described above (these data are shown boldfaced in Tables 1–4). After that we performed data selection based on the criterion (4). If the value of $X^2(T_0)$ did not satisfy the criterion (4), we discarded a measurement which deviated most strongly from the current value of T_0, i.e., that whose value of ξ_i^2 was the largest. If (4) still was not satisfied, the measurement whose ξ_i^2 was the largest among the remaining ones was discarded, and this process was repeated until the criterion (4) could be met. The discarded measurements are shown in italics in Tables 1–4. The result of this procedure were the estimates of the most probable age T_0, Eq. (5), and its confidence interval Δ, Eq. (8). Our results are

Table 5. Screened radiocarbon datings of the UP sites of the East European Plain

No.	Site	Age [years BP]	$\sigma^{(0)}$ [years]	Age [years BP]	Δ [years]	*X*	*Y*
1–42	Kostenki 1/1	21,930		25,300	900	51°22′	39°2′
46	Kostenki 2	23,800	150	27,300	912	51°22′	39°2′
48	Kostenki 3	19,800	210	23,000	924	51°22′	39°2′
50	Kostenki 4	23,000	300	26,200	949	51°22′	39°2′
53	Kostenki 5	22,920	140	25,100	911	51°22′	39°2′
54	Kostenki 8	22,000	160	25,200	914	51°22′	39°2′
57	Kostenki 10	28,250	300	31,450	949	51°22′	39°2′
63	Kostenki 11	19,900	350	23,100	966	51°22′	39°2′
64	Kostenki 11/2	21,800	200	25,000	922	51°22′	39°2′
68	Kostenki 11/3	20,500	300	23,700	949	51°22′	39°2′
72	Kostenki 14	22,780	250	26,000	934	51°22′	39°2′
76	Kostenki 18	21,020	180	21,800	918	51°22′	39°2′
80	Kostenki 19	18,700	600	26,100	1082	51°22′	39°2′
83	Kostenki 21/2	22,900	150	21,250	912	51°22′	39°2′
101, 103–110, 113	Kostenki 1/3	26,383		28,900	1000	51°22′	39°2′
114	Kostenki 8	23,020	320	26,200	955	51°22′	39°2′
117	Kostenki 12/1	26,300	300	29,500	949	51°22′	39°2′
128	Kostenki 12/1a	32,700	700	35,500	1140	51°22′	39°2′
135	Kostenki 14/ii	28,580	420	31,800	993	51°22′	39°2′
139	Kostenki 14/iii	30,080	590	32,900	1076	51°22′	39°2′
141	Kostenki 15	25,700	250	29,000	934	51°22′	39°2′
145	Kostenki 16	28,200	500	31,400	1030	51°22′	39°2′
155	Kostenki 1/5	37,900	2800	40,200	2941	51°22′	39°2′
159	Kostenki 12/iii	36,280	360	38,900	969	51°22′	39°2′
161	Kostenki 14/iv	27,710	410	31,200	989	51°22′	39°2′
164	Kostenki 14/iva	33,280	660	36,100	1116	51°22′	39°2′
167	Kostenki 17	36,780	1700	39,500	1924	51°22′	39°2′
168	Gagarino	21,800	300	25,000	949	52°42′	38°54′
179–194, 196	Avdeevo	20,721		24,100	900	51°44′	36°3′
198	Peny 1	21,600	350	24,800	966	51°2′	35°50′
222	Yudinovo	14,870	150	16,900	912	52°40′	33°14′
230	Yeliseevichi	15,600	1350	17,700	1622	53°13′	33°44′
236	Suponevo	13,920	140	15,700	714	53°11′	34°23′
241	Timonovka	14,530	120	16,300	908	53°11′	34°22′
245	Pushkari 1	20,600	1300	23,800	1581	52°11′	33°17′
247	Pogon	18,690	770	21,800	1184	52°11′	33°17′
248	Novg. Sev.	19,800	350	23,000	966	51°59′	33°17′
249	Chulatovo	14,700	250	16,000	743	51°51′	33°7′
255	Khotylevo 2	23,300	300	26,500	949	53°12′	34°19′
260	Berdyzh	15,100	250	17,200	934	52°50′	30°58′
263	Yurevichi	26,470	420	29,000	993	51°57′	29°33′
265	Sevsk	13,950	70	15,700	703	52°9′	34°27′
266–273, 279	Mezhirichi	14,057		15,800	360	49°43′	31°25′
280	Dobranichevka	12,700	200	14,200	728	50°10′	31°44′
283	Mezin	27,500	800	32,000	1204	51°42′	33°9′
289	Goncy	38,500	1000	41,000	1345	48°8′	23°4′
293	Kirillovskaya	14,350	190	16,050	725	49°59′	33°0′
294	Radomyshl	19,200	250	22,500	934	50°22′	30°32′
298	Korolevo 1a	19,000	300	22,200	949	50°32′	29°14′
299	Korolevo II	25,700	400	29,200	985	48°8′	23°4′
329	Amvrosievka	18,700	220	21,900	926	47°30′	38°0′
333	Muralovka	19,630	200	22,800	922	47°16′	38°40′
340	Anetovka	18,040	150	21,300	912	47°38′	31°6′
345	Sagaidak	20,300	200	23,500	922	47°41′	32°21′
351	Molodova 5-II	11,900	230	23,100	929	48°31′	26°10′
352	Molodova 5-III	13,370	540	15,000	884	48°31′	26°10′
353	Molodova 5-IV	17,100	1400	20,100	1664	48°31′	26°10′
355	Molodova 5-VI	16,750	250	19,600	934	48°31′	26°10′
360	Molodova 5-IX	29,650	1320	32,700	1598	48°31′	26°10′
368	Korman' 4-V	18,000	400	20,900	985	48°34′	27°14′
370	Korman' 4-VII	24,500	500	28,800	1030	48°34′	27°14′
378	Kosaucy II	17,230	140	20,100	911	48°13′	28°17′
381	Kosaucy 1/2b	18,200	500	21,300	1030	48°13′	28°17′
390	Kosaucy 3/4	17,100	250	20,000	934	48°13′	28°17′
392	Kosaucy 4	17,950	100	21,000	906	48°13′	28°17′

