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RADIOCARBON TIME SCALE FOR DEPOSITION OF HOLOCENE CALCAREOUS TUFA FROM POLAND AND INDIA (ORISSA)

ANNA PAZDUR[1], RADOSŁAW DOBROWOLSKI[2], TOMASZ DURAKIEWICZ[3], MANMOHAN MOHANTI[4], NATALIA PIOTROWSKA[1] and SRIKANTA DAS[4]

[1]Department of Radioisotopes, Institute of Physics, Silesian University of Technology, Krzywoustego 2, 44-100 Gliwice, Poland
(e-mail: anna.pazdur@radiocarbon.gliwice.pl)
[2]Department of Physical Geography and Palaeogeography, Maria Curie-Skłodowska University, Akademicka 19, 20-033 Lublin, Poland
[3]Mass Spectrometry Laboratory, Maria Curie-Skłodowska University, Plac Marii Curie-Skłodowskiej 1, 20-031 Lublin, Poland;
Los Alamos Laboratory, Condensed Matter and Thermal Physics Group, Los Alamos, Mailstop K764, NM 87545, USA
[4]Department of Geology, Utkal University Bhubaneswar - 751004 (Orissa) India

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Abstract: **^{14}C concentration measurements together with carbon and oxygen stable isotope analysis in calcareous tufa give possibilities for reconstruction of time scale and palaeoclimatic conditions of sedimentary processes. Results of isotope examinations of 2 profiles with organic and tufa sediments from Eastern Poland and 8 calcareous tufa sites from Eastern India (Orissa) are given. A systematic error of ^{14}C conventional age of carbonate fraction of tufa samples as reservoir age (T_R) was estimated. The T_R values of different type of tufa sediment are determined by stream water energy. On the basis of known experimental dependence between T_R and $\delta^{13}C$ for tufas deposited in high, average and low energy water, unknown values of T_R and corrected ^{14}C ages (T_{CCA}) were calculated for samples from India tufa sites. Continuous deposition of organic and carbonate sediments in Polish profiles give the possibility to calculate the approximated T_{CCA} ages on the basis of dependence between T_{CCA} and a sample depth in a profile, and time scale reconstruction of $\delta^{13}C$ and $\delta^{18}O$ changes in carbonate fraction of tufa samples during the whole Holocene.**

1. INTRODUCTION

Tufas are freshwater carbonate deposits, the deposition of which is affected by physico-chemical and/or biochemical processes. Continental carbonate deposits like tufa are now being used for radiocarbon dating (Geyh and Schleicher, 1990; Pazdur, 1988; Pazdur *et al.,* 1988a; Srdoc *et al.,* 1980, 1982 and 1983; Thorpe *et al.,* 1980 and 1981). These deposits are also considered as reliable recorders of palaeoclimatic and environmental changes (Andrews *et al.,* 1994; Pazdur *et al.,* 1988b and Turi *et al.,* 1986).

Results of ^{14}C measurements of tufa from several sites in southern and eastern Poland indicated significant variability of initial ^{14}C activity and its dependence on sedimentological and geochemical processes (Dobrowolski *et al.,* 1999; Pazdur, 1988 and Pazdur *et al.,* 1988a). A number of factors determine the reliability of ^{14}C dates of the tufaceous sediments. Carbon isotopic fractionation during sedimentation processes are concerned with primary factors, which determine the initial ^{14}C concentration in carbonates. Isotopic studies of groundwater give some information about this process. Radiocarbon studies of groundwater have resulted in formulation of different models which estimate initial ^{14}C activity of HCO_3^- ions dissolved in water (Mook, 1976 and Pearson, 1992). However, physicochemical processes involved in precipitation of tufa are complex and numerous environmental factors may influence them (Friedman, 1970; Usdowski *et al.,* 1979 and Pazdur *et al.,* 1988a, b). Direct application of such models in ^{14}C dating of tufa has led to unsatisfactory results.

All investigated calcareous tufa samples collected from different regions and profiles indicate depletion in ^{14}C isotope in the moment of deposition. It causes a systematic error of conventional radiocarbon dates of carbonate fractions, i.e., so called reservoir (or apparent) age.

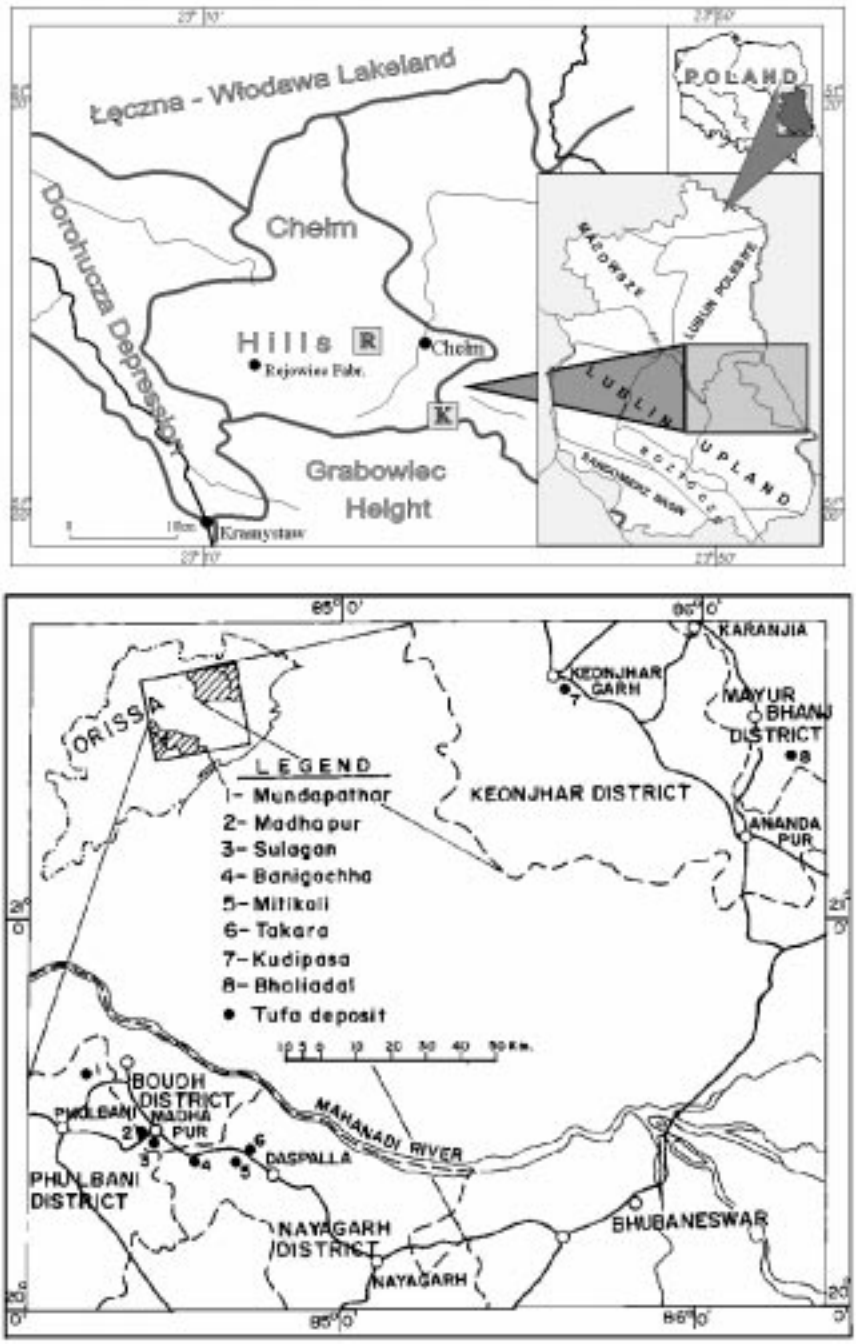

Fig. 1. Location of studied sites with tufa deposits in Eastern India (Orissa State): Phulbani, Boudh, Nayagarh, Keonjhar and Mayurbhanj and in Eastern Poland (Lublin Upland): Krzywice-1(K) and Rudka-2(R).

Conventional ^{14}C age of carbonate sample is "older" than true radiocarbon age. The value of reservoir age has connection with the environment of tufa deposition. In streams with turbulent and fast flow, tufaceous sediments show the highest values of reservoir age, even 4000 years. Deposits of streams with moderate and variable flow show the lowest values of the reservoir age (*ca* 2500-2100 years), while the stagnant water deposits have the lowest values (less than 1000 years).

According to Szulc (1983) and Pazdur and Szulc (1988a) a slightly simplified classification of was done:

- Spring tufa: precipitated in turbulent, high energy water flow (oncoids, stromatolites and moss travertines).
- Tufas (oncoids and moss travertines) and peloidal calcareous muds: precipitated in streams with low or variable water flow.
- Calcareous muds precipitated in shallow, stagnant-water basins in conditions of semilimnic sedimentation.

In the Indian context, tufa deposits (see **Figs 3**, **4** and **5**) are classified as follows (Das and Mohanti, 1997).

- Waterfall tufa (**Fig. 3**): precipitated from turbulent water flow (high energy condition); include stromatolic tufa, phytohermal (moss) tufa, phytoclastic tufa and occasional pisoids.
- Slope tufa (**Fig. 4**): precipitated from moderately agitated water flow conditions; include stromatolitic tufa, phytotermal tufa and phytoclastic tufa.
- Low gradient stream /river channel margin tufa (**Fig. 5**): precipitated from low or variable water flow; include stromatolic tufa and coated pebbles.

None of the deposits indicate shallow or stagnant-water basin conditions.

Redeposition and diagenetic modifications are considered as secondary factors influencing the ^{14}C dates of tufaceous sediments. Post-depositional changes include dissolution and reprecipitation of $CaCO_3$ within the sediment. Cementation of tufaceous sediments leads to contamination of primary carbonates with ^{14}C contained in percolating water. Radiocarbon dating of redeposited and diagenetically modified calcareous tufa yields erroneously high values. Detailed examination of the profile during sampling may help to overcome this type of error.

2. RESERVOIR EFFECT IN ^{14}C DATING OF TUFACEOUS SEDIMENTS

Radiocarbon activity of freshwater carbonate sediment at the moment of precipitation (A_0) is obviously influenced by isotopic composition of carbon compounds dissolved in water.

The conventional radiocarbon age (T_C) of carbonate, determined by the ratio of measured ^{14}C activity (A) in a sample to ^{14}C activity of the contemporary biosphere (A_{OX}), defined as 95% of the activity of NBS oxalic acid standard (Stuiver and Polach, 1977), *i.e.*,

$$T_c = -8033 \times \ln\left(\frac{A}{A_{ox}}\right) \tag{2.1}$$

is greater than the real age of sediments because of depletion of initial ^{14}C activity in precipitated carbonate with respect to biosphere. Difference between T_C and the real age is characterised by so called "reservoir age" T_R (or apparent age T_{APP}; Pazdur, 1988). The value of T_R is related to initial ^{14}C activity of carbonate (A_0) and reservoir dilution factor (q) through the equation

$$T_R = -8033 \times ln\left(\frac{A_o}{A_{ox}}\right) = -8033 \times ln\, q \tag{2.2}$$

The real conventional radiocarbon age T_{CCA} is obviously described by

$$T_{CCA} = T_C - T_R \tag{2.3}$$

The value of reservoir age T_R observed for calcareous tufa, lake marl, lacustrine gyttja and cements is characteristic for depositional environment of carbonate, which includes geographic locality of the karst area, type of vegetation, and type of bedrock as well as it contains information on sources of carbon and its geochemical cycle in environment. Observed T_R values for these sediments range from several hundred to several thousand years and sometimes more (Pazdur, 1988 and 2000 and Pazdur *et al.,* 1995a, b). Speleothems have relatively constant reservoir age determined by stable sedimentation conditions in caves (Hercman, 2000; Holmgren *et al*., 1994 and Pazdur *et al*., 1999).

The scattering of values of T_R observed by various authors could be explained by the dependence of T_R on the bedrock type (which is a source of ^{14}C-free carbon) and the type of sediment. The type of calcareous sediments depends strongly on hydrodynamic conditions of water flow (Szulc, 1983).

Observed values of q in both recent and ancient tufas range from 0.5 to 0.95 (Srdoc *et al.,* 1983; Thorpe *et al.,* 1981; Pazdur 1988; Pazdur *et al.,* 1988a and Pazdur and Pazdur, 1990) and consequently the values of T_R are included in interval from 500 to 5500 yr. They can be of extremely high value *ca* 11 kyr (Pazdur, 1988).

The factors determining the precipitation of freshwater carbonates should be reflected by isotopic composition of carbon ($\delta^{13}C, A_0$) in carbonate samples and should influence the T_R value. The measured values are T_C (see Eq. (2.1)) and some dependence between $\delta^{13}C$ and T_C is expected.

Radiocarbon dating of tufaceous sediments should be associated with detailed sedimentologic studies and carbon stable isotope $\delta^{13}C$ measurements (Pazdur, 1988). Estimating true ages T_{CCA} of individual tufa layers is relatively easy even when few organic horizons can be found in the investigated profile. In such case, measured values of ^{14}C ages of carbonate and organic fractions can be correlated with $\delta^{13}C$ values of tufa carbonate. A constant value of $\delta^{13}C$ in the profile indicates a constant value of apparent age, which can be determined independently by comparing ^{14}C ages of carbonate and associated organic matter or detrital organic matter dispersed in the carbonate, itself. Assuming that the age of organic remnants reflects the actual age of carbonate precipitation, we can define the reservoir age T_R of carbonate

$$T_R = T_C - T_{ORG} \tag{2.4}$$

This value determined for a tufa profile with known values of $\delta^{13}C$ across the profile, can be used for estimation of the real age of tufa horizons on the basis of T_C measurements.

Profiles of tufaceous sediments that do not contain organics, may be characterised by constant value of the reservoir (apparent) age and can be dated with acceptable accuracy. It was found, that constant T_R value in a profile reveals peloidal calcareous muds precipitated from stagnant or low-energy water, and tufas precipitated from turbulent water, which do not exhibit significant correlation of $\delta^{13}C$ and T_C (Pazdur, 1988).

To estimate magnitude of the reservoir age the relation between T_R and $\delta^{13}C$ can be used in the shape of equation characteristic for spring tufa precipitated from higher energy water

$$T_R = (13.50 \pm 3.27) + (0.96 \pm 0.34) \times \delta^{13}C \ [kyr] \tag{2.5}$$

or characteristic for tufas precipitated from average and lower energy water

$$T_R = (4.41 \pm 0.98) + (0.25 \pm 0.11) \times \delta^{13}C \ [kyr]. \tag{2.6}$$

The T_R values may be calculated on the basis of equations (2.5) or (2.6), and in consequence $T_{CCA,}$ using equation (2.3) for each measured pair T_C and $\delta^{13}C$ in tufa samples, may be determined.

3. INVESTIGATED SITES AND SEDIMENTS

Lublin Upland, Eastern Poland

Calcareous tufas and travertines occurring in Poland are formed by precipitation from groundwater circulating through/carbonate rocks of different lithology (limestones, chalks, marls) and stratigraphic position (Devonian, Lower Carboniferous, Jurassic, Cretaceous and Tertiary). Their sites are found mainly in the Southern Poland (Carpathians and Cracow-Wieluń Upland; Szulc, 1983) and Eastern Poland (Lublin Upland; Dobrowolski *et al.,* 1999; see **Fig. 1**). Sites with tufaceous sediments from the Eastern Poland are connected with soligenous mires: carbonate deposition strongly depends on groundwater circulation and structure of the Upper Cretaceous bedrock.

Krzywice-1 and Rudka-2

Carbonate sediments are presented by moss tufas deposited in well oxidised ascending springs, and by calcareous muds formed in shallow, stagnant water basins in conditions of semilimnic sedimentation (Dobrowolski *et al.,* 1999 and 2001; **Fig. 2A**). The thickness of tufa layers in examined profiles varies from ca 0.5 to 40 cm. These unconsolidated carbonate sediments, with no diagenetic changes, were formed as incrustations of hygrophyte plants (*Cyperaceae, Phragmites, Calliergon giganteum* and *Scorpidium scorpioides*). Thickness of organic-carbonate sequence in the Krzywice-1 profile is *ca* 6m and in the Rudka-2 profile - *ca* 4m. Simplified lithology of sediments from both profiles is given in **Fig. 2**.

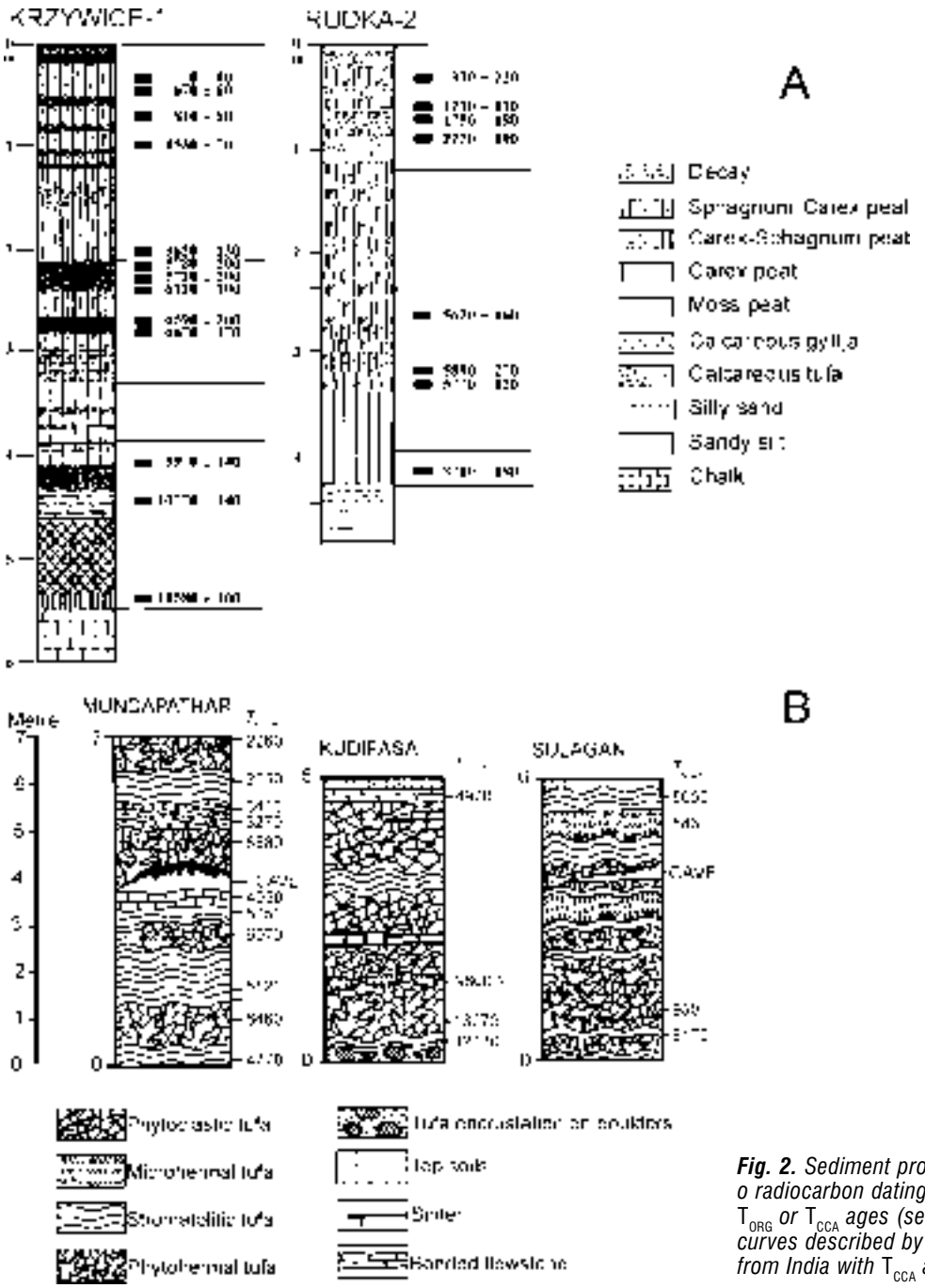

Fig. 2. *Sediment profiles with tufa deposits and results o radiocarbon dating: part A - profiles from Poland with* T_{ORG} *or* T_{CCA} *ages (see* ***Table 1****) used for calculation of curves described by Eqs (5.7) and (5.8); part B - profiles from India with* T_{CCA} *ages of samples (see Table 2).*

Orissa, Eastern India

Several freshwater tufa deposits occur in the tropical setting in Phulbani, Boudh, Nayagarh, Keonjhar and Mayurbhanj districts of Orissa State (**Fig. 1**). The deposits occur as surficial deposits in hilly topography; at sites of waterfalls, where streams have steeper gradients or margins of small river where boulders or bedrock occur. In Phulbani, Boudh and Nayagarh districts the rock types are charnokites, khondalites and granite gneisses belonging to the Easternghat Group. In Keonjhar district, the deposit rests over quartzite, which is overlain by basic lava and tuff of Simlipal Group and underlain by the Singhbhum Granite. The deposits in Mayurbhanj district have been formed at the contact of quartzites of Iron Ore Group and younger dolerite intrusives. The quartzites along with a thin band of ferruginous shale overlie the Singhbhum Granite, which is invaded by numerous dolerite dykes.