Table 5. Continued

No.	Site	Age [years BP]	$\sigma^{(0)}$ [years]	Age [years BP]	Δ [years]	*X*	*Y*
395	Kosaucy 5/6	19,200	130	22,400	909	48°13′	28°17′
398	Kosaucy 9	19,400	100	22,600	906	48°13′	28°17′
408	Brynzeni	26,600	370	30,000	973	48°6′	27°7′
426	Sungir'	25,500	200	29,000	922	56°10′	40°29′
443	Zaraisk	22,300	300	25,600	949	54°45′	38°52′
455	Talicky	18,700	200	21,800	922	58°16′	57°27′
457	Kapovaya Cave	13,930	300	15,600	762	53°26′	57°45′
465	Ignat'evskaya	14,038	192	15,700	726	54°47′	57°35′
495	Byzovaya	25,740	500	29,200	1030	65°1′	57°24′
499	Bear Cave	17,960	200	21,100	922	62°2′	59°16′

Notes: Column 1: the site number according to Sinitsyn *et al.* (1987); Column 2: site name; Column 3: uncalibrated radiocarbon age; Column 3: the age measurement error; Column 4: the calibrated radiocarbon age; Column 5: the total uncertainty of the calibrated age (i.e., the confidence interval for the dates obtained from statistical analysis or the total error including the calibration error for the other data); Columns 6 and 7: the geographical coordinates of the site: northern latitude (*X*) and eastern longitude (*Y*).

additionally characterized by the relative magnitudes of $X^2(T_0)$ and $\chi^{22}_{N \pm k}(p)$; these are given at the bottom of each table.

The confidence interval Δ is invariably smaller than the standard deviation of the subsample dates, despite the fact that Δ corresponds to two standard deviations of *T*. Thus, the above procedure leads to a significant improvement in the accuracy of radiocarbon dating.

Histograms of the dates considered are shown in Figures 2–5. The histograms of the larger samples (Figures 2 and 4) confirm a roughly Gaussian nature of the data scatter. The widths of the histograms exceeds significantly the accuracy Δ of our age estimate T_0; however, the sample age T_0 differs only slightly from the sample mean because the errors of individual dates, σ_i, do not vary much except for a few cases. Therefore, the identification of the mean age of a contemporaneous subsample with its true age would not be unreasonable for large samples with uniform errors (albeit the selection of the contemporaneous subsample requires additional arguments of either statistical or archaeological nature), but the standard deviation of the dates in the subsample strongly underestimates the accuracy of T_0. It should be also stressed that the mean age of a full sample (without discarding deviating datings as described above) can differ from the true age of the sample strongly and systematically.

Kostenki 1/1

The first two dating samples considered here belong to the Kostenki–Borshevo group, a unique cluster of 25 UP sites, systematically studied by Russian archaeologists since 1879 (Praslov & Rogachev, 1982). The site of Kostenki 1, like all UP sites in the Kostenki area, is located on the slope of the elevated right bank of the River Don. In the late 1940s Rogachev has established a complex stratigraphy of the site which comprised five UP levels separated by the sterile loam.

The upper UP level (Level 1) included four "dwelling assemblages", each including several dwellings and peripheral storage pits. The structures discussed in this section were found within the deposits of the Level 1 of the Kostenki 1 site, discovered in 1879. This level includes at least four structures each consisting of several dwellings made of mammoth bones with hearths inside (Praslov & Rogachev, 1982: 43–47).

We restrict our analysis to the Structure No. 2 shown in Figure 1, for which 42 radiocarbon measurements are available, with stratigraphic and planigraphic positions precisely documented for 35 of them (Sinitsyn *et al.*, 1997; 31–33). We have also added a recent measurement published by Praslov & Sulerzhitskii (1999) and labelled 18a in Table 1.

Two presumably contemporaneous groups of objects can be isolated, each belonging to a single dwelling. Five measurements are available for the dwelling A and the same number of measurements have been published for the dwelling K, shown boldfaced in Table 1 and indicated on the margin of Figure 1). Both structures were in use over a limited period of time (shorter than 100 years—see arguments above), and, consequently, the corresponding series of radiocarbon measurements characterize a momentary event in the sense of radiocarbon dating.

The empirical dispersion is $\sigma_0 \approx 862$ years for the dwelling A and 1121 years for the dwelling K; the mean ages for them are $\tilde{T} = 25{,}952$ and 26,134 years BP, respectively. The larger of these two values was accepted as a conservative estimate of σ_0, and then the contemporaneity of the objects belonging to the Structure No. 2 was tested using the criterion (4). Results of these calculations shown in Table 1 confirm that the criterion is well satisfied for the whole data set

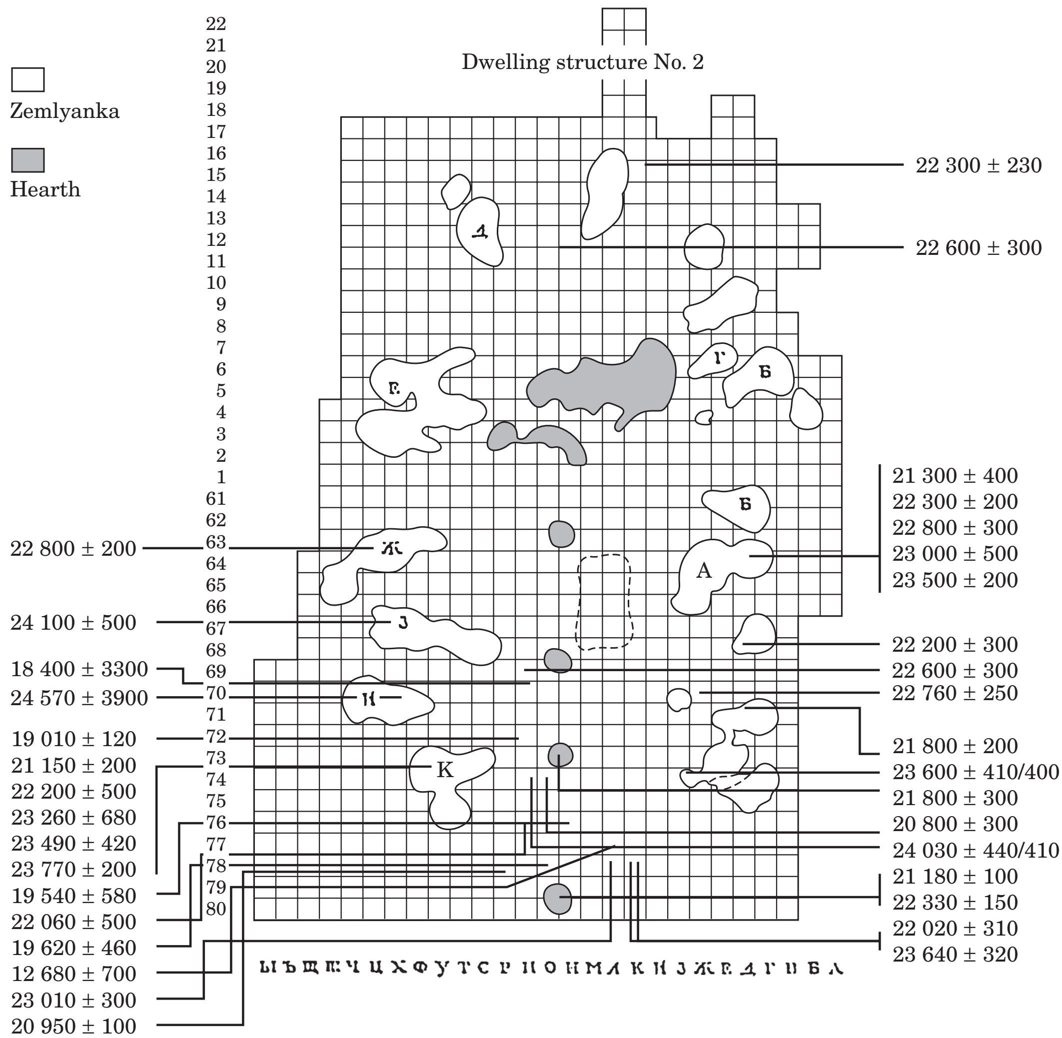

Figure 1. Plan of the dwelling structure No. 2 of the Kostenki 1 site, Level 1 (from Sinitsyn *et al.*, 1997). The precise location of the dated samples is indicated, with the dates given on the margin. The dates from the dwellings A and K have been used to estimate the empirical dispersion for this site.

used. The resulting calibrated age of the contemporaneous sample is

$$T = 25{,}300 \pm 900 \text{ years BP}. \tag{11}$$

A histogram of the occurrence rate of a given date in the contemporaneous sample is shown in Figure 2.

The resulting value of T_0 differs insignificantly from the average of the dates in the contemporaneous subsample, but the confidence interval, 900 years, is significantly smaller than the standard deviation of the calibrated dates in the subsample, 1600 years (we stress that the confidence interval corresponds to two standard deviations since the confidence level chosen is 95%).

Hence we may conclude that all of the radiocarbon measurements obtained for the Structure No. 2 form a homogeneous subsample and thus may be considered as a single date given by equation (11). In other words,

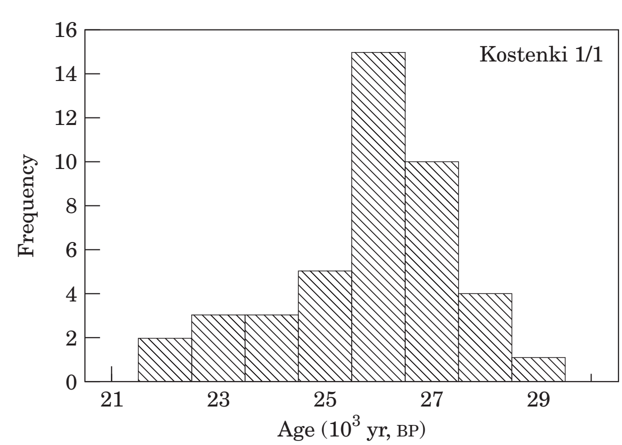

Figure 2. The rate of occurrence of radiocarbon dates in the contemporaneous subsample of the Kostenki 1/1 site. The bin width is 1000 years.

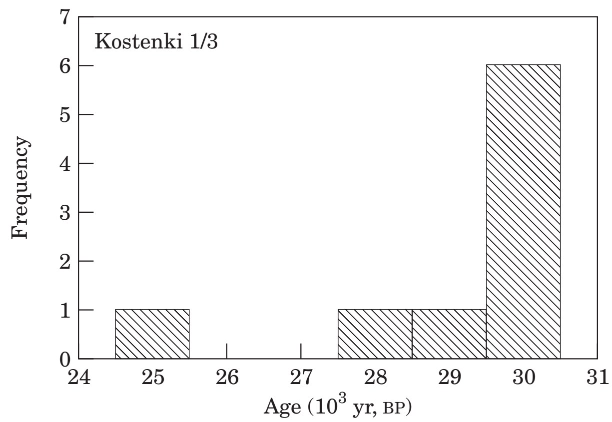

Figure 3. The rate of occurrence of radiocarbon dates in the contemporaneous subsample of the Kostenki 1/3 site binned with the 1000 years interval.