The tufa deposits can be broadly classified as stromatolitic tufa, phytohermal tufa and phytoclastic tufa. The cross sections of these different sediments are shown in **Figs** of **3** to **5**. Phytohermal tufas are mostly calcified mosses (Das and Mohanti, 1997). When the mosses are less than 2 cm in size, these tufa are named as microhermal tufa, in which case some pteridophytic plants and algae may be associated. Occasionally, pisoids also occur along with intraclastic deposits. Porous zones show thin inorganic crusts called sinter. Larger cavernous zones show speleothem-like deposits like stalactites and laminated flowstone.

The deposits show variations in the thickness of different tufa facies. Tufa profiles were constructed from quarry faces and stream-cut sections after careful examination of the sequence of tufa facies and associations (**Figs 3**, **4** and **5**). Samples were collected from various layers showing major sedimentary intervals (**Fig. 2B**). Profile samples were collected from three localities (*i.e.*, Mundapathar, Sulagan and Kudipasa). Some number of tufa samples were found in five other localities (Banigochha, Madhapur, Bhaliadal, Mitikoli and Takara; see **Fig. 1**). Organic-rich soils occurring in small pockets were collected from the profiles.

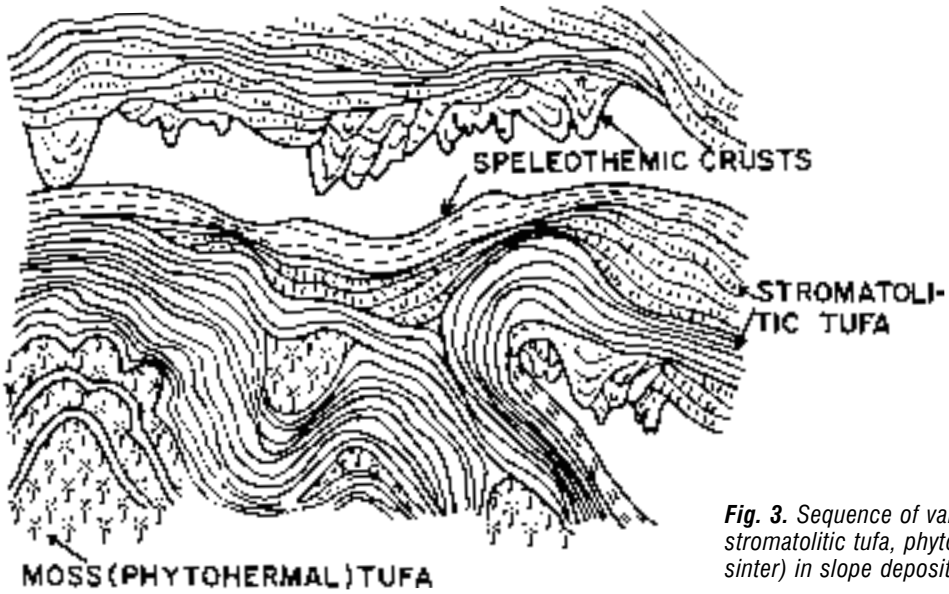

Fig. 3. *Sequence of various tufa facies (encrousted boulders, stromatolitic tufa, phytohermal tufa and phytoclasic tufa with sinter) in slope deposits.*

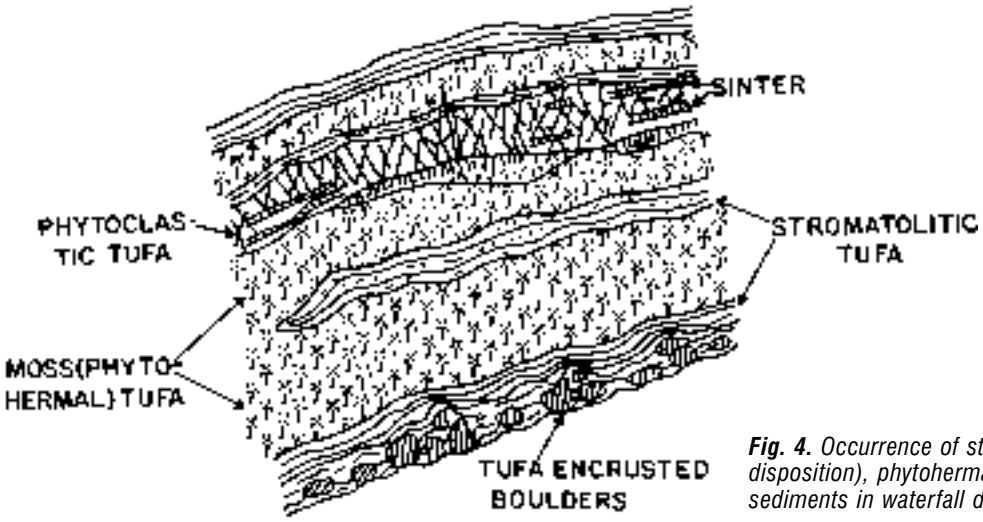

Fig. 4. *Occurrence of stromatolitic tufa (showing varying disposition), phytohermal (moss) tufa and speleothem-like sediments in waterfall deposits.*

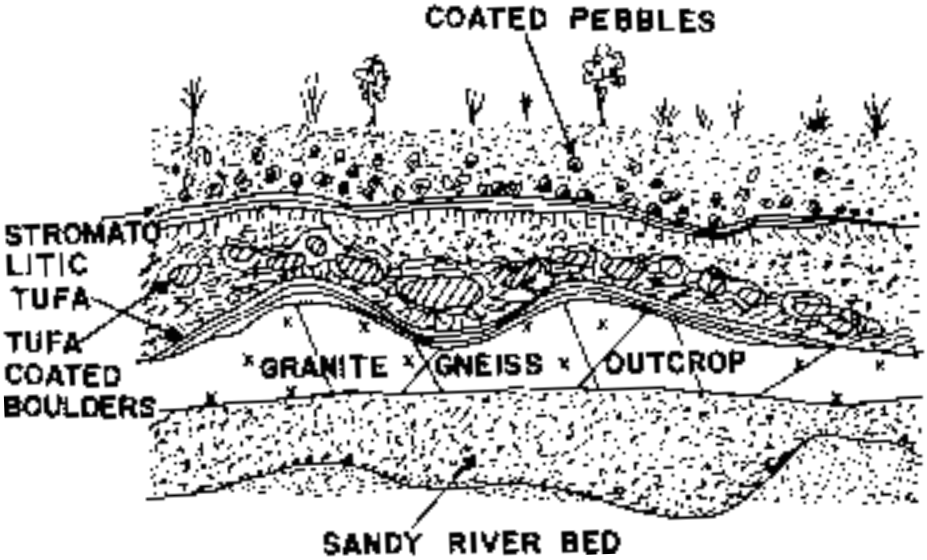

Fig. 5. *River channel margin tufa deposits showing occurrence of tufa-encrusted boulders, stromatolitic tufa and coated pebbles.*

Mundapathar

The deposit is characterized by dominantly stromatolitic and phytohermal (moss) tufa (**Fig. 3**). Above the level of 3.6 m from the bottom (MS-7, **Table 2**), a cavernous zone occurs which shows speleothem-like deposits. Pisoids occur along with intraclastic tufa at the depth 5.5 m (MS-10, **Table 2**) within disrupted crusts of stromatolitic tufa.

Sulagan

The lower parts of the deposit show phytohermal (moss) tufa alternating with thin layers of stromatolitic tufa. At levels of 3.5 m (SS-4) and 5.2 m (SS-6, **Table 2**), microhermal tufas form thick zones. A narrow cave occurs above the level SS-3 showing botryoidal hangings and thin inorganic crusts with ramifying projections. The uppermost part of the deposit shows occurrence of stromatolitic tufa which is partly covered by soil.

Kudipasa

At the lower level of the deposit tufa is found to encrust quartzite boulders. The boulder zone is overlain by a thin layer of stromatolitic tufa, which is overlain by a thick zone of phytohermal (moss) tufa. Microhermal tufa shows pocket-like deposits on the level 1.8 m (KS-3, **Table 2**). In the whole cross section of outcrop the deposits are dominated by very thick zones of phytoclastic deposits. Sinter crusts show plate-like growths within the phytoclastic deposits. The top portion of the deposit shows laminated flowstone, which is covered by soil.

Regional samples

Some number of tufa samples were found in the five localities (Banigochha, Madhapur, Bhaliadal, Mitikoli and Takara; see **Fig. 1**) as single calcareous incrustations in sediments. They are called "regional samples".

The regional samples are stromatolitic tufa. The samples MBS-5 is a modern crust collected from the stream channel where active tufa deposition is observed.

4. RESULTS OF ^{14}C DATING AND $\delta^{13}C$ AND $\delta^{18}O$ MEASUREMENTS

^{14}C dating

All analyzed samples were dated using CO_2-filled proportional counters (Pazdur *et al.*, 2000). Radiocarbon ages T_C or T_{ORG} (**Table 1** and **2**) are the conventional ^{14}C ages of carbonate (T_C) and organic matter (T_{ORG}) normalized to $\delta^{13}C$=-25‰, according to recommendations of Stuiver and Polach (1977). The analysis was carried out at the Gliwice Radiocarbon Laboratory, Silesian University of Technology, Poland.

$\delta^{13}C$ and $\delta^{18}O$ measurements

The measurements of relative stable isotope concentration ^{13}C and ^{18}O in samples from Polish sites were carried out at the Mass Spectrometry Laboratory, Maria Curie-Skłodowska University, Lublin, Poland. The same analysis for samples from India sites was carried out at the Department of Geology, University of California, USA. Measurements were performed using standard mass spectrometry techniques with gaseous CO_2 obtained from chemical reaction of carbonate fraction of tufa samples with concentrated orthophosphoric acid (>103 %). The $\delta^{13}C$ and $\delta^{18}O$ values were expressed relative to the PDB standard (**Tables 2** and **3**).

5. CONVENTIONAL ^{14}C CORRECTED AGE (T_{CCA}) OF TUFACEOUS SEDIMENTS

Krzywice-1 and Rudka-2 sites

Both tufa profiles contain organic matter mixed with carbonate or occurring as separate layers. There are also layers consisting only from carbonate fraction (see **Table 1**). The determination of time scales for sedimentation of carbonates, where possible, was based on ^{14}C dating of organic fraction (T_{ORG}). For layers with no organic fraction, the reservoir age T_R (estimated according to Eq. (2.4)) was assumed the same as for younger (higher) level.

Table 1. *Results of radiocarbon dating of carbonate (T_C) and organic fraction (T_{ORG}), $\delta^{13}C$ measurements and estimation of reservoir effect (T_R) and corrected carbonate age (T_{CCA}) of organic sediments and tufa samples from Polish sites.*

Sample	Depth [m]	Lab.No. Gd-	F	T	T_C , T_{ORG} [BP]	$\delta^{13}C$ [‰, PDB]	T_R [years]	T_{CCA} [BP]
Krzywice-1								
KRZ 1/94	5.37-5.50	10280	O	H	11530 ± 100			11530 ± 100
KRZ 2/94	4.37-4.60	10070	O	PT	10770 ± 140			
KRZ 4/94	4.00-4.10	7516	C	TF	10590 ± 80	-7.43		9970 ± 140
KRZ 4/94	4.00-4.10	10072	O	PT	9970 ± 140			
KRZ 5/94	2.80-2.95	9237	O	PT	6670 ± 170			
KRZ 5/94	2.80-2.95	7517	C	TF	10620 ± 50	-7.32		6670 ± 170
KRZ 6/94	2.70-2.79	7518	C	TF	10540 ± 70	-8.08	3950 ± 250	6590 ± 200
KRZ 7/94	2.42-2.55	10073	O	PT	6120 ± 100			
KRZ 8/94	2.31-2.43	7519	C	TF	9670 ± 60	-6.71	3950 ± 250	5720 ± 200
KRZ 9/94	2.16-2.31	7522	C	TF	9730 ± 70	-6.71	3950 ± 250	5780 ± 200
KRZ 10/94	2.00-2.15	10074	O	PT	3620 ± 130			
KRZ 11/94	1.00-1.12	10079	O	PT	1530 ± 70			
KRZ 12/94	0.79-0.92	7524	C	TF	4340 ± 60	-8.17	3530 ± 60	810 ± 100
KRZ 13/94	0.56-0.66	7525	C	TF	4200 ± 50	-9.04	3530 ± 60	670 ± 80
KRZ 14/94	0.56-0.43	7520	C	TF	3530 ± 60	-8.28	3530 ± 60	0 ± 60
KRZ 14/94	0.56-0.43	9231	O	PT	MODERN			
Rudka-2								
R2 - 1	4.20-4.10	10655	O	TF	8700 ± 180			
R2 - 2	3.21-3.09	10642	C	CM	7130 ± 190	-6.57	1360 ± 130	5770 ± 120
R2 - 3	3.09-3.01	10651	C	CM	6980 ± 180	-6.57	1360 ± 130	5620 ± 160
R2 - 3	3.09-3.01	10649	O	PT	5620 ± 160			
R2 - 4	2.80-2.70	10645	C	CM	7670 ± 150	-7.39	1780 ± 220	5890 ± 270
R2 - 4	2.80-2.70	9816	O	PT	5890 ± 270			
R2 - 5	0.92-0.87	10646	C	CM	2720 ± 140	-7.74	500 ± 140	2220 ± 190
R2 - 5	0.92-0.87	9801	O	PT	2220 ± 190			
R2 - 6	0.87-0.82	10659	C	CM	2870 ± 140	-7.74 (*)		
R2 - 7	0.82-0.74	7980	C	CM	3080 ± 70	-7.74 (*)		
R2 - 8	0.74-0.71	9797	C	CM	3530 ± 210	-7.25	1780 ± 150	1750 ± 180
R2 - 8	0.74-0.71	9807	O	PT	1750 ± 180			
R2 - 9	0.71-0.65	10663	C	CM	2980 ± 140	-7.25	1780 ± 150	1200 ± 110
R2 - 10	0.48-0.37	7983	C	CM	2190 ± 60	-8.27	1860 ± 120	330 ± 220
R2 - 10	0.48-0.37	9809	O	PT	330 ± 220			

F = fraction of the sample; C, O = carbonate and organic fraction; (*) = assumed $\delta^{13}C$ values in carbonate fraction; in organic fraction $\delta^{13}C$ = -25‰ was assumed. Type of sediment: TF = tufa, PT = peat, H = humus/soil, CM = calcareous mu

Much more of small carbonate samples than for ^{14}C dating were collected for stable isotope ^{13}C and ^{18}O analyses. Full time record of $\delta^{13}C$ and $\delta^{18}O$ needed separate construction of time scale. For this experimental dependence between known T_{CCA} and depth d of samples in sediment profiles was used, for Krzywice-1 and Rudka-2 separately. This dependence is shown in **Fig. 6** and described by the best fit of polynomial functions:

$$T_{CCA} = -251.95 \times d^2 + 3924 \times d - 2082.9 \quad [years\ BP] \qquad (5.7)$$

for Krzywice-1 profile, with correlation coefficient r^2=0.9938, and

$$T_{CCA} = 374.62 \times d^3 - 2748.1 \times d^2 + 7670.5 \times d - 2630.6 \quad [years\ BP] \qquad (5.8)$$

for Rudka-2 profile, with correlation coefficient r^2=0.9937. Results of T_{CCA} calculations and $\delta^{13}C$ and $\delta^{18}O$ measurements are listed in **Table 3**. The errors of estimation are less than 100 years.