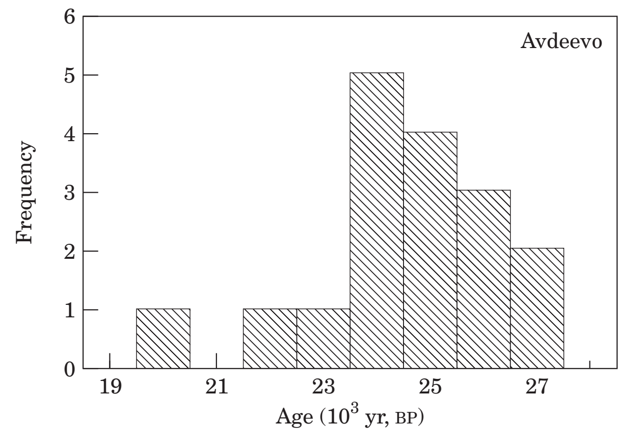

Figure 4. The rate of occurrence of radiocarbon dates in the contemporaneous subsample of the Avdeevo site. The bin width is 1000 years.

the existence of this whole structure was a momentary event within the accuracy of radiocarbon dating.

Kostenki 1/3

The Level 3 of the Kostenki 1 site is found at a considerable depth below the Level 1. The fact that the excavated structures of the Level 3 were found directly beneath those of the Level 1 and reported in the same grid system, allowed us to determine the stratigraphic and planigraphic position of each dated object. We assumed that samples of charcoal and bone coal collected from a single hearth in the grid D-72 (four samples, Nos 103–106) are coeval. The value of empirical uncertainty σ_0 for them is 572 years, and $T = 28{,}788$ years BP. We note that here the number of the measurements, $M = 4$, may be too small to allow a reliable estimation of σ_0. Indeed, in most cases the calculated empirical dispersion σ_0 turns out to be significantly smaller than the reported measurement uncertainly $\sigma_i^{(0)}$. The results of testing the temporal homogeneity of the sample are shown in Table 2. The measurement No. 102 has been discarded as no error has been provided for it in the original publication.

The statistical test has proved that the measurements No. 101, and 103–110 and 113 form a temporally homogenous subsample and thus may be considered as a single date,

$$T = 28{,}900 \pm 1000 \text{ years BP}. \qquad (12)$$

A histogram of the occurrence rate of a given date in the contemporaneous subsample is shown in Figure 3. For comparison, the average age of the contemporaneous subsample is 29,800 BP and its standard deviation is about 4200 years. The most probable date T_0 given in equation (12) somewhat differs from the average, and the estimated confidence interval of T_0, 1000 years, is about four times smaller than even one standard deviation of the dates in the contemporaneous subsample.

On the other hand, a cluster of three dates (Nos 111–113) in excess of 35 ka BP may indicate the presence of an older structure, but their small number precludes any further statistical analysis. Stratigraphic position is unknown for all three samples. The last of the three measurements, No. 113, fits the contemporaneous subsample because of its large error.

Avdeevo

The site is located on a hill within the flood-plain of the River Seim, 40 km west of the city of Kursk in Central Russia. The excavated area includes a "dwellings assemblage" with several dwellings of the same type as those found at Kostenki 1, Level 1 (Rogachev & Anikovich, 1984: 193). Three samples (No. 186, 187 and 192) originating from a single object (Hearth 6) were considered coeval, and for them the empirical uncertainty was found to be $\sigma_0 \approx 1200$ years (with $\tilde{T} = 24{,}400$ years BP) which is larger than most of the measurement uncertainties shown in Table 3. Although the number of measurements on which the estimate of σ_0 is based is rather small, we applied this value to the whole sample and then the criterion (4) was tested. The results are shown in Table 3. The measurements Nos 179–194 and 196 can be considered as a single date,

$$T = 24{,}100 \pm 900 \text{ years BP}.$$

A histogram of the occurrence rate of a given date in the contemporaneous subsample is shown in Figure 4. The average age in the contemporaneous subsample is 24,000 years BP, and its standard deviation is 1700 years.

The discarded measurements, Nos 176–178, are all apparently younger than the retained data. The samples No. 176 and 177 have no stratigraphic position published, while No. 178 was obtained in old

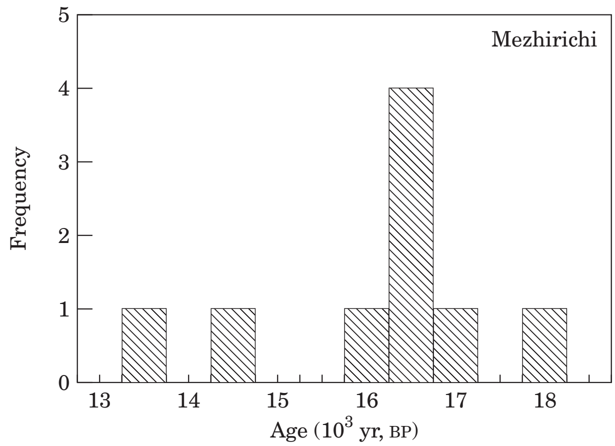

Figure 5. The rate of occurrence of radiocarbon dates in the contemporaneous subsample of the Mezhirichi site. The bin width is 500 years.

excavations of 1948. The measurement No. 195 was discarded because it represents just another determination of age of the object No. 194 with a different method and deviates significantly from all other data of the Avdeevo group.

Mezhirichi

The site is located on the right bank of the River Dnieper, near the town of Kaniv. The excavations yielded remains of at least four complex structures made of regularly patterned mammoth bones.

The empirical uncertainty obtained for three samples from the Structure 3, Nos 266, 267 and 271, is $\sigma_0 \approx 250$ years, with $\tilde{T} = 16{,}300$ BP. In this case the main contribution to σ_i is due to the calibration error and the published instrumental uncertainty $\sigma_i^{(0)}$ as the latter most often exceeds σ_0 (see Table 4). The conclusion is that the measurements Nos 266–273 and 279 can be coeval with

$$T = 15{,}800 \pm 360 \text{ BP}.$$

A histogram of the occurrence rate of a given date in the contemporaneous subsample is shown in Figure 5. The mean date in the contemporaneous sub sample is 15,800 BP, and its standard deviation is 1300 years. We note that the dates reported by the Kiev laboratory (No. 274–278) show a systematically larger age, supposedly due to a systematic instrumental error, and all them have been rejected by the statistical testing.