Sites from Orissa

As we can study from the data sheet (see **Table 2**) all organic fractions of tufa samples from all profiles are relatively young. This may suggest that there is some input from modern carbon sources. The tufas are generally porous and permit movement of water, which might have

Table 2. *Results of radiocarbon dating of carbonate (T_C) and organic fraction (T_{ORG}), stable isotope measurements ($\delta^{13}C$ and $\delta^{18}O$) and estimation of reservoir effects (T_R) and corrected carbonate ages (T_{CCA}) of tufa samples for sites from India.*

Sample	Lab. No. Gd-	F/T, WE	T_C, T_{ORG} [BP]	$\delta^{13}C$ [‰] PDB]	$\delta^{18}O$ [‰] PDB]	T_R [years] (5)	T_R [years] (6)	T_{CCA} [BP] (5)	T_{CCA} [BP] (6)
Kudipasa									
KS-1	12065	C/ST,M	15470 ± 120	-4.30	-3.83	9370	3340	6100	**12130#**
KS-1/S-1		C/H, M		-4.30	-3.83				
KS-1/S-1	9841	O/H, M	90 ± 180	-25 (*)					
KS-2	12059	C/PHT, M	16570 ± 180	-4.46	-3.98	9220	3300	7350	**13270#**
KS-3	12070	C/PHT, M	16600 ± 180	-6.78	-4.74	7000	2720	**9600#**	13880
KS-3/S-2		C/H, M		-6.78	-4.74				
KS-3/S-2	9828	O/H, M	102.0 ± 2.7 PM	-25 (*)					
KS-4		C/PCT, M		-3.89	-4.21				
KS-5		C/S, M		-4.54	-4.30				
KS-6		C/ST, M		-4.26	-4.15				
KS-7		C/PCT, M		-5.35	-3.87				
KS-8	12067	C/S, M	10970 ± 90	-7.80	-4.01	6000	2460	**4970#**	8510
Mundapathar									
MS-1	12008	C/ST, H	7050 ± 80	-8.53	-5.60				
MS-1/M-1		C/H, H		-8.53	-5.60	5310	2280	1740	**4770#**
MS-1/M-1	9824	O/H, H	1120 ± 180	-25 (*)					
MS-2	10678	C/PHT, H	8270 ± 210	-10.41	-6.01	3510	1810	4760	**6460#**
MS-3		C/ST, H		-10.47	-5.98				
MS-4	12007	C/ST, H	7620 ± 90	-9.26 (-9.28)	-6.21 (-6.27)	4610	2100	3010	**5520#**
MS-5		C/H, H		-11.27	-6.06				
MS-5/M-2	12001	C/PHT, H	7660 ± 100	-11.27	-6.06	2680	1590	4980	**6070#**
MS-6	10674	C/ST, H	9070 ± 230	-10.60	-5.60	3320	1760	**5750#**	7310
MS-7	10677	C/S, H	6920 ± 190	-9.75	-6.54	4140	1970	2780	**4950#**
MS-8	12004	C/PHT, H	8310 ± 60	-11.92	-5.84	2060	1430	6150	6880
MS-9	10675	C/ST, H	5220 ± 180	-9.84	-6.02	4050	1950	1170	**3270#**
MS-10	10671	C/P, H	5220 ± 180	-10.40	-5.97	3520	1810	1700	**3410#**
MS-11	12000	C/ST, H	5770 ± 80	-10.92	-6.01	3020	1660	**2750#**	4110
MS-12	10679	C/PHT, H	4350 ± 180	-9.29	-5.83	4580	2090	MOD	**2260#**
Sulagan									
SS-1	12072	C/ST, H	10280 ± 110	-9.20	-3.36	4670	2110	5610	**8170#**
SS-2	12069	C/PHT, H	11400 ± 120	-6.65	-3.72	7160	2750	4240	**8650#**
SS-2/R-1	9822	C/H, H	3700 ± 220	-6.65	-3.72	7160	2750	MOD	**950#**
SS-2/R-1	9831	O/H, H	110 ± 8 PM	-25(*)					
SS-3		C/ST, H		-4.77	-6.04				
SS-4		C/PHT, H		-8.48 (-8.48)	-3.49 (-3.44)				
SS-5		C/ST, H		-9.51	-4.09				
SS-6		C/?, H		-8.92	-4.27				
SS-6/R-2	9818	C/PHT, H	8010 ± 300	-8.92	-4.27	4940	2180	3070	**5830#**
SS-6/R-2	10669	O/H, H	109.5 ± 1.4 PM						
SS-7	12071	C/ST, H	8930 ± 110	-9.97	-4.63	3930	1920	**5000#**	7010
Regional samples									
BA-1		C/ST, L		-10.74 (-10.95)	-5.02 (-5.05)				
MA-1	12067	C/ST, M	10970 ± 90	-9.74	-4.23	4150	1980	6820	**8990#**
MB-4	12061	C/ST, M	19850 ± 290	-2.52	-3.39	11080	3780	**8770#**	16070
MB-5	12058	C/PHT, M	12780±140	?	?				
MBS-5	11385	C/ST, M	220 ± 90	-11.67	-6.82	2300	1490	MOD	MOD
MI-1	11375	C/ST, M	10750 ± 210	-8.26	-3.79	5570	2350	5180	**8400#**
MUC-1	12068	C/ST, H	9370 ± 100	?	?				
TA-2		C/ST, L		-7.81	-4.0				

F = fraction of the sample; C, O = carbonate and organic fraction; MOD = modern; (*) = assumed $\delta^{13}C$ values in organic fraction; (5) and (6) indicate the number of equation in chapter 2, used for estimation of T_R (and T_{CCA}); (#)= estimated ages of tufa carbonate fraction giving the best stratigraphy of sediments. Type of tufa samples T: P = Pisoid, PCT = Phytoclastic tufa, PHT = Phytohermal (moss) tufa, S = Sinter/flowstone, ST = Stromatolitic tufa, H = Humus/soil. Name of regional samples: BA = Banigocha, MA = Madhapur, MB = Bhaliadal, MI = Mitikoli, MUC = Mundapathar, TA = Takara. Water energy WE: H = High, M = Moderate, L = Average and Low.

dissolved the modern carbon from the upstream area and contributed to the organic deposits. Secondly, as the tufas are dampened by water films, they support the growth of modern/recent cyanobacterial/algal flora. These might have possibly contributed some modern carbon to organic samples. Because of this, the dates of organic fraction associated with tufa carbonate are not real ages of tufa samples. The ^{14}C time scale for studied changes of sedimentary conditions and $\delta^{18}O$ in tufa carbonates from the study area can be reconstructed on the base of relation between the reservoir age T_R and $\delta^{13}C$ values (see Eqs (2.5) and (2.6)).

The measured values are T_C and $\delta^{13}C$; some dependence between them is expected. Values of $\delta^{13}C$ of carbonate are plotted in **Figs. 7** and **8** against the carbonate age T_C of samples of all investigated profiles, each of the separate profiles and regional samples. Smoothed dependence of $\delta^{13}C$ upon T_C is shown by solid lines

$$\delta^{13}C = a_{0C} + a_{1C}T_C \qquad (5.9)$$

obtained by least squares method. Parameters of least squares line (a_{0C}, a_{1C}), the value of correlation coefficient R, and number (n) of experimental points used in calculation for separate profiles are listed in **Table 4**. The dependence of $\delta^{13}C$ upon T_C is insignificant for separate profile and has relatively high confidence level for experimental points from regional samples and all points together. To estimate magnitude of the reservoir age, the relation T_R and $\delta^{13}C$ can be used in the shape of equation characteristic for spring tufa precipitated from high energy water or characteristic for other tufas (Eqs (2.5) and (2.6)).

The T_R values and corrected carbonate ages for the reservoir effect (T_{CCA}) of tufa carbonate are listed in **Table 2**. The T_R and T_{CCA} values were determined on the basis of both relation (5) and (6) for each measured pair T_C and $\delta^{13}C$ in tufa samples. For reconstruction of the radiocarbon time scale for sedimentary processes and palaeoclimatic interpretation of stable isotope results (Pazdur *et al.,* 2002) we assume, that the best calculated ages are ages which give corrected stratigraphy of investigated sediment layers in profiles. These results are indicated in Table 2. It may be noted, that the best stratigraphy order of T_{CCA} ages in profile is not in agreement with information about relation of tufa type to water energy. The relative errors of such estimated T_{CCA} ages range within 25-30 %. Inverses observed for samples in profiles; Kudipasa (Gd-12001), Mundapathar (Gd-12008 and Gd-10678, Gd-12007 and Gd-12001), Sulagan (Gd-9822 and Gd-9818) can partly result from great estimation errors, but the main determinant is the mechanism of sedimentary and post-sedimentary processes and possibilities of contamination of tufas by "younger" or "older" carbon.

It appears that the older deposits at the lower levels of the tufa profiles have been partly affected by cementation in the vadose realm. The meteoric water might have dissolved younger carbon from humus/ soil zone or modern tufas, and while moving through the porous older tufas have probably contaminated the tufas. Contamination by older carbon seems very unlikely. It is possible too, that cementation processes provide discrepancy of calculated T_{CCA} ages and classification of type tufa sediments.

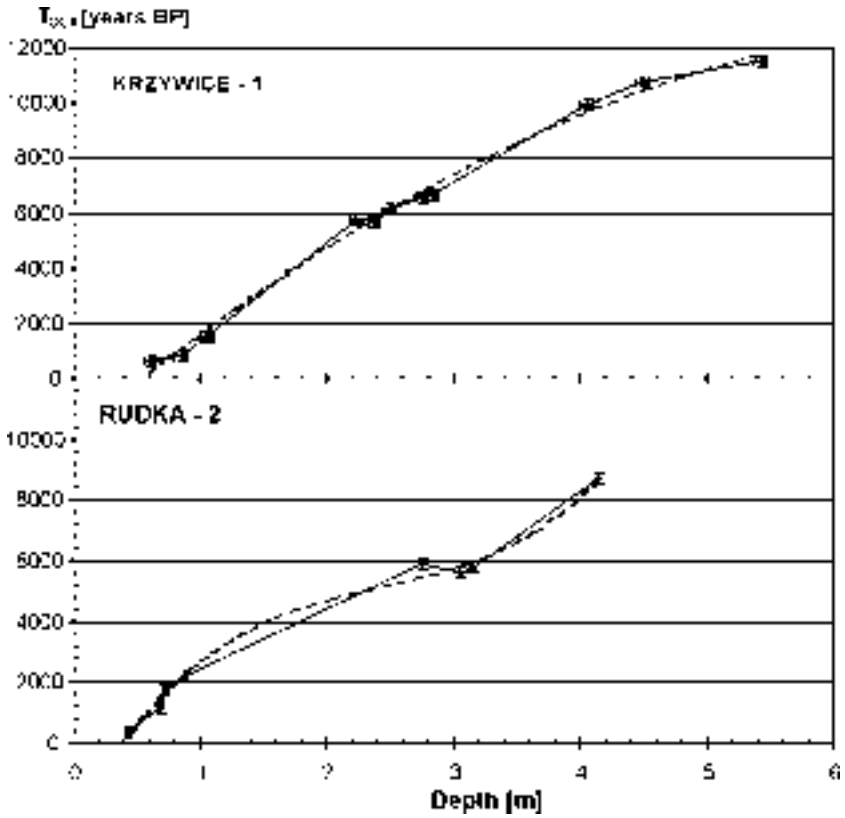

Fig. 6. *Dependence of experimental values of T_{CCA} on the depth of a sample in the Krzywice-1 and Rudka-2 profiles (Poland).*

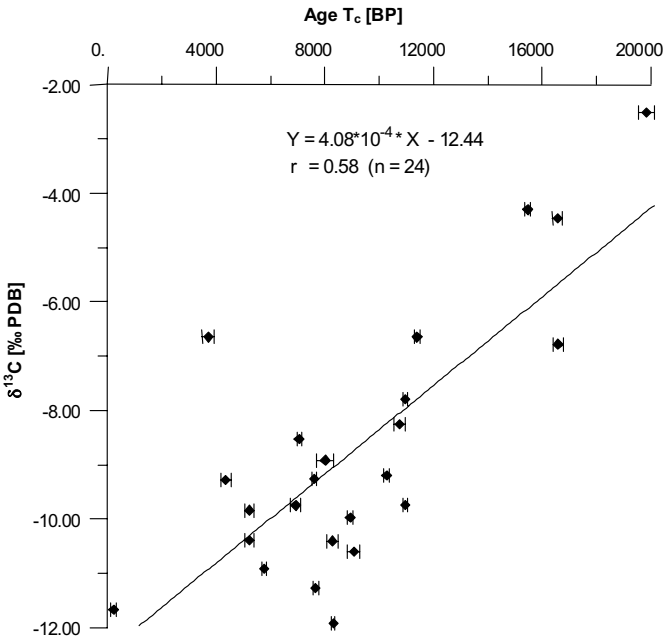

Fig. 7. *Dependence of $\delta^{13}C$ upon T_c for all investigated profiles from the Eastern India (Orissa) sites. Straight line is described by equation shown in Figure. n - number of experimental points, r - correlation coefficient.*

Table 4. *Parameters of the least squares lines described by Eq. (5.9). a_{0C} and a_{1C} - least square estimates of the coefficients of straight line (**Figs 7** and **8**); r - correlation coefficient; n - number of experimental points.*

Profile	a_{0C} [‰]	a_{1C} [‰/kyr]	r	N
Kudipasa	0.00043	-0.0123	0.45	4
Mundapathar	-0.00022	-0.0086	0.12	11
Sulagan	-0.00015	-0.0070	0.08	5
Regional samples	0.00045	-0.0128	0.86	4
All samples	0.00041	-0.0124	0.58	24

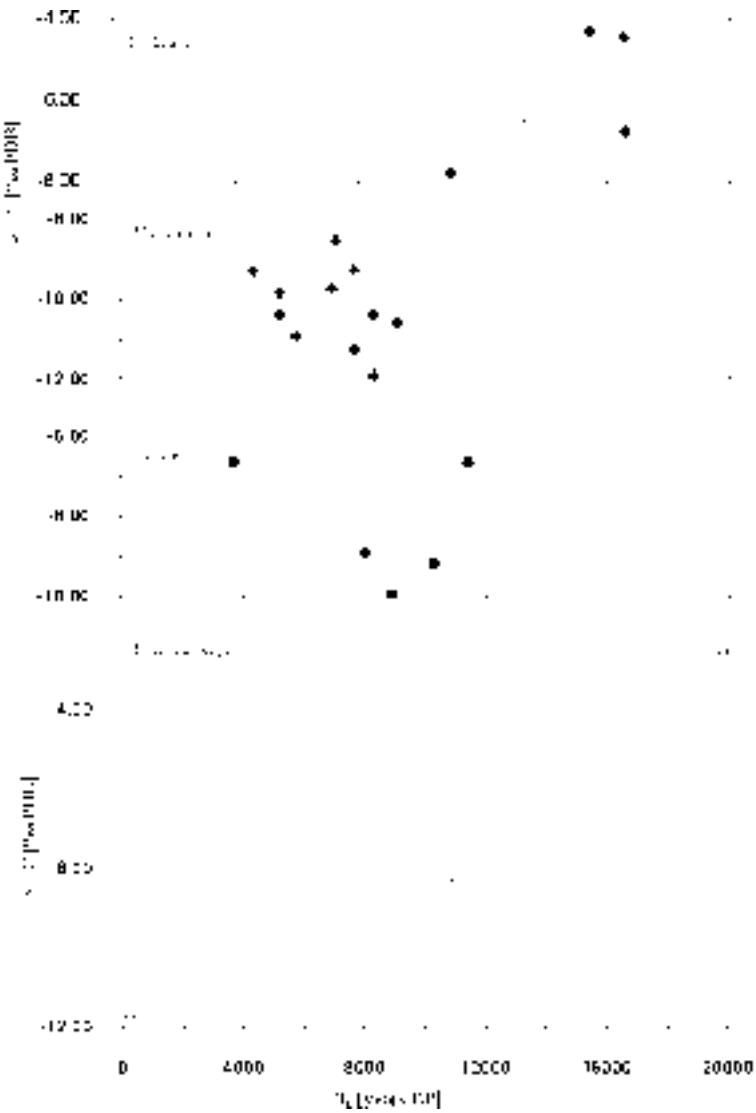

Fig. 8. *Dependence $\delta^{13}C$ upon T_c for separate profiles and for regional samples from the Eastern India (Orissa) sites. Values of correlation coefficients are given in Table 4.*

Table 3. *Values of unknown corrected radiocarbon ages T_{CCA} of samples analysed on $\delta^{13}C$ and $\delta^{18}O$ from Krzywice and Rudka sites (Poland), estimated on the basis of approximation of T_{CCA} as function of depth, described by Eqs (5.7) and (5.8).*

Krzywice

Depth [m]	T_{CCA} [BP]	$\delta^{13}C$ [‰, PDB]	$\delta^{18}O$ [‰, PDB]
0,6	180	-9,04	-7,95
0,7	540	-8,68	-8,76
0,8	894	-8,17	-8,22
1,1	1927	-8,21	-8,27
1,4	2915	-7,75	-8,29
1,55	3392	-7,52	-8,81
1,6	3548	-7,33	-8,65
2,05	4898	-9,35	-5,68
2,08	4985	-9,58	-5,4
2,23	5410	-7,16	-7,88
2,35	5742	-6,71	-8,18
2,4	5878	-7,24	-8,34
2,54	6252	-7,49	-7,95
2,6	6410	-9,61	-3,18
2,65	6539	-7,58	-8,6
2,74	6770	-7,44	-8,23
2,78	6871	-8,08	-9,98
2,8	6921	-7,43	-8,63
2,9	7169	-7,32	-8,63
3,35	8224	-6,47	-8,7
3,85	9275	-6,23	-8,83
4,14	9827	-7,43	-9,8
4,17	9882	-7,01	-9,84
4,21	9954	-7,4	-9,65
4,23	9990	-7,07	-9,93
4,27	10061	-6,36	-9,75
4,29	10096	-7,41	-10,06
4,31	10131	-7,09	-10,4
4,38	10252	-6,74	-9,88
4,4	10286	-9,6	-10,21
4,42	10319	-6,24	-11,53
4,43	10336	-6,34	-10,61
4,58	10583	-9,95	-11,72
4,7	10772	-3,67	-13,78
4,75	10849	-3,04	-13,1
4,95	11143	-0,77	-12,55
5,4	11731	-7,03	-11,27

Rudka

Depth [m]	T_{CCA} [BP]	$\delta^{13}C$ [‰, PDB]	$\delta^{18}O$ [‰, PDB]
0,5	564	-7,52	-7,75
0,65	1297	-7,25	-7,5
0,85	2134	-7,74	-7,93
1,05	2827	-7,64	-7,12
1,1	2980	-7,25	-7,61
1,15	3126	-8,44	-6,34
1,2	3264	-7,99	-8,33
1,25	3395	-6,96	-8,55
1,35	3638	-7,06	-7,49
1,45	3856	-6,96	-8,84
1,55	4051	-6,43	-8,73
1,65	4227	-7,46	-7,6
1,75	4384	-7,15	-8,85
1,85	4526	-6,87	-8,09
2	4715	-6,46	-8,53
2,15	4881	-6,66	-8,23
2,4	5128	-7,12	-6,11
2,55	5271	-6,1	-9,14
2,65	5369	-7,41	-9,67
2,7	5420	-7,39	-8,15
2,8	5525	-7,4	-8,59
2,9	5639	-6,6	-8,58
3	5763	-7,29	-7,64
3,1	5899	-7,13	-7,72

6. CONCLUSIONS

To estimation of ^{14}C ages of calcareous tufa, the reservoir age T_R, dependent on type of tufa sediments (water energy conditions) should be known. Two independent ways of T_R determination were made.

The calcareous tufa of Krzywice-1 and Rudka-2 profiles in Lublin Upland, Poland represent calcareous muds formed in shallow, stagnant water basins in conditions of semilimnic sedimentation. Comparison of conventional radiocarbon ages of carbonate and organic fraction of several samples from each profile gave possibilities to estimate reservoir age T_R and use these values to determine corrected conventional ^{14}C ages T_{CCA} (corrected for reservoir effect) of samples containing only carbonate fraction. Non linear dependence between known T_{CCA} and depth of the carbonate samples in sediment profiles was used for determination of unknown T_{CCA} of samples destined for $\delta^{13}C$ and $\delta^{18}O$ analysis.

The smoothed dependence between $\delta^{13}C$ and T_C for calcareous tufa deposited in high and mean energy water in Orissa state, India, has been useful in calculating the best corrected ages (T_{CCA}) of the dating samples. The model used for calculation of reservoir age $T_{R,}$ on the basis of observed relation, has empirical character and give only approximated values. Some anomalies in ^{14}C ages observed in a few samples of the profiles are probably a function of post-depositional changes or contamination due to excursion of modern carbon in the depositional system.

The $\delta^{13}C$ values indicate greater input of biogenic lighter carbon. The role of photosynthesis and evaporation in the deposition of tufa is considered to be low due to low residence time. The absence of any marine carbonate source and high-energy conditions due to water turbulence for Indian tufas, suggest partial disequilibrium during isotopic fractionation.

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$\delta^{13}C$ and $\delta^{18}O$ TIME RECORD AND PALAEOCLIMATIC IMPLICATIONS OF THE HOLOCENE CALCAREOUS TUFA FROM SOUTH-EASTERN POLAND AND EASTERN INDIA (ORISSA)

ANNA PAZDUR[1], RADOSŁAW DOBROWOLSKI[2], TOMASZ DURAKIEWICZ[3], NATALIA PIOTROWSKA[1], MANMOHAN MOHANTI[4] and SRIKANTA DAS[4]

[1]Department of Radioisotopes, Institute of Physics, Silesian University of Technology, Krzywoustego 2, 44-100 Gliwice, Poland
(e-mail: anna.pazdur@radiocarbon.gliwice.pl)
[2]Department of Physical Geography and Palaeogeography, Maria Curie-Skłodowska University, Akademicka 19, 20-033 Lublin, Poland
[3]Mass Spectrometry Laboratory, Maria Curie-Skłodowska University, Plac Marii Curie-Skłodowskiej 1, 20-031 Lublin, Poland;
Los Alamos Laboratory, Condensed Matter and Thermal Physics Group, Los Alamos, Mailstop K764, NM 87545, USA
[4]Department of Geology, Utkal University Bhubaneswar - 751004 (Orissa) India

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POLAND, INDIA

Abstract: Measurements of $\delta^{18}O$ and $\delta^{13}C$ in tufa samples dated by ^{14}C method have been used to reconstruct climatic changes in Southern and Eastern Poland and in Eastern India (Orissa) for the last *ca* 13,500 years. Stable isotope time record $\delta^{18}O$ in calcareous tufa profiles can be interpreted as palaeoclimatic record if dependence between oxygen isotope composition and temperature for the specific climatic region is known. Estimated sedimentation temperatures of calcareous tufas from Polish sites indicate the mean year of air temperatures during the last 12,000 years and mean winter and summer temperature for Orissa state, using stable isotope analysis for calcareous tufa from Indian sites. The estimated temperatures have real values, comparable with contemporaneous sedimentation temperature. The characteristic trend of the temperature changes increasing for Poland and decreasing for Orissa, since the beginning of the Holocene till today, can be observed with climatic optimum *ca* 5000-6000 BP synchronous in both countries.

1. INTRODUCTION

Calcareous tufa and speleothems appear to be significant indicators of palaeoenvironmental and palaeoclimatic changes. These deposits reflect the combined effects of karst processes, controlled to a great extent by climatic factors, especially temperature and humidity. Freshwater tufas in continental realm, deposited by physicochemical and/or biochemical processes are also considered as reliable recorders of palaeoclimatic and environmental change (Andrews *et al.*, 1994 and Pazdur *et al.*, 1988b). Stable isotopes, like ^{18}O and ^{13}C, and chemical analysis, frequency distribution of U/Th and ^{14}C dates have frequently been used as a tool for analysis of sedimentological processes and reconstruction of palaeoclimatic conditions, as well as for stratigraphic purposes. Measurements of $\delta^{18}O$ and $\delta^{13}C$ in tufa samples dated by ^{14}C method have been used to reconstruct Holocene climatic changes in southern and eastern Poland (Pazdur, 2000).

Precise dating of speleothems by ^{14}C and other dating methods along with $\delta^{13}C$ and $\delta^{18}O$ measurements have been used to interpret palaeoclimatic changes (Pazdur *et al.*, 1995). The frequency distribution of ^{14}C and U/Th dates has been successfully applied to palaeoclimatic studies using speleothems (Goslar *et al.*, 2000; Hercman, 2000).

Interpretation of isotopic investigations in lacustrine carbonates is much more sophisticated and difficult because of the complex nature of sedimentation, influenced by a number of physicochemical and biological factors. Palaeolake level changes of the Gościąż Lake (Central Poland) have been studied from the lake and lake-margin sediments with help of deposits constituted of laminated sediments, peat, lacustrine gyttja and beach sediments together with radiocarbon chronology and carbon isotope content interpretation. The behaviour of this lake during the last 12 ka reflects global climate change in the temperate zone fairly well (Pazdur *et al.*, 1994 and 1995b).

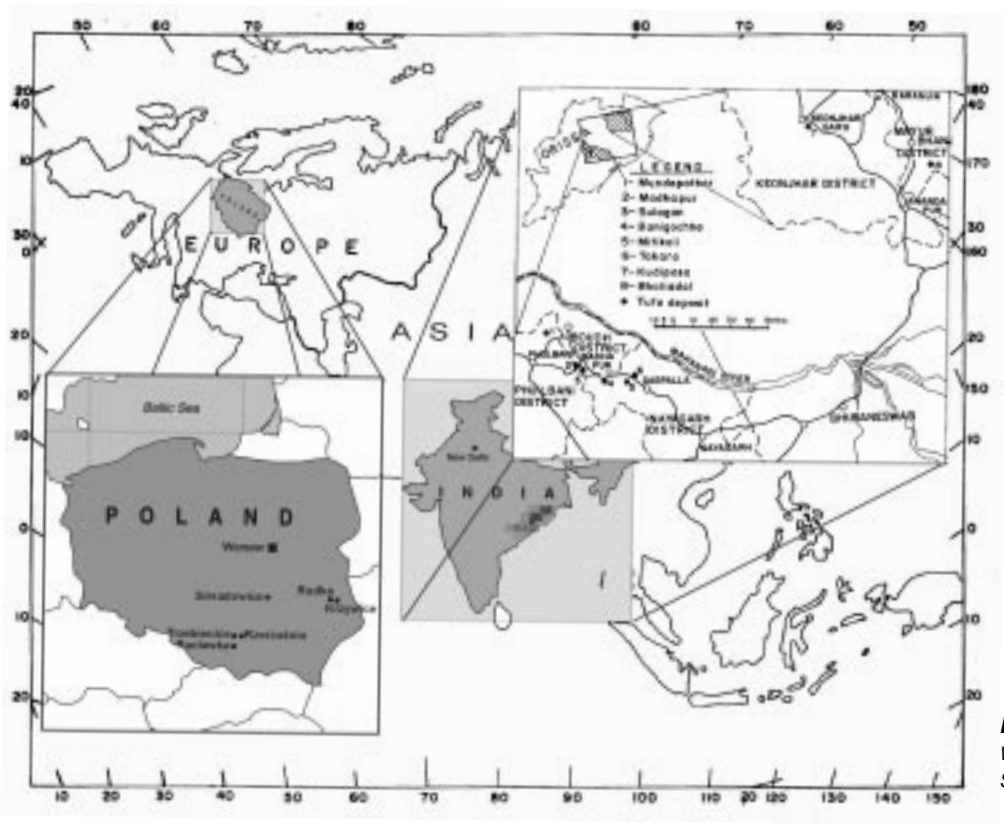

Fig. 1. *Map of Europe and Asia where tufa samples have been studied in Poland and India (Orissa).*

The significance of undisturbed lacustrine calcareous sediments as potential geochemical archives of isotopic records of palaeoenvironmental changes has been recognized. Isotopic studies of pedogenic carbonates (caliche, concretions) and cements provide information related to circulation of groundwater and precipitation, and, indirectly, lead to palaeoclimatic conclusions (Pazdur *et al.*, 1995a).

Several authors dealing with freshwater carbonates assumed that kinetic effects during isotopic fractionations are small (except at spring heads) and used the isotopically derived temperature for studying local and regional palaeoclimatic and palaeoenvironmental records (Andrews *et al.* 1993 and 1994; Pazdur *et al.* 1988b). Usdowski *et al.*, (1979) and Dandurand *et al.,* (1982), while studying calcite precipitation at springs and streams, attributed the variations in isotopic composition to disequilibrium condition due to kinetic effects. Turi (1986) noted that isotopic equilibrium is seldom attained in the deposition of travertines mainly as a consequence of kinetic effects. Recently, Chafetz and Lawrence (1994) demonstrated that $\delta^{18}O$ values of the precipitates can change drastically within a travertine system and stressed that the overall changes with water flow, microenvironmental controls and disequilibrium precipitation determine the isotopic signatures of these freshwater deposits. It is, therefore, necessary to stress the depositional conditions before establishing the isotopic signatures and reconstructing the palaeoclimatic change.

Generally, tufa deposits, for example European tufas, involve headwaters, which contain dissolved calcium carbonate derived from marine (isotopically heavy) carbonates. In contrast to these deposits, tufas of Orissa State are formed in a Precambrian terrain of crystalline and metasedimentary rocks. Due to the absence of any marine limestone or dolomite, the tufa depositional system forms an interesting geochemical system. Das and Mohanti (1997) recently presented the fabrics of microbial tufas and discussed depositional processes. In this paper, we have attempted to date the tufa carbonates and apply the stable isotopic signatures to understand the implications of climatic changes in Orissa during the Holocene.

For reconstruction of time record of palaeoenvironmental conditions of the sedimentary processes the time scale of carbonate deposition should be reconstructed. Radiocarbon, U/Th, TL and AAR dating methods may be usually used.

The large number of dating results obtained by different methods enable interpretation of results with use of probabilistic methods (Baker *et al.,* 1993; Smart and Richards, 1992; Srdoc *et al*., 1983; Hercman, 2000). Frequency distributions of dates may be compared with results obtained by other methods, like changes of temperature and precipitation in the past, reconstructed from pollen analyses of peat-bog profiles and lake sediments of non-glaciated areas, and with palaeoclimatic records from deep sea cores (Guiot *et al*., 1989; Schackleton, 1967).

2. INVESTIGATED SITES IN POLAND AND IN INDIA

The radiocarbon time scale record of $\delta^{13}C$ and $\delta^{18}O$ from sites situated in the Cracow-Wieluń Upland (Racławka, Rzerzuśnia, Trzebienice; southern Poland) and the Holy Cross Mountains (Sieradowice; south-

eastern Poland) and their palaeoclimatic interpretation was given by Pazdur *et al.* (1988b). In this paper the results are used for comparison of those from Krzywice-1 and Rudka-2 (Lublin Upland, eastern Poland; Dobrowolski *et al.*, 1996) with Mundapathar, Kudipasa and Sulagan (Orissa, eastern India). Dobrowolski *et al.* (1999 and 2002), presenting $\delta^{13}C$ and $\delta^{18}O$ record in time related to Holocene stratigraphical division, but without detailed radiocarbon time scale. Das and Mohanti (1997) and Pazdur *et al.* (2002) described results of radiocarbon dating, $\delta^{13}C$ and $\delta^{18}O$ measurements, and sedimentological description for sites in India.

Poland

Sedimentological and isotopic studies were made for profiles from the following geographical regions:

- Cracow-Wieluń Upland (southern Poland): 27 samples of calcareous tufa of biogenic origin (autochthonous calcareous muds, stromatolites, oncoids, and moss travertines; Pazdur *et al.,* 1988a) from three sites (Racławka, Rzerzuśnia and Trzebienice). The sites represent different hydrodynamic conditions of tufa sedimentation. They are situated in small valleys entrenched in carbonate rocks of Lower Carboniferous (Racławka), Jurassic and Cretaceous (Trzebienice and Rzerzuśnia).
- Holy Cross Mountains (south-eastern Poland): 11 samples of fine-grained calcareous muds, rich in organic matter, precipitated in shallow stagnant water basin (Pazdur *et al.,* 1988a). The Sieradowice profile is situated in a small valley cut in Devonian carbonate rocks.
- Lublin Upland (eastern Poland): both sediment profiles, Krzywice-1 and Rudka-2, consist of calcareous muds rich in organic matter precipitated, like tufa from Sieradowice, in low-energy water conditions. They are situated on Upper Cretaceous rocks (Dobrowolski *et al.,* 1999 and 2002).

Radiocarbon chronology of sedimentation was made on the basis of 8 organic and the same number of carbonate ^{14}C dates for Krzywice-1, and 6 organic and 9 carbonate ^{14}C dates for Rudka-2 profiles (Dobrowolski *et al.,* 2002). Sixty three carbonate samples for stable isotope ^{13}C and ^{18}O analyses were taken (37 from Krzywice-1 and 26 from Rudka-2 profile) and radiocarbon time scale for $\delta^{13}C$ and $\delta^{18}O$ time record was reconstructed (Pazdur *et al.,* 2002). The construction of similar time scale for other profiles from Poland and India was based on dependence between reservoir age and $\delta^{13}C$ values in tufa samples. The methodology and details of the reconstruction are given by Pazdur (1988) and Pazdur *et al.* (2002).

India (Orissa)

Detailed description of profiles and classification of tufa samples is given by Pazdur *et al.* (2002). Sedimentological and isotopic studies are based on:

- Mundapathar: 13 tufa samples from one profile, including stromatolic tufa, moss (phytohermal) tufa, phytoclastic tufa, pisoid and sinter. The deposit of about 7 m in thickness is situated at a small waterfall formed on charnockite under high-energy conditions.
- Kudipasa: 8 tufa samples from one profile, including stromatolic tufa, moss tufa, phytoclastic tufa and sinter. The deposit measuring about 6 m in vertical thickness is located on a hill slope. Streams depositing the tufa drain basic lava, tuff and quartzite under moderate hydrodynamic conditions.
- Sulagan: 7 tufa samples including stromatolic tufa and moss tufa. The deposit is about 6 m in vertical thickness. It is located at a small waterfall formed on charnockite under high-energy conditions.
- Single tufa samples from various sites (regional samples). Miticoli and Mundapathar represent high-energy conditions, Madhapur and Bhaliadal represent moderate energy conditions, Takara and Banigochha represent low hydrodynamic conditions.

Fig. 2. *Stromatolitic crusts draping over moss-rich pockets on the lower part (close to the hammer). Upper part shows stromatolitic crusts alternating with phytohermal (moss-rich) deposits. Central region of the photograph shows speleothemic crusts. Locality: Mundapathar.*

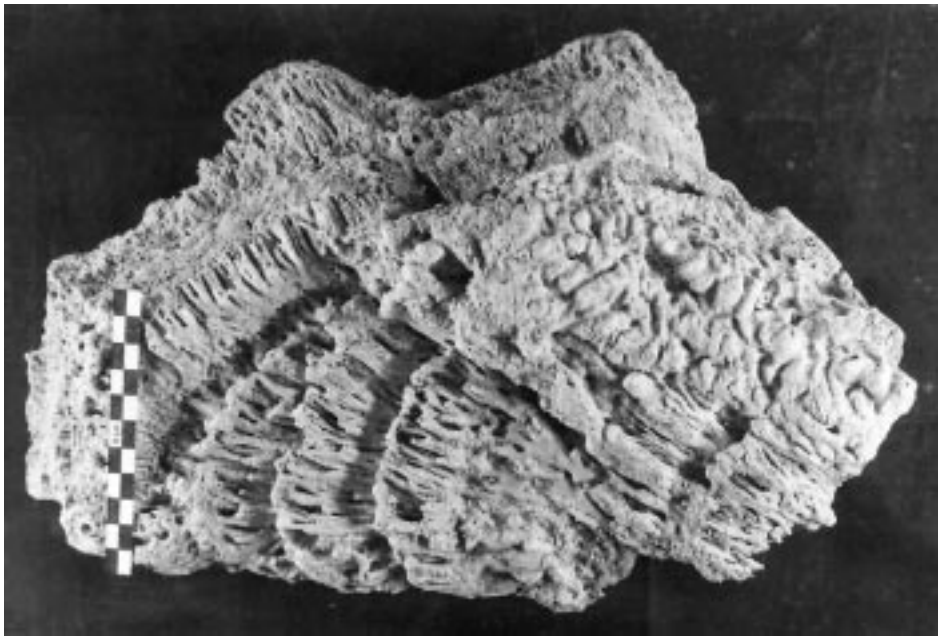

Fig. 3. *Phytohermal tufa (calcified moss) showing several stages of growth and high porosity. The unidirectional orientation of the moss indicate hydrodynamic control on phytoherms. Sample from Mundapathar. Each division of the scale is 1 cm.*

Fig. 4. *Stromatolitic crusts showing alternate dark and light laminae. The darker laminae are thicker at the lower parts and appear convex due to growth over small bushy mosses. Sample from Bhaliadal.*

Radiocarbon time scale of sedimentation of the tufa profiles was made on the basis of 11 carbonate and 2 organic ^{14}C dates for Mundapathar, 6 carbonate and 2 organic ^{14}C dates for Kudipasa, and 4 carbonate and 2 organic ^{14}C dates for Sulagan. Radiocarbon dating of the regional samples was made for the carbonate fractions. Thirty three carbonate samples were taken for stable ^{13}C and ^{18}O analysis from all sites together (Pazdur *et al.*, 2002).

3. PRESENT CLIMATIC BACKGROUND

Sites from Poland

Sedimentation of biogenic calcareous tufa occurs mostly during spring months. In the southern and south-eastern Poland, the temperature of spring water at this time is equal to mean annual air temperature; therefore, the mean annual temperature of meteoric water coincides with temperature of tufa sedimentation. Climatic data from the Cracow Upland show that the mean annual temperature varies from 7 to 8°C and mean temperature of springs from 7 to 9°C (after Pazdur *et al.,* 1988b). The temperature of streams fluctuates between 7 and 12°C.

Studied tufas from the Cracow Upland were sampled with a thickness less than 5 cm. It means that each sample covers 10- to 20-yr time interval according to determined sedimentation rate (several mm/yr). This intervals are insignificant when compared to errors of the age determination. Sampling of Krzywice-1 and Rudka-2 sites was made across profiles, with small (ca 30 mg) amounts of carbonate. The results of $\delta^{18}O$ analysis present mean values in a shorter period of time than in the case of samples from the Cracow Upland profiles, even though the sedimentation rate is about several or more mm per year.

Sites from India (Orissa)

The warm and humid tropical climate of Orissa is characterised by seasonal southwest monsoon rainfall. The annual mean precipitation is *ca* 150-200 mm. Major part of the rainfall is concentrated in the monsoon season (Mid-June to Mid-October, with an average of *ca* 200-350 mm of rainfall).

The ranges of air temperature change are as follows: in winter 8-12°C minimum and 25-28°C maximum and in summer 25-28°C and 36-42°C, respectively. Water temperatures when tufa precipitates are influenced by general thermal conditions. Water temperatures are as follows: 19-20.5°C in winter (December-January) and 27.5-29°C in summer (April-May).

The deposition of tufas takes place mostly during spring (February-March) and summer (April-May) periods. Presently, summer deposition is negligible – possibly due to the groundwater table fall and limited or missing surface flow. The sparitic and micritic laminae in stromatolitic tufa indicate seasonal deposition (spring-summer and rainy-winter periods). Thickness of laminae couplets suggests a depositional rate of 1 mm to a little more than 1 cm per year.

Stream waters depositing the tufa show a pH value of 8.0 to 8.6. Concentrations of Ca^{2+}, Mg^{2+} and HCO^-_3 vary within the range of 30-80 mg/l, 9-28 mg/l and 200-310 mg/l respectively (Das and Mohanti, 2001).

4. TIME RECORD OF $\delta^{13}C$

The enrichment of carbonate in heavy carbon isotope, in comparison to water solution, may be induced by partial disequilibrium between HCO^-_3 in water and atmospheric CO_2 during precipitation. This is attributed to kinetic effects during $CaCO_3$ precipitation from highly supersaturated solution in which the rate of carbonate precipitation is faster than equilibrium fractionation with the respect to the stable isotopes (Usdowski *et al.,* 1979; Dandurand *et al.,* 1982; Turi, 1986; Chafetz *et al.,* 1991). In natural environments, the exchange of CO_2 can only lead to equilibrium if sufficient residence time is available, which can be attained in standing water bodies like lakes. The geomorphic setting of our tufa deposits indicates a very low residence time and great water turbulence. This situation favours the idea of partial disequilibrium precipitation.

We believe that dominant part of the carbon has been derived from biogenic sources and may be partly from the atmosphere. The range of $\delta^{13}C$ values indicates relative enrichment of tufa in heavy isotopes. The enrichment in heavy isotopes may be determined by photosynthesis of plants, which preferentially use lighter carbon (^{12}C) leaving the remaining HCO^-_3 enriched in ^{13}C (Pentecost and Spiro, 1990; Merz, 1992; Casanova and Hillaire-Marcel, 1993; Guo *et al.,* 1996). But the photosynthetical removal of CO_2 requires relatively longer residence time. Tufas in the Orissa State originate in discharge basins with low residence time of water. Even though profuse amount of cyanobacteria, diatoms and mosses are involved, the rate of photosynthetic removal of CO_2 by these plants is small in comparison to the rate of physical degasation due to turbulence of water. Photosynthesis may be locally significant, depending on the amount of biomass, especially where cyanobacteria or algae and moss thrive together.

The range of $\delta^{13}C$ of tufa from Poland sites is *ca* from -10.5 ‰ to -6 ‰ for the last 10,600 years (Pazdur, 1988). The significantly higher values are observed for the Krzywice-1 site, with the longest time record, in the time of 11,800-10,800 BP (**Fig. 5**). The $\delta^{13}C$ values from the Orissa sites receive *ca* -2.5 to -11.7 ‰ in the whole investigated period between 13,500 BP and the present time. The range of $\delta^{13}C$ values of tufa from the Polish and Orissa sites is in accordance with a deposition from freshwater and suggest the presence of isotopically lighter organic carbon.