Methodological implications

Based on the experience reported above, we can recommend several simple methodological criteria which could facilitate the analysis and interpretation of large series of radiocarbon measurements of archaeological sites.

Precise stratigraphic and planigraphic positioning of the objects is very important for the reliable age estimation, since the identification of definitely contemporaneous samples is essential for the analysis of this kind. It is especially important to isolate samples originating from an object that real lifetime is as short as possible (e.g., a single hearth or a single structural element of a dwelling) as they can provide information about the true accuracy of the datings. Whenever possible, datings with precise stratigraphic characteristics should be used.

Inter-laboratory cross-dating of samples is equally important as it allows to eliminate (or at least to detect) systematic instrumental errors. In most cases the date list of UP sites discussed here shows no significant discrepancies between the dates obtained in different laboratories. No significant discrepancies in the dates obtained for various organic materials have been identified in our analysis, although such differences have been discussed by other authors (see, e.g., Kuzmin & Tankersley, 1996).

If the radiocarbon ages of the same sample obtained in different laboratories are apparently contradictory, they should be rejected as potentially misleading unless one of the measurements can be deemed to be more reliable, e.g., as being obtained using a more reliable measurement techniques. This rule equally applies if different methods yield conflicting results.

Discussion

Table 5 presents a data set of radiocarbon age measurements for UP sites in East European Plain compiled using the criteria discussed above. For each dating, we provide the sample number (according to the data list of Sinitsyn *et al*., 1997). The sites for which statistical age determinations are available from the analysis section have the corresponding range of numbers in Column 1. The remaining data sets are too small to warrant statistical analysis. Column 2 gives the site name, and the geographical latitude and longitude of the site are shown in Columns 7 and 8. The uncalibrated radiocarbon age and its measurement error are shown in Columns 3 and 4, respectively, whereas Columns 5 and 6 give the calibrated age and the total uncertainty (including the calibration error), as given by equation (10) for single measurements and equation (7) for statistically interpreted samples. Sites included into Table 5 can be found in the map shown in Figure 7.

Figure 6 shows the number of radiocarbon-dated sites per millennium from Table 5. We also show, with a solid line, a composite record of oxygen isotope variations derived for 17 sediment cores from the Atlantic Ocean (Imbrie *et al*., 1990), an indicator of the ocean surface temperature: the removal of isotopically light water during the glacial period leads to an increase in the $^{18}O/^{16}O$ ratio (Bradley, 1999), so the

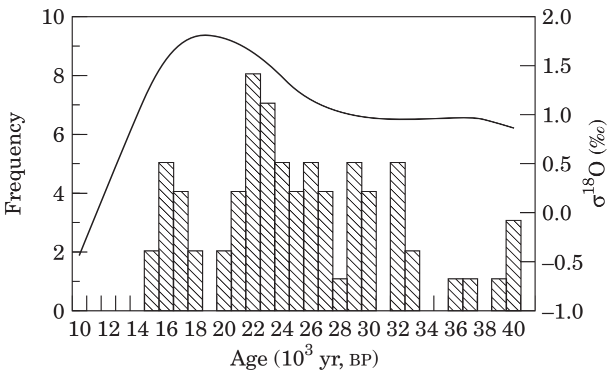

Figure 6. Histogram: the rate of occurrence of radiocarbon dates (per millennium) in the screened sample of radiocarbon dates for UP sites of the East European Plain as given in Table 5. Solid line shows the ^{18}O deviation (Imbrie *et al.*, 1990): larger $\delta^{18}O$ values indicate colder climate.

colder is the climate, the larger is the excess in ^{18}O, denoted by $\delta^{18}O$.

The period discussed here corresponds to the Oxygen Isotope Stages (OIS) 3 and 2, or the Last Ice Age, an epoch of considerable fluctuations in temperature, sea-level and ice volume. The dates for all the UP sites cluster in three main age intervals, 41–36 ka BP, 33–20 ka BP (the main maximum with a peak at 22 ka BP), and 18–15 ka BP.

The cluster of radiocarbon dates in the range of 41–36 ka BP marks the incipient spread of the UP in East European Plain; this period corresponds to the OIS 3, or the Middle Wurm, which was a period of dry and cold climate in Western Europe with several short temperate intervals (Turon, 1984; Guiot *et al.*, 1989). In North-Western Russia, this was a prolonged, iceless, "mega-interstadial" period (Zarrina *et al.*, 1989). Several milder episodes have been identified within this period, with one of them, "Grazhdanski Prospect", attributed to 43·7–38·7 ka BP (Arslanov, 1992).

Pollen analysis of early UP sites in the Kostenki area (Spiridonova, 1991) indicates a variable environment with common occurrence of pine forests. As the climate grew colder, spruce forests became increasingly dominant and wider areas were taken up by cold-resistant "periglacial" grassland. The wild horse (*Equus latipes*, V. Gromova) was the principal hunting prey at the early Kostenki sites. Its bones comprise 35–70% of the total faunal assemblage, other contributors being the mammoth (3–4%) and reindeer (1–2%) (Praslov & Rogachev, 1982).

Those early UP sites belong to at least three cultural traditions: Streletskian, Aurignacian, and "Protogravettian" (Sinitsyn *et al.*, 1997: 42). The Streletskian tradition has initially been identified at several sites in the Kostenki area. Similar industries have been found later on the Severski Donetsk River in the Ukraine, in Central Russia (Sungir') and also on the Kama River in the Urals (Bradley, Anikovich & Giria, 1995). The inventories of all these sites include typical Mousterian side-scrapers and points (the triangular bifacial points with concave basis being particularly common). These archaic implements were found together with typical Upper Palaeolithic tools.

Similar cultural phenomena have been identified in various parts of Europe: Chatelperronian in France, Uluzzian in Italy and Szeletian in Central Europe. The lithic inventories in all these cultures combined an advanced Upper Palaeolithic technology with the elements apparently inherited from the Mousterian tradition. Several authors, notably Mellars (1998, 1999), consider these industries as having being manufactured by the latest Neandertal populations that plausibly coexisted with early groups of anatomically modern humans over a prolonged period of time (42–30 ka BP).

The Aurignacian industries were fairly uniformly spread throughout Europe and featured a fully developed Upper Palaeolithic core-and-blade technique; they are usually considered as belonging to anatomically modern humans. This was well documented in several cases, e.g., Layer 11 at the Bacho Kiro Cave in Bulgaria and Mladec Cave in Moravia (Kozłowski, 1998).

The frequency of radiocarbon-dated UP sites in East European Plain reached its maximum during the OIS 2, at 33–20 ka BP, with a peak at *c.* 22 ka BP. (The frequency exhibits noticeable fluctuations within this period, but their assessment needs more data and further analysis.) This period includes the Last Glacial Maximum (LGM) and corresponds to the coldest climatic conditions reflected in the increased values of $\delta^{18}O$ (see Figure 6).

Earlier studies based on the faunal record indicated that polar conditions prevailed throughout the North Atlantic from *c.* 35 to 15 ka BP (Bradley, 1999: 228). General circulation models (Bard, 1999) estimate the period of the LGM as 24–18 ka BP. The average tropical LGM cooling estimated by Bard (1999) was about 2·4°C on oceans and 4·6°C on continents. The cooling at higher latitudes can be expected to be even stronger.

The region of the central East European Plain, where the sites 33–20 ka old are located, was a periglacial zone with an intense accumulation of loess (see Figure 7). These sites are usually located on elevated, well-drained terraces of river valleys (Gribchenko & Kurenkova, 1997). In several cases the sites were strongly affected by the permafrost.

Pollen evidence (Spiridonova, 1991) indicates treeless landscape: the periglacial grassland with rare cold-resistant shrubs restricted to the deep valleys and ravines.

The faunal remains in Kostenki area at this stage were dominated by cold-resistant animals, the mammoth (60%), reindeer (2%) and polar fox (7%) (Praslov & Rogachev, 1982). At the same time, the sites spread further south, into the Pontic steppe. These sites (Amvrosievka, Anetovka, Muralovka and Sagaidak)

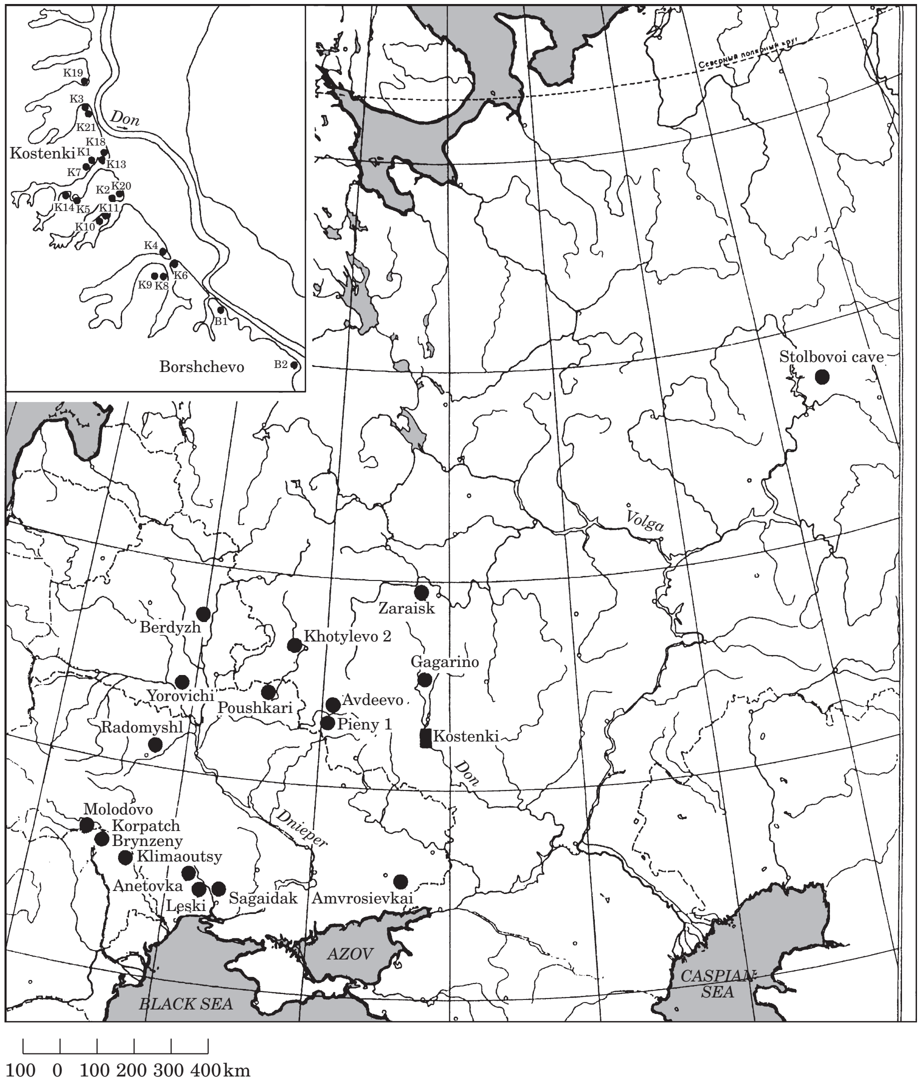

Figure 7. The map showing the location of the UP sites in East European Plain in the range 32–20 ka BP presented in Table 5, Figure 6. Insert: the map of the Kostenki area. (From Sinitsyn *et al*., 1997.)

were predominantly bison-hunting camps, yet the hunting prey included also the wild horse, antelope saiga and reindeer (Stanko, Grigor'eva & Shvaiko, 1989).