As there is no marine limestone and/or dolomite in the studied area of Orissa, we believe that the carbonates have originated mostly from organic matter. Ca^{++} ions are derived from weathering of silicates, mostly plagioclase and pyroxene. Kalsotra and Prasad (1979) and Pawar *et al.* (1988) have reported tufa deposits from sandstones and shales and basaltic areas in India. Augustithis (1982) also noted the formation of carbonate nodules from disintegration of olivine basalts in Duncan, south of Addis-Ababa.

Tufas are depleted in heavy isotope ^{18}O in all Polish and Indian sites (see **Fig. 7**), when compared to $\delta^{18}O$ values expected for equilibrium sedimentary processes. The low and negative $\delta^{18}O$ values suggest a low rate of evaporation.

Individual $\delta^{13}C$ values of tufa samples shown in **Fig. 5** as time records reveal short-time fluctuations and increase/decrease trends, different in detail from a profile to profile. The co-variation of oxygen isotope data with the carbon isotope ones (**Fig. 6**) indicate similar trend of changes in disequilibrium condition for all the India samples; correlation coefficient is equal to r = 0.73 (22 pairs of $\delta^{13}C$ and $\delta^{18}O$). For all Polish samples, the dependence between both delta values is positive (r = 0.20), if we remove 6 extreme points with $\delta^{13}C > -4$ ‰ and $\delta^{18}O > -6$ ‰ (Krzywice-1 profile) from period older than 10,000 BP. It means high confidence level and confirm disequilibrium sedimentary conditions and presence of isotopic kinetic fractionation effect. The relations indicate, that organic consumption of CO_2 may be significant because of the presence of chemo- and heterotrophic bacteria (Pazdur *et al.,* 1988b) observed for tufa sites in the southern Poland. Enrichment of tufas in the heavier carbon isotope (^{13}C) during the warmer periods may be connected to some extent with activation of plant consumption.

5. TIME RECORD OF $\delta^{18}O$ AND TUFA SEDIMENTATION TEMPERATURE

$\delta^{18}O$ of tufa in palaeoclimatic studies

Isotopic investigations of tufa from Poland deals with sites of spring tufa deposition in variable conditions of river water energy (southern Poland; Pazdur *et al.*, 1988a) and semi-limnic conditions (south-eastern Poland; Pazdur *et al.*, 1988a; Dobrowolski *et al.*, 1999). The palaeotem-

perature curve was constructed (Pazdur *et al.*, 1988b) on the basis of the time scale reconstruction using radiocarbon dating and interpretation of stable isotope carbon and oxygen composition in sedimentary processes. The curve describes the annual mean temperature changes for the southern Poland in the period of 2000-9600 BP, *i.e.*, in which sedimentation of tufa took place in Racławka, Rzerzuśnia, Trzebienice and Sieradowice (see **Figs 5** and **7**). Thirty eight results of ^{14}C dating and stable isotope analysis were used for palaeoclimatic reconstruction. Dobrowolski *et al.*, (1999) carried out isotopic investigations on two eastern Polish sites, Krzywice-1 and Rudka-2. Radiocarbon time scale of tufa sedimentation was constructed for those sites (Pazdur *et al.*, 2002) and palaeoclimatic interpretation of 61 new results of stable isotope analyses can be done together with the previous results. Time record of $\delta^{18}O$ measurements in individual and all tufa sites from Poland and India is shown in **Fig. 7**.

The variation in $\delta^{18}O$ values indicates differences in isotopic composition of tufa depositing waters controlled by water temperature. The temperature of cold spring waters in continental conditions is influenced by rainfall and atmospheric temperature, *i.e.*, climate controls the tufa deposition.

Temperature precipitation of tufaceous sediments in Poland and India

Despite difficulties caused by disequilibrium precipitation of $CaCO_3$, it may be expected that the isotopic composition of oxygen of Holocene tufa might be useful for the reconstruction of the approximate thermal condition of sedimentation, or strictly speaking, the temperature of water, from which carbonate precipitated. Reconstruction of palaeotemperature changes for a given geographical region may be based on known seasonal dependence of $\delta^{18}O$ in meteoric water upon temperature (Van der

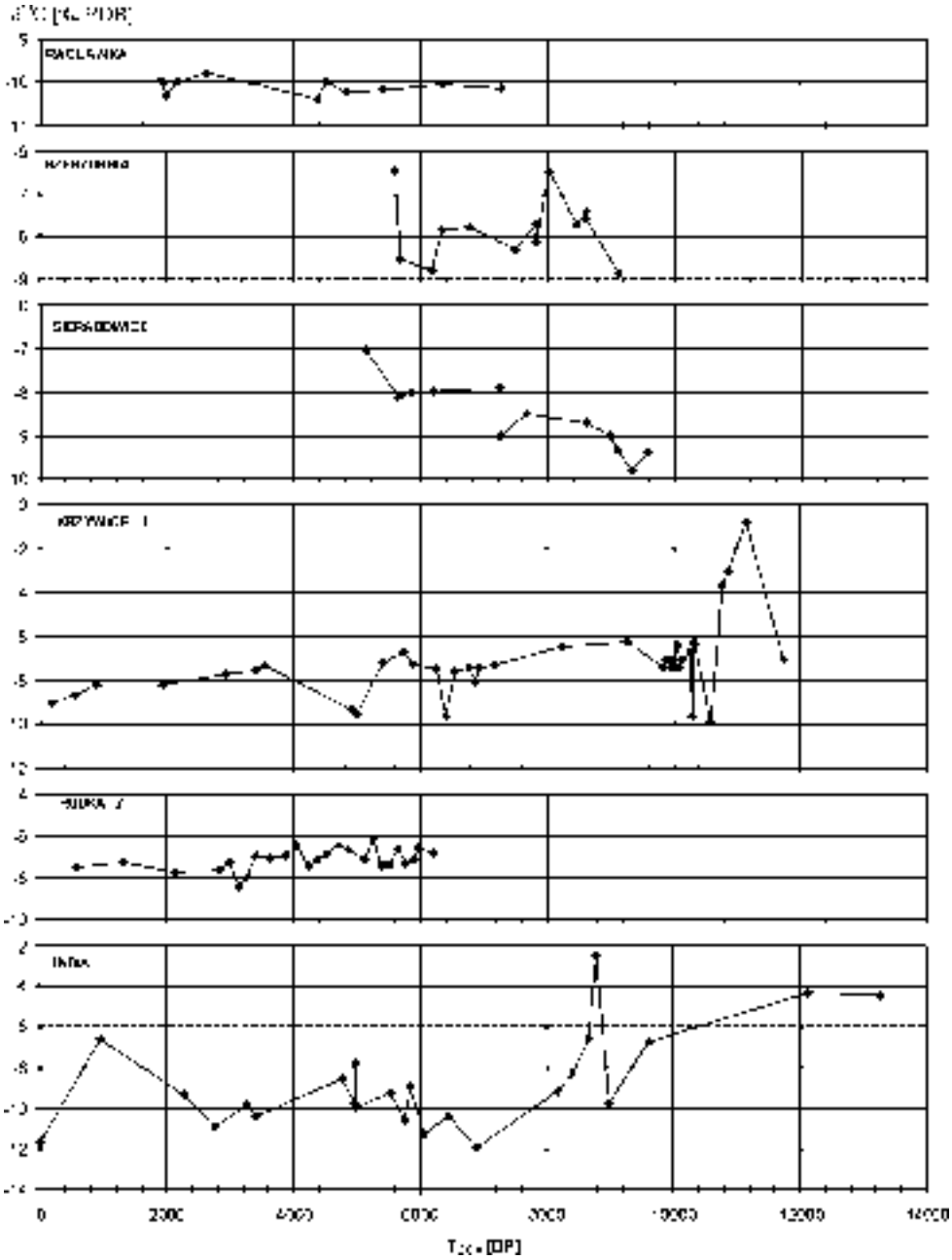

Fig. 5. *Time record of $\delta^{13}C$ in separate tufa sites of Poland and all sites together from India.*

Straaten and Mook, 1983). Any attempt to estimate temperatures of sedimentation from measured values of $\delta^{18}O$ in calcareous tufa requires several simplifying assumptions, which are based on the results of investigation of recent tufas (Pazdur *et al.*, 1988b). One of this is that the temperature gradient of $\delta^{18}O$ is not changed in the process of deposition, i.e., the temperature gradient of $\delta^{18}O$ in the sediment is the same as in precipitation and stream water, and second – kinetic fractionation effect of oxygen isotopes is independent on sedimentation temperature. To reconstruct temperature record for the Late Glacial and Holocene, the constant values of temperature oxygen gradient and kinetic effect in the whole period must be assumed (Pazdur *et al.*, 1988b). It means that in this whole time period the circulation of air mass was the same (Różański, 1985). The temperature t of tufa sedimentation may be estimated on the basis of simple equation (Pazdur *et al.*, 1988b):

$$(\delta^{18}O)_C = \left[\frac{d(\delta^{18}O)}{dt}\right]_W \cdot t + A + \Delta, \qquad (5.1)$$

where A means extrapolated $\delta^{18}O$ value of water in 0 °C, equal to -13.0±0.4 ‰ (Pazdur *et al.*, 1988b) and Δ – the value of kinetic fractionation effect for oxygen isotopes in sedimentary processes of carbonates, *i.e.*, the difference between the $\delta^{18}O$ value in carbonate (vs. PDB) and the same value in water solution, from which the sediment was deposited (vs. SMOW).

The global temperature gradient for coastal region in meteoric water is equal to 0.72 (Van der Straaten and Mook, 1983) and 0.37 ‰ /°C for continental climatic area (Pazdur *et al.*, 1988b). The estimation Δ (Pazdur *et al.*, 1988b) receive values between -1.7 and -2.5 ‰ for recent tufa from the southern England (Thorpe *et al.*, 1980) and change from +0.26 to -0.04 ‰ for Germany, Central Europe (Usdowski *et al.*, 1979).

To estimate the temperature time record in Poland, the mean 500-year $\delta^{18}O$ values were used for calculations of t, on the basis of Eq. (5.1); the maximal and minimal values of Δ like for Germany were applied. Such values of Δ give correct value of present water spring temperature in the southern Poland (*ca* 8 °C) if the measured value

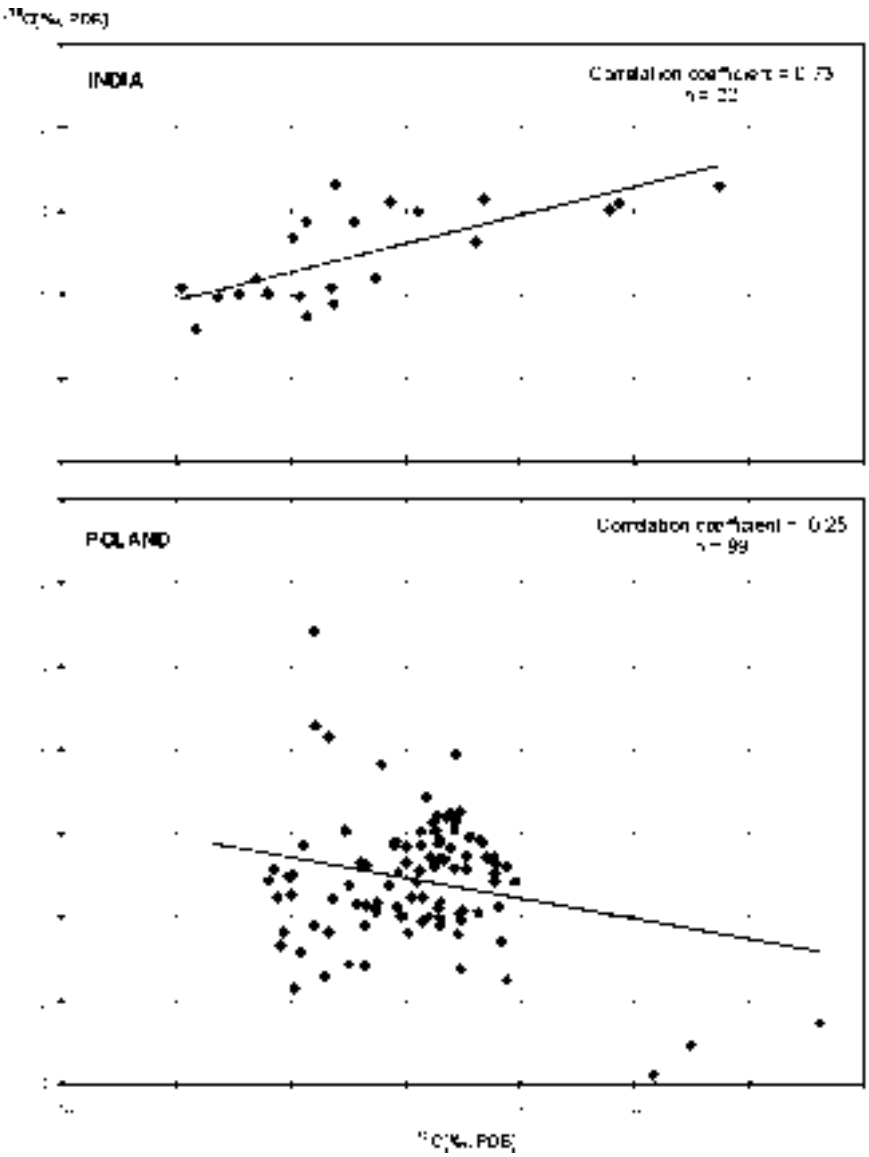

Fig. 6. *Dependence between $\delta^{13}C$ and $\delta^{18}O$ for all tufa profiles of India and Poland. Correlation between both delta values is negative for Polish samples and positive for samples from India.*

of $\delta^{18}O$ in contemporaneous spring water (*ca* 10 ‰) is taken into account. It confirms assumed way of temperature reconstruction in the past.

The estimation of temperature time record for India is more problematic, as the dependence between $\delta^{18}O$ and temperature of precipitation and spring water is unknown. If we assume the gradient temperature of $\delta^{18}O$ the same as in Poland and Δ values characteristic for the southern England (-1.7 and -2.5 ‰), the precipitation temperature at present, estimated on the basis of $\delta^{18}O$ in modern tufa sample, would be *ca* 22°C. This value is too low in comparison with 28-29°C of water in streams, if deposition of tufa took place in summer time mainly, when biogenic processes are intensive. The other combinations of model parameters (grad $\delta^{18}O$ and Δ values) give lower temperature values in every case.

The reconstructed temperature curves in ca 500-12,000 for Poland and 0-13,400 BP for India are shown in **Fig. 8**. The width of both curves is bordered by temperature values calculated for maximum and minimum Δ values.

6. WARM/DRY AND WET/HUMID PHASES IN THE HOLOCENE OF POLAND AND INDIA

The time records of $\delta^{18}O$ and estimated temperature cover 500-12,000 BP for Poland and 0-13,500 BP for Orissa (India). Periods of carbonate sedimentation started in different times in the southern and south-eastern Poland, *i.e.* at 9600 BP in Cracow and at 11,800 BP in the Lublin Upland. This difference is determined by environment of sedimentation, which determined the type of tufas: high-energy water tufas in the Cracow Upland

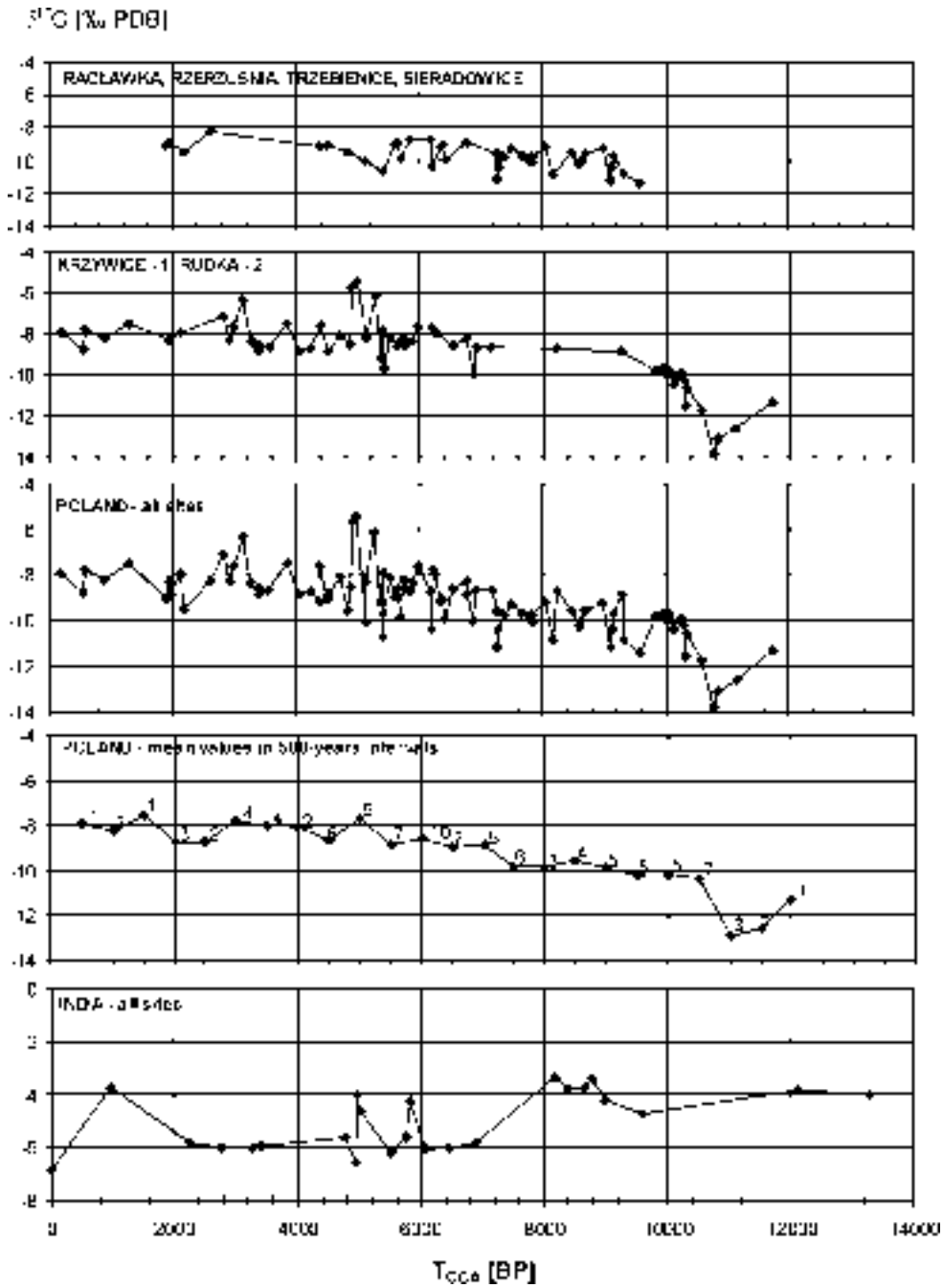

Fig. 7. *Time record of $\delta^{18}O$ of southern (Racławka, Rzerzuśnia, Trzebienice and Sieradowice), south-eastern Poland (Krzywice-1 and Rudka-2), all sites of Poland together and all India sites. Additionally, curve of mean values of $\delta^{18}O$ in 500-years intervals is given, which was used for estimation of temperature ranges shown in Fig. 8. The numbers near points on the Figure give the numbers of $\delta^{18}O$ results in 500-years intervals.*

(Racławka, Rzerzuśnia and Trzebienice) and low-energy water in the Lublin Upland (Krzywice-1, Rudka-2 and Sieradowice). The longest time records of $\delta^{18}O$ and $\delta^{13}C$ are observed for Krzywice-1 (**Figs. 5** and **7**) depending also on possibility of more detailed sampling of semi-limnic sediments. The processes of tufa deposition have been still observed both in Poland and in Orissa, although no isotope analysis of Polish sites for the last 500 years has been made.