All the sites belonging to this period are often collectively labelled as the "Eastern Gravettian". Based on peculiarities in the dwelling structures and specific features in the lithic inventory such as the "shouldered points", Russian archaeologists have identified the "Kostenki–Avdeevo" Culture, which included, apart of the eponym sites, Khotylevo 2 and Zaraisk (Sinitsyn *et al*., 1997). Grigor'ev (1993) has recognized considerable similarities between these sites and several sites in Central Europe, such as Willendorf, Predmosti and Dolni Vestonici; he argued that all of them form a "cultural entity". Grigor'ev has also remarked that, judging from the radiocarbon dates, the sites in Central Europe were by "some 2000 years" older than those in the east. Motivated by these observations, both Grigor'ev (1993) and Soffer (1993) suggest that a gradual outflow of the population occurred at that time from the Central Europe in the eastern direction in the form of "several population incursions separated in time".

The most recent peak in the UP site frequency occurred at 18–15 ka BP. This period corresponds to the recession of the ice sheets caused by the rapid increase in temperature and the summer insolation (Bradley, 1999: 496). A clear maximum in the density of the UP sites occurred at 16 ka BP. It may be significant that this peak coincides with a prominent glacial readvance recorded both in the North-Western Russia (the Vepsy stage at 17–15 ka BP; Arslanov, 1992) and on the British Isles (McCabe & Clark, 1999).

The sites belonging to this later stage show a different spatial pattern: they all lie along the major waterways. Numerous sites were found in the basin of the Dnieper and its tributaries, the Desna and Sudost', and also in the basin of the Dniester, the Don (Kostenki) and on the littoral of the Sea of Azov. This stage features a cultural fragmentation, where each cultural unit is restricted to its river basin: the Prut-Dniestrian, Upper Dnieprian, Uralian, etc. (Sinitsyn *et al*., 1997). The UP sites completely disappeared from the central area of East European Plain by 15 ka BP, at the beginning of the warm Allerød Interstadial.

Conclusions

The precision of radiocarbon dating of a stratigraphically reliable archaeological site can be considerably improved if a statistically significant number of date measurements is available for that site. Then statistical analysis can identify a contemporaneous set of datings and its most probable age. The confidence interval of the age estimate is close to the expected lifetime of a dwelling structure.

At least three stages can be distinguished in the early colonization of East European Plain by anatomically modern humans:

The initial stage, 41–36 ka BP, which corresponds to a comparatively mild interval of the OIS 3 when the entire continent of Europe was uniformly populated by a few culturally distinct groups.

The OIS 2, which included the LGM, saw a marked increase in the population density in East European Plain in the period of 33–20 ka BP (with a peak at about 22 ka BP). At the same time, the population density in Central and Northern Europe markedly decreased with several areas, such as southern Germany and Britain, almost totally depopulated (Houseley *et al*., 1997). Only two areas formed refugia sustaining considerable population densities, Franco-Cantabria in the west (Straus, 1999) and the periglacial Eastern Europe in the east (this work). This leads to a picture of an outflow of the population from the Central and Western Europe both to the west and to the east.

The final stage in the colonization of East European Plain occurred during the period of glacial recession, 20–15 ka BP. Culturally distinct UP groups spread at that time in East European Plain along major river valleys. Radiocarbon dating indicates a significant increase in the population density in East European Plain during a cool stage of glacial readvance, and their total disappearance at 15 ka BP.

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References

Arslanov, Kh. A. (1992). Geochronological scale of the Late Pleistocene of the Russian Plain. In (V. E. Murzaeva, J.-M. K. Punning & O. A. Chichagova, Eds) *Geochronology of the Quaternary Period*. Moscow: Nauka, pp. 10–19 (in Russian).

Bard, E. (1999). Ice Age temperatures and Geochemistry. *Science* **284,** 1133–1134.

Beaulieu, de J.-L. & Reille, M. (1984). A long Upper Pleistocene pollen record from Les Echets, near Lyon, France. *Boreas* **13,** 111–132.

Bradley, B., Anikovich, M. & Giria, E. (1995). Early Upper Palaeolithic in the Russian Plain: Streletskyan flaked stone artefacts and technology. *Antiquity* **69,** 989–998.

Bradley, R. S. (1999). *Paleoclimatology. Reconstructing Climate of the Quaternary* (2nd edition). San Diego: Academic Press.

Cramér, H. (1946). *Mathematical Methods of Statistics*. Princeton: Princeton Univ. Press.

Efimenko, P. P. (1958). *Kostenki I*. Leningrad: Nauka Publishers (in Russian).

Gribchenko, Yu. N. & Kurenkova, E. I. (1997). Environment and Late Palaeolithic human settlement in Eastern Europe. In (J. Chapman & P. Dolukhanov, Eds) *Landscape in Flux. Central and Eastern Europe in Antiquity*. Oxford: Oxbow, pp. 241–252.

Giot, J., Pans, A., Beaulieu, de J.-L. & Reiile, M. (1989). A 140,000-year continental climate reconstruction from two European pollen records. *Nature* **338,** 309–313.

Grigor'ev, G. P. (1967). A new reconstruction of the above-ground dwelling of Kostenki. *Current Anthropology* **8,** 344–349.

Grigor'ev, G. P. (1993). The Kostenki-Avdeevo archaeological culture and the Willendorf–Pavlov–Kostenki–Avdeevo cultural unity. In (O. Soffer & N. D. Praslov, Eds) *From Kostenki to Clovis. Upper Palaeolithic–Palaeo-Indian Adaptations*. New York: Plenum Press, pp. 51–66.

Housley, R. A., Gamble, C. S., Street, M. & Pettitt, P. (1997). Radiocarbon evidence for the late glacial human colonisation of Northern Europe. *Proceedings of the Prehistoric Society* **63,** 25–54.

Imbrie, J., *et al.* (1990). SPECMAP Archive No. 1 IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series No. 90-001. NOAA/NGDC Paleoclimatology Program, Boulder CO, U.S.A. (ftp://ftp.ngdc.noaa.gov/paleo/pale-ocean/specmap/specmap1/specmap.017).