The changes of oxygen isotope composition as the function of the age can be transformed on temperature time record. The frequency distribution of tufa samples, in division on time ranges, should be connected with intense precipitation and, because of this, with humid climatic phases. Warm and humid phases are especially favourable environmental conditions for tufa deposition.

Both climatic curves for Poland and India (**Figs 7** and **8**) indicate trends of temperature changes. They are opposite – increasing for Poland and decreasing for India in the whole period of 12,000 years. Numerous warmer and cooler fluctuations are visible on curves. The confidence level of fluctuations for Poland is higher owing to a greater number of experimental points (99) than for India (24).

The shape of both temperature curves at their beginning is completely different. The Holocene warming is visible before 10,000 years BP on the Polish curve, immediate decrease of temperature to this time is clear on the Indian curve. The similar directions of changes of $\delta^{18}O$ (and temperature) for both curves are shown in time periods:

- Lower values, indicating cooler climatic conditions, are observed at *ca* 9600-9400, 8000-7500, 5800-5200, 4500-4200, and 2500-1800 BP;
- Higher values, dependant on warmer periods, are visible at *ca* 9200-8200, 6200-4500 (with several relatively high fluctuations on both curves), and 1800-500 BP. After *ca* 1000 BP until present, the temperature decreased to final 23 in India and 9°C in Poland.

It may be noticed that frequency of samples in warmer periods are the highest, which means humid climatic conditions. Because of difference in geographical position of India and Poland, we can assume, that indicated warm and cool periods have global character.

7. CONCLUSIONS

$\delta^{18}O$ time records, based on the radiocarbon time scale, in calcareous tufa provide information on temperature changes during the last *ca* 12,000 years in the south-eastern Poland and 13,500 years in India (Orissa). Reconstructed temperature values are realistic and reflect mean annual temperature of air in Poland and mean annual temperature of water in streams for Orissa. The mean annual water temperature is several degrees lower than the mean annual air temperature. The general trends of temperature changes in both countries are opposite; starting at *ca* 13,500 BP the mean annual temperature is decreasing in Orissa until present. In the range of 12,000-11,000 BP the temperature decreased, and after this time increased again in Poland. Observed temperature fluctuations, with different amplitudes, have been correlated in time. Some warmer and cooler phases of the same age ranges occurred in Poland and India, indicating their global character.

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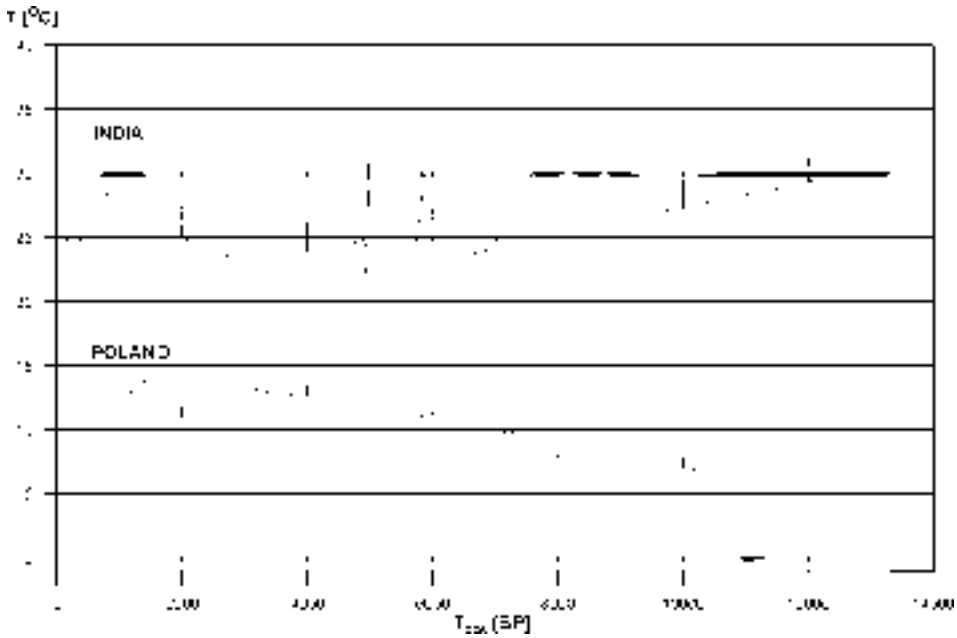

Fig. 8. *Temperature time record for Poland and India estimated with assumption of isotope kinetic fractionation effect in sedimentary processes of tufa. The ranges of temperature were determined for minimal and maximal values of Δ according to (5.1) Equation.*

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TIME RECORD OF PALAEOHYDROLOGIC CHANGES IN THE DEVELOPMENT OF MIRES DURING THE LATE GLACIAL AND HOLOCENE, NORTH PODLASIE LOWLAND AND HOLY CROSS MTS

SŁAWOMIR ŻUREK[1], DANUTA J. MICHCZYŃSKA[2] and ANNA PAZDUR[2]

[1]*Institute of Geography, Świętokrzyski University,*
Świętokrzyska 15, PL-25-406 Kielce, Poland
(e-mail: slavomir.zurek@pu.kielce.pl)
[2]*Department of Radioisotopes, Institute of Physics, Silesian University of Technology,*
Krzywoustego 2, PL-44-100 Gliwice, Poland
(e-mail: danuta.michczynska@radiocarbon.gliwice.pl)

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Abstract: Radiocarbon dating of mire sediments is useful tool for reconstruction of time scale of wet and dry phases during the Late Glacial and Holocene. The method is applied here to determine palaeohydrological conditions of some Polish regions. On the basis of ^{14}C dating of sediment profiles from North Podlasie Lowland and southern piedmont of Holy Cross Mts., duration of wet (1100-1400, 2100-2600, 4700-5000, 7300-7500, 8000-8400, 8800-9200 and 10,500-10,850 BP) and dry (1700-2200, 2600-2800, 3400-3700, *ca* 4000 and 4500, 5100-5700, *ca* 6400, 6900-7100, 9200-9300, *ca* 10,100 and 10,900 BP) periods is suggested.

1. INTRODUCTION

The mire is composed of four parts: vegetation, water, acrotelm and peat deposit. Decomposition of plant remains in mire differs in the relation to above and underground parts of plants. In contrast to the complete decomposition and mineralization of the aboveground parts, resulting in the production of humus, decay processes of underground, submerged plant remains produce undecomposed peat fibre. Transformation of plant matter into peat takes place in the acrotelm layer, where aerobes, actinomycetales and fungi transform biomass into humus in periodical aerate conditions. Structural plant remains together with humus reach lower, highly hydrated deposit layer. Here, in anaerobic conditions, minor changes occur; peat is exposed to anaerobic bacteria activity that leads only to weak mineralization process, not to peat humification.

The ratio of undecomposed remains to humus in peat depends on different water conditions. In wide valley flooded by stagnating water for a long time medium and highly decomposed, plastic, often silt-covered reed fen peat is deposited. Under conditions of short-time flooding and constant inflow of ground water medium decomposed, rather fibrous tall sedge peat is accumulated. When shorter flooding with longer ground water presence occur, accumulation of highly decomposed, granulous-amorphous forest peat is observed as well. Regular and constant ground-water inflow, often ascending, and absence of flooding lead to accumulation of slightly decomposed sedge-moss peat with fibrous-spongy structure. Gradual reduction of ground-water flow creates transition bogs, and, when supplied with rainfall, raised bogs. Whole year's superiority of rainfall over evaporation, and its corollary - presence of ground water in the surface level of mires leads to sedimentation of slightly decomposed sphagnum peat, whereas its periodic subsidence results in accumulation of medium and highly decomposed cotton-grass peat material. Presence of wood and tree trunks in raised bog peat testifies to the reduction of water level and mire afforestation, what can result from climatical change (dry phase) or other, local changes (e.g. erosion of the dome and drainage of its slopes). As a consequence, cessation or considerable reduction of the raised bog peat production follows. When wetter period comes and ground-water table rises slightly humified raised bog grass peat is accumulated again. Persisting lowering of ground-water table in fen bogs causes high peat humification and its gradual mucking. Thus climate, through changes of humidity and temperature, controls development of valley

fen bog, transition bog and raised bog in watershed zone. The control is realised by supplying of concave landforms i.e. various depressions and valleys, where the peat formation process is located, with water.

Initial stage of mire formation in the territory of Poland is dated back to the late Vistulian (Żurek 1990, 1993). During warm periods of the Late Glacial more than tencentimetre strata of the moss-fenn were deposited in shallow depressions. Melting of dead or ground ice resulted in greater depth of hollows and in their flooding, what is reflected by the presence of gyttja superimposed over the peat. During the cold oscillations, dunes often encroached onto wetlands, and so blown sands covered the peat.

The dominant feature of the early Holocene landscape represented lakes, with moss fen mires on the shores. At first deep, these concave landforms were subjected to paludification because of the ground-water table was few metres beneath its present state; bottom of the depressions were often supplied by waters of head from deeper water-bearing horizon. In isolated depressions, moss fenn peat accumulated. Initial process of peat formation did not cease generally but was rather reduced to peat production in dry periods. While at the beginning of Mezoholocene water level raised, during the second half of the period it dropped. At that time a lot of shallower lakes that were subjected to the process of peat accumulation disappeared. On the other hand, rise of water level, resulting from permanently increasing accumulation, caused swamping of hitherto dry depressions and higher altitude areas within the local relief. A variety of mires characterised with a particular peat type appeared during the period: apart from moss fen mire, forest fen, reed fen and transitional bog are to be encountered. Further, intensification of mire development occurred at the beginning of Subboreal and Subatlantic periods. In valleys dominated supreme mires supplied with surface and ground water such as sedge fen and alder swamp; for watershed area transition and raised bogs are to be mentioned.

Reflection of human activity can be traced in the Polish peat deposits through the past thousand years. Various form and intensity of deforestation has contributed to transformation of forest communities into open moss-sedge mires and sedge fens, clearance of vegetation on slopes in valleys and depressions has triggered process of covering the valley mires by alluvial or deluvial silts. However, substantial cause of the mire development variations is still the natural water regime. The evidence of environmental humidity represent gyttja, chalk lake insertions in peat, decrease of peat decomposition degree, paludification of hitherto dry depressions, fen spring development, forest and shrubs retreat for the benefit of open associations like rushes, moss-sedge mires or rushes entering into transitional or moss-sedge mires. Conversely, increase of peat decomposition degree, afforestation of mires, lake terrestrialization, appearance of open communities with ferns, shrubs and sedge *Carex paradoxa* testify to dry climatic phase, drainage and lowering of ground-water level.

2. MATERIAL FOR ^{14}C ANALYSIS

Profiles of sediments from North Podlasie Lowland

The Białostocka Plateau that belongs to the North Podlasie Lowland (**Fig. 1**) is apparently distinguished from other early glacial marainic plateaux. Numerous outflow depressions with fossil lakes, narrowing and widening river valleys, lofty kame hills, morainic and outwash plains resemble the last glaciation landscape. It differs only in absence of lakes and outflowless depressions. Two of the kettle holes, covered by forest vegetation and protected within natural reservations "Stare Biele" and "Jesionowe Góry" with mire Machnacz, have been meticulously explored from the point of genesis of the peat deposits (Żurek, 1992, 1996a and 2000). Stare Biele mire is an outflow depression with numerous bays, of elliptic shape with 4 km and 1.5 km long axes. Position plan and cross section of the mire can be found in the article of S. Żurek and A. Pazdur (1999). Marginal zone of this carr mire includes fragments of transition and raised bogs. Sondage that was to bring the evidence on strata succession in few sections demonstrated that the thickness of peat, superimposed over thin gyttja layers, varied from 1.5 to 2 metres for most of the sampled spots (**Table 1**). Sedge-moss schwingmoore spread throughout the lakes, which, consequently, suffered from rapid afforestation with alder communities dominating for a long period. In places, within the upper part of the strata succession, alder peat is covered by sedge-moss fen peat. At the bottom of alder peat, in depth of some 1-1.3 m, occurs dark, highly humified, clammy layer indicating the period of the deposit's drainage. This layer was sampled for dating at three different places within the mire. Far away from the centre, in south-western bay, two highly humified layers were found in the peat that overlies a fossil upper terrace. Drilling (up to 10 m) in a deep kettle hole with a diameter little more than 10 m situated in northern bay showed that peat deposits, which are underlain with fine detrital gyttja (see **Table 1**) reach depth of 4.25 m.

Profiles of sediments from Białe Ługi, Holy Cross Mts.

Mire Białe Ługi, (southern piedmont of Holy Cross Mts., **Fig. 1**) occupies 1 km wide and few km long fossil valley between Belnianka (Nida tributary) and Czarna Staszowska (Vistula tributary). The valley is filled by raised peat over transitional and fen peat. There is also carr peat located on the both valley banks, where small rivers Trupień and Czarna are being formed. In 1994-1998, ten stratigraphical cross-sections of deposits were made and a macro-remain analysis of 18 bores was carried out (Żurek, 2001); the stratigraphical section and the geological profiles can be found in Żurek and Pazdur (1999). Roof part of the succession (up to 0.8-1.0 m depth) is built by slightly decomposed raised sphagnum peat over highly decomposed cotton-grass raised peat. Beneath the latter slightly and medium decomposed sedge-moss transition peat is present, and in the bottom part of the profile sedge-moss fen peat and brown-moss peat are encountered. In the sediments of the Białe Ługi mire two 5-15 cm thick strata of highly decomposed black peat were distin-

guished. The upper one occurs at the depth of 0.8 to 1-1.2 m, on the border between deposits of transition and raised peat. Within the black peat stratum, under it or over a dozen centimetres above fine 2-3 cm thick fire indicating layers of charcoal are incorporated. These represent probably an evidence of dry stage, when large fire may likely have occurred. The second, lower stratum of highly humified deposit, richer in wood remains, is located at the bottom part of the whole succession, on the border between transition bog and fen peat.

3. METHODS AND RESULTS OF ^{14}C DATING

Samples that were submitted for radiocarbon dating consisted of solely organic sediments. According to low portion of carbon in the samples, the pre-treatment of 4% HCl washing was chosen. After pre-treatment and carbonisation the samples were combusted, and CO_2 was purified by standard method used in Gliwice Radiocarbon Laboratory (Pazdur and Pazdur, 1986). Finally, ^{14}C activity measurements were carried out by gas proportional counting techniques (Pazdur *et al.,* 2000). Results of ^{14}C dating from Gliwice Radiocarbon Laboratory are listed in **Table 1**, marked with laboratory code Gd. Apart from these, determinations measured in other radiocarbon laboratories are to be found here, namely, dates with lab codes SRR-NERC (Scotland), Hv (Hannover, Germany), TA (Tartu, Estonia), Lod (Łódź, Poland) and those from Leningrad, now Petersburg, laboratory (Russia).

The values of ^{14}C age listed in **Table 1** represent conventional radiocarbon age determinations calculated according to the procedure of Stuiver and Polach (1977).

4. ^{14}C EVIDENCE OF PALAEOHYDROLOGIC EVENTS

Long-term hydrologic changes have specific consequences for the environment of mires. Climate desiccation causes lowering of ground-water table, what effect changes of physical and chemical properties of upper peat layer. At first, increase of the peat decomposition degree should be mentioned. Highly humified peat layers of dark colour (when fresh) thick from 5 up to 20-30 cm have been identified in course of stratigraphic studies of various fen and bog deposits (Żurek, 1995). Sometimes in higher decomposed peat (carr, reed fen, high-sedge fen, cottongrass) black and clammy layers are observed. These testify to the dry period of longer duration, when peat production was drastically limited or stopped. Instead of organic matter accumulation, decomposition process and its mineralization began, proceeding from top towards the bottom levels. Nowadays, in artificially drained peatlands, this process, called mucking, leads to high decomposition and further to granulization of upper peat layers (Okruszko, 1960).

In the peat profiles from Biebrza basin or Białostocka Plateau, dated by ^{14}C, drainage led only to the increase of decomposition degree (to 60-80%) without indices of muck granules. Clamminess of highly decomposed peat

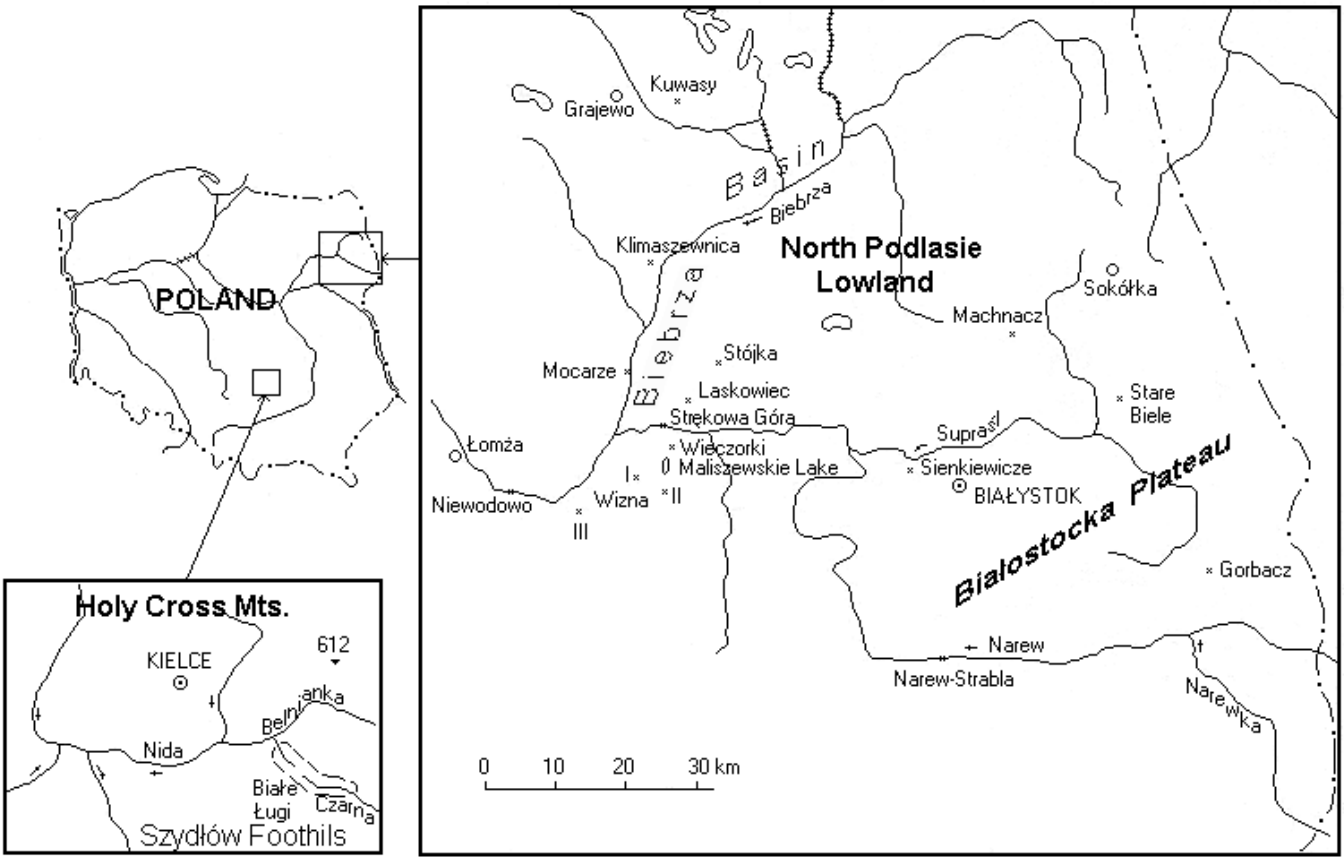

Fig. 1. Localization of investigated mires. Linear scale is the same for both window.

Table 1. *^{14}C dating results of peat samples from different sites of Poland. All dated samples came from NE Poland except Białe Ługi site (Central Poland). The symbols and numbers after slash in the column "Name of samples" indicate profile. Roman numbers (I, II, III)for Wizna mean different sites. Depth = conventional depth in profile.*

No.	Name of sample	Depth [cm]	Lab. no.	^{14}C Age [BP]	Material	Altitude [m asl]	References
1	Białe Ługi 1/13	315-320	Gd-9498	10880±250	sedge-moss fen p.	256,3	Żurek, Pazdur, 1999
2	Białe Ługi 2/21	95-100	Gd-11211	3480±80	cotton-grass p.	256,5	Żurek 1996b
3	Białe Ługi 3/21	175-185	Gd-10320	10170±120	sedge-sphag. p.	256,5	Żurek, Pazdur, 1999
4	Białe Ługi 4/14	405-408	Gd-9508	6940±750	humus with sand	256,3	Żurek, Pazdur, 1999
5	Białe Ługi 13/21	100-105	Gd-15137	2630±90	*Eriophorum p.*	256	not published
6	Białe Ługi 14/21	110-115	Gd-12266	6470±80	*Sphagnum-Carex p.*	256	not published
7	Białe Ługi 15/21	180-185	Gd-15135	8890±140	*Carex p.*	256	not published
8	Białe Ługi 16/21	190-195	Gd-15131	8750±150	*Carex p.*	256	not published
9	Białe Ługi 17/14	90-95	Gd-15129	1830±100	*Carex-Sphagnum p.*	256	not published
10	Białe Ługi 18/14	100-105	Gd-15127	2450±90	*Carex-Sphagnum p.*	256	not published
5	Biebrza Dolna 1/ Stójka (Ławki)	112-118	Gd-7825	2810±60	osier peat	104,1	Żurek, Pazdur, 1999
6	Biebrza Dolna 2/ Stójka (Ławki)	125-130	Gd-7826	5110±60	osier peat	104,1	Żurek, Pazdur, 1999
7	Biebrza Dolna 3/ Stójka (Ławki)	270-280	Gd-10491	8450±100	brown-moss peat	104,1	Żurek, Pazdur, 1999
8	Gorbacz 1	254-267	Gd-4487	8000±170	detrital gyttja		Wicik, 1989
9	Gorbacz 2	180-200	Gd-6172	1460±90	bog peat		Wicik, 1989
10	Klimaszewnica /27	145-152	Gd-10492	7150±80	reed-sedge peat	107,0	Żurek, Pazdur, 1999
11	Kuwasy 1/EO	95-100	Gd-7827	3650±50	alder peat	114,6	Żurek, Pazdur, 1999
12	Kuwasy 2/EO	186-191	Gd-10497	10850±150	brown-moss peat	114,6	Żurek, Pazdur, 1999
13	Laskowiec	18-23	Gd-2301	830±80	peaty formation	103,5	Żurek1987
14	Machnacz 1/ 6	405-415	Gd-5683	> 40800	sedge-moss peat	152,0	Żurek 1992
15	Machnacz 1/18	150-160	Gd-10494	7300±130	reed-sedge peat	150,5	Żurek, Pazdur, 1999
16	Machnacz 2/ 6	425-435	Gd-5864	> 43500	sedge-moss peat	152,0	Żurek 1992
17	Machnacz 2/18	372-382	Gd-10495	11690±150	brown-moss peat	150,5	Żurek, Pazdur, 1999
18	Machnacz 3/14	368-375	Gd-10499	29470±180	detrital gyttja	151,1	Żurek, Pazdur, 1999
19	Machnacz/ 14	138-148	SRR-3176	4040±50	cotton-grass p.	151,1	Haslam 1987
20	Machnacz/ 14	72-82	SRR-3175	1120±50	cotton-grass p.	151,1	Haslam 1987
21	Machnacz/ III 14	380-390	Gd-4959	11100±140	brown-moss peat	151,1	Kupryjan.1994
22	Machnacz/ III 14	330-340	Gd-6818	10370±100	detrital gyttja	151,1	Kupryjan.1994
23	Machnacz/ III 14	280-290	Gd-6819	8570±100	sedge-moss peat	151,1	Kupryjan.1994
24	Machnacz/ III 14	165-175	Gd-6824	7470±100	cotton-grass p.	151,1	Kupryjan.1994
25	Machnacz/ III 14	130-140	Gd-6820	3430±80	cotton-grass p.	151,1	Kupryjan.1994
26	Machnacz/ III 14	50-60	Gd-4966	1720±60	cotton-grass p.	151,1	Kupryjan.1994
27	Maliszewo I/Ia	477-481	Hv-5527	11460±210	peaty formation	104,1	Żurek 1978
28	Maliszewo II/Ib	186-191	TA-1077	5170±100	detrital gyttja	104,1	Żurek 1986
29	Maliszewo III/II	370-380	TA-1078	8940±120	sedge peat	104,5	Żurek 1986
30	Maliszewo IV/II	125-135	TA-1076	2350±100	reed peat	104,5	Żurek 1986
31	Maliszewo V/Ic	205-212	Gd-10490	5720±110	detrital gyttja	104,1	Żurek, Pazdur, 1999
32	Mocarze Ia	27-32	Gd-2302	1460±100	mud	102,5	Żurek1987
33	Narew/ Narew-Strabla	160-170	Leningrad	3800±70	wood of alder	121,5	Czeczuga1979
34	Narew/Narew-Strabla	50	Leningrad	1470±50	wood of oak	121,5	Czeczuga1979
35	Niewodowo	200-230	Lod-27	1420±130	oak trunk	98,0	Musiał, Strasz.,1988
36	Sienkiewicze 2	33-38	Gd-2306	940±100	muddy-alluvium f.	119,0	Żurek1987
37	Sienkiewicze 3	13-18	Gd-2303	670±90	peaty-muddy f.	119,0	Żurek1987
38	Stare Biele 1/I	115-120	Gd-9506	1700±210	alder swamp peat	143,0	Żurek, Pazdur, 1999
39	Stare Biele 2/I	180-190	Gd-11212	2690±70	alder peat	143,0	Żurek, Pazdur, 1999
40	Stare Biele 3/I	245-255	Gd-10321	4000±120	alder peat	143,0	Żurek, Pazdur, 1999
41	Stare Biele 4/I	995-1005	Gd-9503	13900±310	fine-detrital gyttja	143,0	Żurek, Pazdur, 1999
42	Stare Biele 5/II	94-100	Gd-9497	2190±130	alder peat	143,0	Żurek 1996b
43	Stare Biele 6/VII	120-130	Gd-10337	5310±100	alder peat	143,0	Żurek, Pazdur, 1999
44	Stare Biele 7/24	170-180	Gd-7748	6420±60	alder peat	146,0	Żurek, Pazdur, 1999
45	Stare Biele 8/29	110-118	Gd-10388	4480±130	alder peat	143,0	Żurek, Pazdur, 1999
46	Stare Biele 9/63	150-163	Gd-10493	9010±120	moss p. + wood	143,0	Żurek, Pazdur, 1999
47	Wieczorki	20-25	Gd-1820	1520±70	peaty formation	105,0	Żurek1987

48	Wizna 1/I	525-535	Gd-2017	12610±190	sedge-moss peat	104,5	Żurek 1986
49	Wizna 10/I	535-542	Gd-2084	12710±240	detr.-clayey g.	104,5	Żurek 1986
50	Wizna 11/85/ Maliszewo I	467-473	Gd-2562	11730±450	peaty formation	104,1	Balw.Żur.1989
51	Wizna 11/Góra Strękowa	145-155	Gd-1726	2210±70	sedge peat	101,5	Żurek1987
52	Wizna 12/Góra Strękowa	110-120	Gd-1727	1430±60	sedge peat	101,5	Żurek1987
53	Wizna 13/85/ Maliszewo I	362-367	Gd-2563	9400±500	calcareous gyttja	104,1	Balw.Żur.1989
54	Wizna 14/ Maliszewo I	240-245	Gd-2504	7960±180	calc. gyttja, wood.	104,1	Balw.Żur.1989
55	Wizna 15/ Maliszewo I	165-170	Gd-4020	3340±120	detrital g. + peat	104,1	Balw.Żur.1987
56	Wizna 16/ Maliszewo I	47-52	Gd-4021	1600±100	detr.-calc. gyttja	104,1	Balw.Żur.1989
57	Wizna 18/ Maliszewo I	140-145	Gd-4334	4820±100	detrital gyttja	104,1	Balwierz1986
58	Wizna 19/ Maliszewo I	70-78	Gd-4299	2770±90	calcareous gyttja	104,1	Balwierz1986
59	Wizna 2/I	425-435	Gd-2010	9270±120	sedge peat	104,5	Żurek 1986
60	Wizna 20/ Maliszewo I	35-40	Gd-2869	1770±100	detrital gyttja	104,1	Balwierz1986
61	Wizna 4/II	310-320	Gd-1530	9450±90	osier peat	106,0	Żurek 1986
62	Wizna 5/III	130-142	Gd-1534	4270±70	sedge peat	102,0	Żurek 1986
63	Wizna 6/II	65-75	Gd-1595	2050±40	alder-swamp peat	106,0	Żurek 1986
64	Wizna 7/III	50-60	Gd-1596	1150±40	reed-sedge peat	102,0	Żurek 1986
65	Wizna 8/ Maliszewo II	200-210	Gd-2086	7440±150	sedge peat	104,5	Żurek 1986
66	Wizna 9/I	518-525	Gd-2085	12430±170	sedge-moss peat	104,5	Żurek 1986

did not resulted from silting but from partly mineralization of organic matter, since the ash content in the discussed layers is little higher than in underlying and overlying strata. Hard granules found now and then are small fragments of charcoal coming from thin, black, fire-indicating layers. Highly decomposed layers (ca. 40-50 %) occur also within slightly humified sedge-moss fen peat. Besides sedge and brown-moss, remains of shrubs, ferns and some tall-sedge growing in mires with lowered water e.g. *Carex paradoxa* appear here as well.

Beginnings of biogenic accumulation

Postglacial accumulation of biogenic formation was initiated by climatic change. In warmer Lateglacial periods brown-moss peat or peaty formation were deposited, representing thus first stage of periglacial tundra paludification. Covering of biogenic deposits by gyttja testifies to the beginning of thermokarst process, which in Maliszewskie Lake (**Fig. 1**), as results of peaty formations dating (Gd-2562: 11,730±450 BP, Hv-5527: 11,460±210 BP) manifest it, took place during Alleröd (Żurek, 1978; Balwierz and Żurek, 1987 and 1989). Melting of permafrost in the Machnacz mire (Białostocka Plateau) began probably earlier, in Bölling (Kupryjanowicz, 1991) and was intensified in Alleröd, as backed by one date for brown-moss peat (Gd-10495: 11,690±150 BP). However, the opinion based on palynological analysis of brown-moss peat at the bottom of the Machnacz I profile about its Bölling origins has not found support in the radiocarbon dates. First result for the brown-moss peat brought value 11,100±170 BP (Gd-4959), second determination for sample from the bottom part of gyttja was as early as 29,470±170 BP (Gd-10499). The beginning of under-gyttja peat accumulation in mire Kuwasy was palynologically dated to the second part of Alleröd (Żurek, 1970), in Lower Biebrza basin (Stójka) to the Late Glacial (Oświt, 1973). These results are supplied with the radiocarbon dates from the Biebrza basin area, where was sampled a bottom of brown-moss peat, which developed in isolated depressions and was not covered by gyttja. The dates for the bottom layers of brown-moss peat in Kuwasy and Lower Biebrza are 10,850±150 BP (Gd-10497) and 8450±150 BP (Gd-10491), respectively; localisation of Kuwasy profile EO and the section was published by Żurek and Dzięczkowski (1971). It cannot be excluded that the beginning of peat accumulation in Lower Biebrza is not connected with ground ice melting in substratum but with rise of ground-water table or lake-water level in the neighbourhood, since in the nearby situated profile Stójka 14a (Oświt, 1973) Late Glacial brown-moss peat is covered by gyttja. Gyttja from the deep thermokarst depression of Stare Biele, dated to 13,900±310 BP (Gd-9503), is probably of later origin, since the pollen analysis (Kupryjanowicz 1998 and 2000) point to the Older Dryas period. Accordingly, the beginnings of mire formation in the North-East of Poland varied, and ranged from Bölling to Alleröd. It cannot be determined whether this initial stage of peat formation is connected only with the melting processes and when it came to an end. Current state of knowledge does not allow to choose any of alternatives (Nowaczyk, 1994) represented by the Late Glacial (Kozarski, 1963) and early Holocene periods (Stasiak, 1971; Seibutis, 1963).

Dry phases in mires

Approaching from the point of stratigraphy and changes of peat decomposition degree, humidity changes in Polish mires have not been dated in detail. Two recurrent surfaces in raised bog Bór nad Czerwonym (Podhale Basin) were observed in Subboreal Period (Obidowicz, 1978). One highly decomposed layer connected with Subboreal period was also found in a fen in the Biebrza basin (Oświt, 1973; Żurek, 1970). Recently, 2-3 highly decomposed layers situated one above the other have been identified in the mires Stare Biele (Knyszyńska Wilderness: Żurek, 1996a) and Białe Ługi in southern

piedmont of the Holy Cross Mts (Żurek, 1996b). These enable to undertake a test dating of dry periods and humidity fluctuations recorded in peat.

In the shallow profile 21 in Białe Ługi mire (see **Table 1**) both of two highly decomposed layers were dated, resulting in the determinations 3480±80 BP (Gd-11211) for the upper (in the depth of 95-100 cm) and 10,170±120 BP (Gd-10320) for the lower (depth 175-185cm) one. In the profile 13, located some 100 m away from the former one, the bottom layer in the depth of 315-320 cm was dated to 10,880±250 BP (Gd-9498). Considering the situation in the profile 14, initially, the age of the lowermost part of the 4m deep succession could not be determined by the ^{14}C. The dating of organic layers (humus with sand) under the peat gave result 6940±750 BP (Gd-9508) and surprisingly, the age of the bottom part of peat over humus has been stated as 12,900±360 BP (Gd-14015). In the profile 6A (Żurek, 2001a, not included in **Table 1**) of this mire 2 cm thick organic layer from the depth of 212-214 cm, under the peat, was dated to 18,300±600 BP (Gd-14020). Hypsometric differences between position of bottom highly humified layers in the profiles 21 and 13 (ca. 1.5 m, **Table 1**) can be viewed as indicating subsidence of the central part of the deposit in a Younger Dryas as a consequence of the permafrost extinction.

The date 13,900±310 BP (Gd-9503, see **Table 1**) for the bottom sample of detrital gyttja from the kettle hole in northern bay of Stare Biele mire seems to be too early when compared to the palynological investigations setting the sample towards the end of Older Dryas (Kupryjanowicz, 2000). In the 4m deep succession of forest and sedge-moss peat deposit, three strata of highly humified peat (with the decomposition degree of 60-70%) were observed, the dating of which brought following results. The lower layer of highly humified dark forest peat from the depth of 170-180 cm located in north-western bay, representing the earliest Atlantic drainage period, was dated to 6420±60 BP (Gd-7748). The second drainage period, reflected by highly humified clammy alder peat in the central part of the mire (profile 7, **Table 1**), deposited 120-130 cm under present surface, is set to 5310±100 BP (Gd-10377); it is the period, when terrrestrialization of lakes and afforestation of the central part of the mire took place. Profile 29 situated in western bay brought the evidence of highly humified layer in the depth of 1.1-1.18 m, which was dated to 4480±130 BP (Gd-10388). In northwestern bay, within a small area of transition bog (sedge moss coniferous forest *Carici chordorrhizae – Pinetum*) 10 m deep kettle hole was discovered. Here, where the accumulation rate was three times higher in comparison to alder swamp peat in the rest of the mire, three highly humified forest peat layers originated in Neoholocene were identified at 1.15-1.20, 1.8-1,9 and 2.45-2.55 m below present surface. According to ^{14}C dating, two earlier dry stages took place around 4000±120 BP (Gd-10321) and 2690±70 BP (Gd-11212), respectively; the latest is dated back to 1700±210 BP (Gd-9506). Regarding the palynological evidence, the earliest layer suffered from the lack of material and therefore it can be only stated that it is situated over Early Subboreal phase of *Pinus-Quercus* (Kupryjanowicz, 2000), the second dry period corresponds to *Pinus-Carpinus-Betula* phase; the BP date of the latest dry phase seems to be a bit younger than palynology would suggest. With the latest dry phase corresponds value Gd-9497: 2190±130 BP, measured on sample of highly decomposed deposit located in the depth of 0.94-1.00 m within the profile 2, situated in the distance of 130m from the kettle hole. Subatlantic period recorded within the mighty succession of the kettle hole probably began with moisten, sedge-moss fen associations supplanted alder carr. Dry conditions of the latest period opened the area for alder-birch forest.

In the cotton-grass bog peat of mire Machnacz an evidence of distinct dry period is represented by layer in the depth of 138-148 cm, dated to 4040±50 BP (SRR-3176, **Table 1**); in the layer hummock sphagnum and pine needles dominate (Haslam, 1987). Given the higher decomposition of peat and distinct increase of the humus content observed, Haslam showed that dry phases occur also at the levels of 136 cm, 107 cm and 96 cm under present surface.

In Biebrza basin, highly humified layers were dated at three sites. Profile Stójka 14a in the East of lower Biebrza Basin (not included in Table 1) incorporated, at the depth of 95-105 cm, a layer of osier peat that was connected with Subboreal period in the early seventies (Oświt, 1973). In the vicinity a profile with rather mighty, highly humified layer situated a little deeper (112-130 cm) has been sampled. Two radiocarbon dates, Gd-7826: 5110±60 BP and Gd-7825: 2810±60 BP, obtained for the bottom and the top of this layer show that in Subboreal period peat accumulation process was interrupted or was very slow indeed, and later, for the final phase of Subboreal, just decomposition is indicated.

Another evidence of dry phase represents highly humified dark layer, found in the depth of 150-160 cm, in deep sedge-moss fen peat of Klimaszewica. Entering of hummock sedge *Carex paradoxa* and reed communities to *Caricetum diandre* community attest to drainage. The dating of decomposed peat at 145-152 cm giving the result of 7150±80 BP (Gd-10492) brought evidence of the earliest Atlantic dry phase in this region.

Regarding situation of highly decomposed layer and its thickness, the Kuwasy profile is essentially the same as the profile 21 from Białe Ługi, what is shown also by date Gd-7827: 3650±50 BP, measured on sample coming from the bottom of forest peat at the level of 95-100 cm. While drainage in the Biebrza area caused afforestation with alder, in Białe Ługi it was cotton-grass raised bog community that entered into moss-sedge association of the transition bog.

As for the sample collection is concerned it should be stated that, unless highly decomposed layer was not thick some 5-10 cm, it was sampled as a whole and in this case an average age was received, without an opportunity of determining the length of period when peat formation was hibernated. Exceptionally, the discussed type of layer was outstandingly mighty, namely in sediments of Lower Biebrza mire, where 18 cm thick, highly humified stratum enabled to take samples from its top and the bottom;

radiocarbon dating of these samples showed that there had been a large hiatus of some 2300 years in the local peat accumulation. Furthermore, more detailed information on rate of peat accumulation processes were received when dates for peat under and over highly decomposed layer were determined. In the vicinity of the profile 21 in Białe Ługi mire, highly decomposed layers of which were dated to 3480±80 and 10,170±120 BP (see **Table 1**), respectively, almost no interruption occurred (8890±140 and 8750±150 BP), or, during later development, its duration could have been as long as 3840 years, from 6470±80 to 2630±90 BP. In the profile 14 representing the deepest spot of this mire, indices for some 620 BP-years long interruption were gathered (2450±90, 1830±100 BP). So long stagnation in the accumulation of peat as shown by dates for the profile 21 (approx. 6000 years) from the shore part of Białe Ługi mire is even more difficult to explain, when we consider that some 300 m away it lasted only some 600 years. It is possible, that Subboreal peat layer was burnt as a consequence of mire's fire.