Kozłowski, J. K. (1998). The Middle and early Upper Palaeolithic around the Black Sea. In (T. Akazawa, K. Aoki & O. Bar-Yosef, Eds) *Neandertals and Modern Humans in Western Asia*. London: Plenum Press, pp. 461–482.

Kutschera, W. (1993). Accelerator Mass Spectrometry. Counting Atoms Rather Than Decays. *Nuclear Physics News* **3,** 15–21.

Kuzmin, Y. V. & Tankersley, K. B. (1996). The colonisation of Eastern Siberia: an evaluation of the Palaeolithic age radiocarbon dates. *Journal of Archaeological Science* **23,** 577–585.

Leonova, N. B. (1993). Criteria for estimating the duration of occupation at Palaeolithic sites: an example from Kamennaia

Balka. In (O. Soffer & N. D. Praslov, Eds) *From Kostenki to Clovis. Upper Palaeolithic–Palaeo-Indian Adaptations*. London: Plenum Press, pp. 149–158.

Lisitsyn, N. F. & Svezhentsev, Y. S. (1997). Radiocarbon chronology of Northern Asia. In (A. A. Sinitsyn & N. D. Praslov, Eds) *Radiocarbon Chronology for the Palaeolithic in Eastern Europe and Northern Asia. Problems and Perspectives*. St Petersburg: IIMK RAN, pp. 67–108 (in Russian).

McCabe, A. M. & Clark, P. U. (1998). Ice-sheet variability around the North Atlantic Ocean during the last deglaciation. *Nature* **392,** 373–377.

Mellars, P. (1998). The impact of climatic changes on the demography of late Neandertal and early anatomically modern population in Europe. In (T. Akazawa, K. Aoki & O. Bar-Yosef, Eds) *Neandertals and Modern Humans in Western Asia*. London: Plenum Press, pp. 493–508.

Mellars, P. (1999). The Neandertal problem continued. *Current Anthropology* **40,** 341–358.

Praslov, N. D. & Rogachev, A. N. (1982). *Palaeolithic of the Kostenki–Borshevo Region on the River Don, 1879–1979*. Leningrad: Nauka Publishers (in Russian).

Praslov, N. D. & Sulerzhitskii, L. D. (1999). New data on the chronology of Palaeolithic sites at Kostenki on the Don. *Doklady Ross. Akad. Nauk* **365,** 236–240.

Rogachev, A. N. & Anikovich, M. V. (1984). The late Palaeolithic in the Russian Plain. In (P. I. Boriskovsky, Ed.) *Paleolitic in the USSR*. Moscow: Nauka Publishers, pp. 162–271 (in Russian).

Sinitsyn, A. A., Praslow, N. D., Svezhentsev, Y. S. & Sulerzhitskii, L. D. (1997). Radiocarbon chronology for the Upper Palaeolithic in Eastern Europe. In (A. A. Sinitsyn & N. D. Praslov, Eds) *Radiocarbon Chronology for the Palaeolithic in Eastern Europe and Northern Asia. Problems and Perspectives*. St Petersburg: IIMK RAN, pp. 21–66 (in Russian).

Soffer, O. (1985). *The Upper Palaeolithic of the Central Russian Plain*. Orlando, FL: Academic Press.

Soffer, O. (1993). Upper Palaeolithic adaptations in Central and Eastern Europe and man-mammoth interactions. In (O. Soffer & N. D. Praslov, Eds) *From Kostenki to Clovis. Upper Palaeolithic–Palaeo-Indian Adaptations*. London: Plenum Press, pp. 31–50.

Spiridonova, A. A. (1991). *Evolution of the Vegetation Cover in the Don Basin during the Pleistocene and Holocene*. Moscow: Nauka (in Russian).

Stanko, V. N., Gladkikh, M. I. & Segeda, S. P. (1999). *The History of Primeval Society*. Kyiv: Libid' Publishers (in Ukrainian).

Stanko, V. N., Grigor'eva, G. V. & Shvaiko, T. N. (1989). *The Late Palaeolithic Settlement of Anetovka II*. Kiev: Naukova Dumka (in Russian).

Straus, G. L. (1999). The Upper Palaeolithic settlement of north-central Spain. In (P. M. Vermeersch & J. Renault-Miskovsky, Eds) *European Late Pleistocene, Isotope Stages 2 and 3: Humans, Their Ecology and Human Adaptations*. Liege: Eraul 90, pp. 175–198.

Stuiver, M. & Polach, H. A. (1977). Reporting of ^{14}C data. *Radiocarbon* **19,** 355–363.

Taylor, R. E. (1987). *Radiocarbon Dating: An Archaeological Perspective*. Orlando, FL: Academic Press.

van Andel, T. H. (1998). Middle and Upper Palaeolithic environments and the calibration of ^{14}C dates beyond 10,000 BP. *Antiquity* **72,** 26–33.

van der Plicht, J. (1999). Radiocarbon calibration for the Middle/Upper Palaeolithic: a comment. *Antiquity* **73,** 119–123.

Vinogradov, V. I. & Sokoloff, D. D. (Eds) (1988). *Mathematical Methods in Data Processing of Radiological Dating*. Moscow: Geological Institute of the Academy of Sciences (in Russian).

Zaitseva, G. I., Marsadolov, L. S., Sementsov, A. A., Vasil'ev, S. S., Dergachev, V. A. & Lebedeva, L. M. (1996). Application of mathematical statistics to the correlation of dendrochronological and radiocarbon data (on the materials of elitary barrows in the Sayan–Altai Mountains). In (G. I. Zaitseva, V. A. Dergachev & V. M. Mason, Eds) *Radiocarbon and Archaeology*. St Petersburg: IIMK RAN, pp. 39–48 (in Russian).

Zarrina, E. P., Krasnov, I. I., Malakhovsky, D. B. & Spiridonova, D. B. (1989). Climatic Rhythms of the Late Pleistocene. In (A. A. Velichko, Ed.) *Palaeoclimate and Ice Ages of the Pleistocene*. Moscow: Nauka, pp. 47–58 (in Russian).