Peat formation of Maliszewskie Lake

From the shore of Maliszewskie Lake (Wizna mire, see **Fig. 1**), a sample of detrital gyttja indicating a drainage phase and lowering of the water table (connected with the local peat formation; Żurek, 1978 and 1986) was submitted for dating. The first result of the gyttja dating (Gd-4020: 3340±120 BP) from this reference site of north-eastern Poland is questionable, because of probable contamination and rejuvenation of the deposit (Balwierz and Żurek, 1987). In the synthetic study on the palaeohydrology of Polish lakes and mires (Ralska-Jasiewiczowa and Latałowa, 1996) a hiatus spanned between 3500 and 7000 years BP was suggested for this profile. Dating of dark, detrital gyttja, located approximately 10 cm lower than in other profiles (205-212 cm), gave result 5720±110 BP (Gd-10490) connecting thus the local drainage period towards the end of Atlantic period, what has already been shown by measurement TA-10077: 5170±100 BP (Żurek, 1986). It seems that hiatus in so long period of time is absent - derital-calcareous gyttja from level 140-145 cm was dated to 4820±100 BP (Gd-4334). Temporary results of pollen analysis of the detrital gyttja sediment (205-212 cm) also point to the boundary of Atlantis and Subboreal periods (Balwierz, personal communication).

Wet phases in mires

Principal indicators of rise of the ground-water table are decrease of peat decomposition degree, retreat of trees and shrubs, increase of reeds and sedges populations, and finally, submerging of the peat deposit.

The latest phase of increase of moisture appeared in the vicinity of Góra Strękowa. Peat from the old riverbed exposed by lateral erosion of the channel was covered by sandy alluvial loam dated to 1430±60 BP (Gd-1727; Żurek, 1987). Climatic change leading to more humid conditions caused avulsion of the river channel. Oaks found in the river deposit of upper Narwia at Strabla (Czeczuga, 1969) and at Niewodów near Łomża (Musiał and Straszewska, 1988) were felled at this time (1470±50 and 1420±130 BP). In the channel zone of Moczarze area (Lower Biebrza basin), erosions and flows caused that around 1460±100 BP (Gd-2302) mud formations started to accumulate over sand-muddy sediments. Wet phase began little earlier, because from around 1520±70 BP (Gd-1820) peaty accumulations were formed in the shore zone of shallow raised bog in the environs of Wieczorki village (neighbourhood area of Maliszewskie Lake). Wet phase marked by increase of hollow sphagnums (*Sphagnum cuspidatum, Sphagnum recurvum*) at raised bog in Machnacz was dated to 1120±50 BP (SRR-3175; Haslam, 1987). Haslam's study (1987) that dealt with 18 sites of mires from western Ireland to north-eastern Poland allowed to establish the pattern of climatic change during Subboreal and Atlantic periods (Barber, 1993). From works on wet phases recorded abroad we would like to mention here article of Blackford and Chambers (1991) pointing to distinct decrease of peat decomposition degree in the blanket mires of Ireland and Great Britain in1400-1300 BP.

After 2810±60 BP (Gd-7825) the evidence of profile Stójka in Lower Biebrza region shows increasing amount of reed contemporarily with the birch decrease down to 25%, and peat decomposition degree going almost up to 50%. Similar situation was noted in the profile Stare Biele 1 (Żurek, 2000). Here, after 2690±70 BP alder forest retreated and bryales appeared, with birch and reed remains, i.e. sedge-moss shrub fen with constant and abundant water supply developed.

In the shore profile of Maliszewskie Lake, over dark detrital gyttja dated to 5170±110 BP (TA-1077; Żurek, 1986) grey-brown detrital-calcareous gyttja was accumulated, and in the upper whitish calcareous gyttja, indicating rapid rise of the lake water table, was present. Detrital-calcareous gyttja from the depth of 140-145 cm was dated to 4820±100 BP (Gd-4334), so wet phase began around 5000 BP and could have lasted until around 4700-4500 BP when in the profiles 1 and 29 of Stare Biele (see **Table 1**) dry phases occurred. Similarly to Stare Biele, in the kettle hole at Machnacz mire (Białostocka Plateau) after phase of moss-fen mire, with moss and low sedge, supplied with constant, moderate ground-water inflow, tall-sedge fen phase with dominating reed and tall sedge began to develop (Żurek, 1992). Surface water, connected with increased precipitation, and water inflow from little catchments supplied the mire. This moist phase lasted around 7300±130 BP (Gd-10494), what is in agreement with gyttja of Maliszewskie Lake, appearing over the sedge-moss fen peat dated to 7440±150 BP (Gd-2086).

The earlier wet period is related to the beginnings of Boreal period (Żurek, 1986). Planting mires of central Wizna with shrubs and lowering of water level were dated to 9270±120 BP (Gd-2100). Later rise of water level, decrease of peat decomposition degree and spread of low sedge *Carex lasiocarpa* resulted from abundant ground-water inflow. In the profile 9 of Stare Biele, the layer of gyttja covering the sedge-moss fen peat dated to 9010±120 BP (Gd-10493) testifies to increasing of water level as well. Uplift of water level during the initial

Younger Dryas can be reflected by presence of peat with gyttja over highly decomposed layer dated to 10,880±250 BP (Gd-9498) in the profile 13 of Białe Ługi mire and by accumulation of brown-moss peat in Kuwasy profile, which began around 10,850±250 BP (Gd-10497). It is to be added that the presence of peat with gyttja was stated only according to macroscopically observations and should be confirmed by the pollen analysis.

5. PALAEOHYDROLOGIC CHANGES IN NORTH PODLASIE LOWLAND AND THE HOLY CROSS MOUNTAINS IN LATE GLACIAL AND HOLOCENE

It seems that certain phenomena observed in the stratigraphy of mires, particularly changes of peat decomposition degree and botanical taxa spectrum, can be used to determine hydrologic conditions in the past and to reconstruct succession of dry and wet phases. As for chronology, radiocarbon dating of peat layers should be confirmed by pollen analysis. It may happen, however, that ^{14}C dates are in a strong disagreement with results of palynological investigation, being earlier or later than dating suggested by pollen spectra. Such case of major difference represent set of radiocarbon determinations for samples from profile Machnacz III (Kupryjanowicz, 1994). M. Kupryjanowicz suggested that the situation could be explained by contamination caused by using a small-diameter corer. According to him, sampling with a help of corer with bigger diameter decrease probability of contamination during sampling distinctively.

The radiocarbon dating of highly decomposed peat layers has enabled to state approximate duration of dry phases (**Fig. 2A**, after Żurek and Pazdur, 1999, changed), namely: in Subatlantic period 1700-2200 BP; in Subboreal

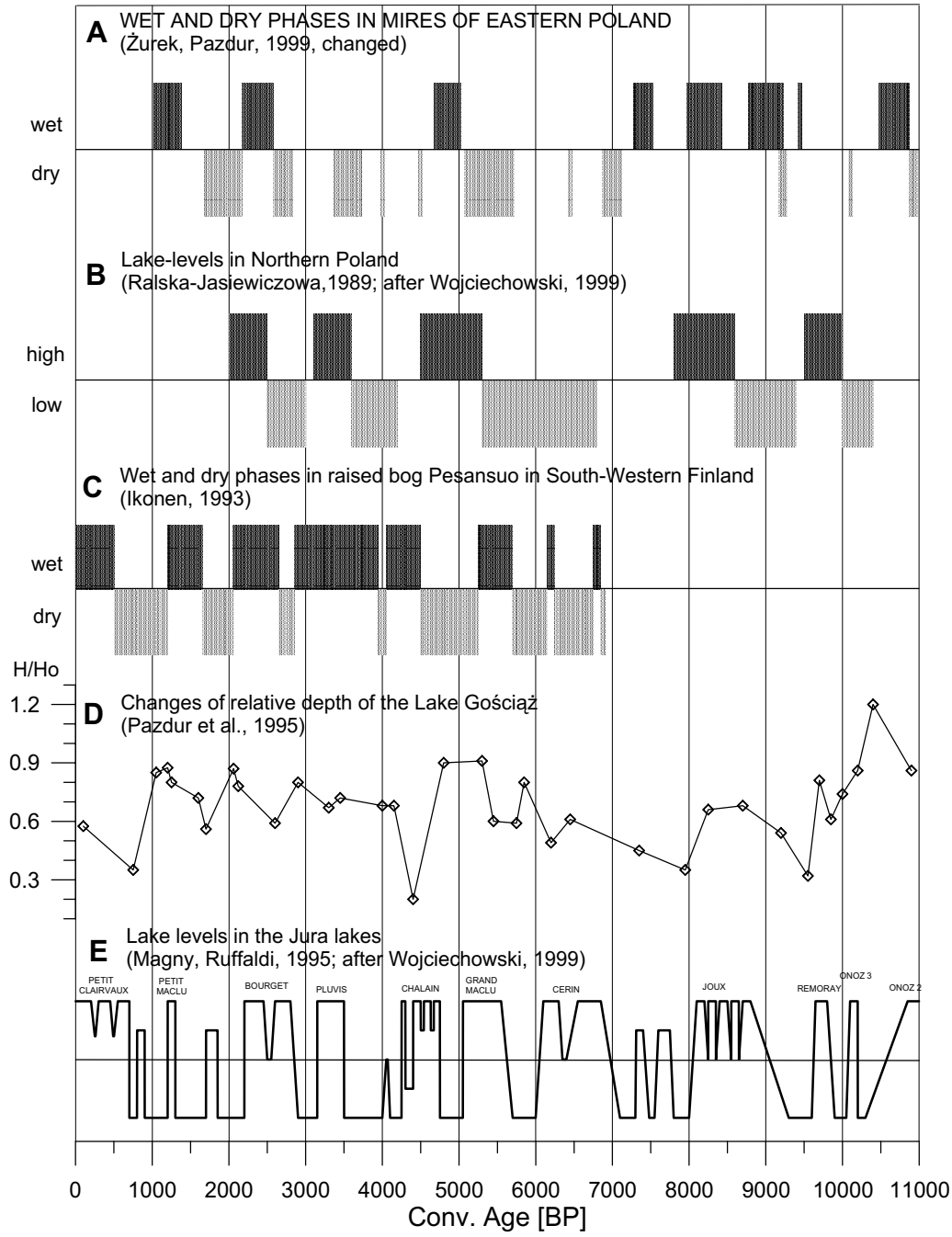

Fig. 2. *Correlation between wet and dry phases in mires of Eastern Poland and other changes of climatic features during Late Glacial and Holocene in Poland, Finland and France.*

period 2600-2800 BP, 3400-3700 BP, *ca.* 4000 BP and 4500 BP, in Atlantic period 5100-5700 BP, *ca.* 6400 BP and 6900-7100 BP; at the end of Preboreal 9200-9300 BP; at the beginning and at the end of Younger Dryas *ca.* 10,100 and 10,900 BP. On the other hand, wet phases can be approximately marked, according to the presented evidence, as follows: the middle (1100-1400 BP) and the beginning (2100-2600 BP) of Subatlantic period, the beginning of Subboreal period (4700-5000 BP), in Atlantic period 7300-7500 BP, the end (8000-8400 BP) and the beginning of Boreal period (8800-9200 BP). In Younger Dryas water table was raised during its earlier stage (10,500-10,850 BP).

Moisture changes plot for north-eastern Poland is in good agreement with the results for lakes and mires in Poland plotted in Figure 2B, elaborated by Ralska-Jasiewiczowa (1989; Starkel, 1990; Ralska-Jasiewiczowa and Latałowa, 1996).

Good agreement is apparent also for the moist phases up to 3 ka BP as recorded in the sites of north-eastern Poland and raised bog Pasänsuo (**Fig. 2C**) in south-western Finland (Ikonen, 1993). Dry and wet phases were distinguished here according to presence of rhizopod *Amphitrema flavium*, and 6 m long profile was dated by means of radiocarbon in the way that every 5 cm of succession was sampled (120 dates). The divergence refers periods 3400-3700 BP, 4700-5000 BP and 5200-5700 BP.

Similar agreement refers to high and low water level noted in Gościąż Lake (**Fig. 2D**; Pazdur *et al.*, 1994; Pazdur *et al.*, 1995), Biskupińskie Lake (Niewiarowski, 1995; Starkel *et al.*, 1996) and Kórnik-Zaniemyśl Lakes (Wojciechowski, 1999) sediments. High water levels in both regions are connected with the beginning of Subboreal and beginning of Subatlantic periods. Low water levels occurred at the end of Preboreal period, in the beginning and at the end of Atlantic period and in Subboreal period. Relatively good coincidence of high and low water-level stands with Polish and French Jura lakes (**Fig. 2E**; Magny and Ruffaldi, 1995) was shown in **Fig. 2**.

CONCLUSIONS

It should be noted that changes stated in mires sediments, especially changes in peat decomposition degree and botanical composition exploited to determine hydrologic changes in the past, especially to reconstruct of dry and moist phases in the Late Glacial and Holocene. Comparison of wet and dry phases reconstructed on basis of mires sediments from Eastern Poland are generally in good agreement with periods of high and low water level stands observed for Polish lakes, especially Gościąż Lake and lakes from Northern Poland. The disagreement between wet and dry periods pattern recorded in the Polish mires and the one reflected by the sediments of raised bog Pesänsuo in Finnland is observed for the time horizon prior 3 ka BP.

To conclude, authors' forthcoming research in the field of reconstruction of time scale for wet and dry periods pattern during the Holocene on the basis of radiocarbon dating is to be focused on exploiting of statistical methods for analysis of large sets of ^{14}C dates for peat and gyttja from various geographical regions.

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CHRONOSTRATIGRAPHY OF LATE PLEISTOCENE FLUVIAL DEPOSITS IN THE WISŁOK RIVER VALLEY BETWEEN RZESZÓW AND ŁAŃCUT, SOUTH POLAND

PIOTR GĘBICA[1], ANDRZEJ BLUSZCZ[2], ANNA PAZDUR[2] and KAZIMIERZ SZCZEPANEK[3]

[1]*Institute of Geography and Spatial Organisation, Polish Academy of Sciences, Św. Jana 22, 31-018 Cracow, Poland*
[2]*Silesian University of Technology, Institute of Physics, Department of Radioisotopes, Krzywoustego 2, 44-100 Gliwice, Poland (e-mail: pazdur@zeus.polsl.gliwice.pl)*
[3]*Institute of Botany, Jagiellonian University, Lubicz 46, 31-512 Cracow, Poland*

Key words: ALLUVIAL SEDIMENTS, WISŁOK RIVER VALLEY, RADIOCARBON DATING, LUMINESCENCE DATING, QUATERNARY

Abstract: This paper presents results of absolute dating of alluvial sedimentary series forming a rendzina terrace (higher floodplain) 7-8 m high above the Wisłok River channel and a sandy terrace 8-10 m high in the Subcarpathian Pradolina section of the Wisłok River valley. The organic mud infilling fossil depressions (palaeochannels?) in the lower part of the rendzina terrace have been dated by the radiocarbon method to more than 38,500 BP. The organic series occurring within the sandy terrace yielded three ages >36,000 BP. Results of palynological analyses carried out on both sites indicate tundra or forest-tundra environments with water-filled depressions at the time of organic sediments deposition. The top of the 8-10 m high sandy terrace is built of fluvial sands and eolian cover sands with dunes in the uppermost part. Their age has been established by means of the OSL method to 11.2±0.9 ka BP. The younger alluvial inset fill is formed of sands and silts with involutions occurring under Holocene muds. They were deposited by a braided river during the Upper Plenivistulian as indicated by two other OSL dates of 22.2±2.2 ka BP and 14.0±1.5 ka BP. Within the rendzina terrace the youngest series of Vistulian age is built with peats and silts, infilling the wide depression at the foots of sandy hillocks, dated to about 11,800 BP.

1. INTRODUCTION

The geological survey of the Wisłok River valley started at the beginning of the 20th century when Friedberg (1903) elaborated Rzeszów and Łańcut sheets of the Geological Atlas of the former Austrian Galicia. Friedberg (1903) described grey-blue clays underlying glacial gravels in the lower part of rendzina terrace in Terliczka and Łukawiec. He assigned them to the Young Pleistocene or early Holocene period. Klimaszewski assigned the middle terrace (up to 20 meters above the river bed) loess-covered to the Middle Polish (Saalian) Glaciation, and the lower-lying terrace (up to 10 meters) with overbank loams in the top to the Last Glaciation. The structure and age of the Wisłok terraces in Rzeszów were studied by Jahn (1957), Laskowska-Wysoczańska (1971) and Starkel (1972 and 1980) who dated the higher terrace sediments bearing a cover of loess or dunes to the North Polish (Vistulian) Glaciation. According to Jahn (1957) and Starkel (1960) the 6-8 m high rendzina terrace is apparently inserted in the loess-covered terrace. Starkel (1960) provided evidence for the Holocene age of the rendzina terrace in Rzeszów, which comprise alluvial inset fills of different age. It also hides remnants of older alluvia as, for example, documented by the profile in Brzeźnica in the neighbouring Wisłoka River valley, where paleochannel deposits have been dated to between 46 and 36 ky BP (Mamakowa and Starkel, 1974). Starkel (1980) cited a date of 43.9±2.1 ky for peat sample taken by himself in Łukawiec and obtained by M. Geyh in 1975. Several years ago, in the frame of the Detailed Geologic Map of Poland 1:50,000 project, geological mapping of the Rzeszów, Łańcut and Jarosław sheets has been undertaken. Results of geological mapping have been published in the form of several notes and presented during the VI Conference on Stratigraphy of Pleistocene in Poland, Czudec 1999 (Wójcik *et al.*, 1999; Zimnal, 1999).

During spring freshets of the year 2000, with the highest water level reaching 5 m above the river bed, Wisłok River made numerous undercuts in banks in the section behind Łąka where the river runs within the Subcarpathian Pradolina. When floodwaters subsided, P. Gębica found in several new exposures in the lower part of the rendzina terrace a cohesive layer of silty clay and organic mud, truncated in the upper part and covered with younger alluvial series. A similar organic series and silts were found nearby in Czarna-Podbór, in the open sand pit located on the higher 8-10 m terrace.

Undertaken researches aimed at finding an age of different sequences of Vistulian fluvial sediments. Geomorphological mapping of the Wisłok River valley bottom between Rzeszów and Łańcut was performed by P. Gębica. On the same occasion a number of accessible exposures, presenting different stratigraphical units was profiled. Information related to the range and thickness of terrace sequences have been supplemented with data obtained through geological drillings and taken from rich archive documentation on earlier boring projects. The fieldwork was also an occasion for taking samples for palynological and granulometric analyses, and for radiometric dating. Radiocarbon dating was performed on samples of peat and organic silt sediments while OSL (optically stimulated luminescence) dating was made on samples of mineral sediments.

2. GEOMORPHOLOGICAL AND GEOLOGICAL SETTING

The Wisłok River beyond Rzeszów flows within an erosional depression of the Subcarpathian Pradolina. The pradolina is distinctively bordered from the south and the north (**Fig. 1**). To the south an edge of the Kańczucka Plateau (220-280 m a.s.l.) rises, which is covered with a sequence of alluvial and glacial sediments, frequently overlain by loess, deposited on a Miocene clays (Laskowska-Wysoczańska, 1971; Zimnal, 1999). The edge of the Kolbuszowski Plateau constitutes the north border. It is built with Miocene clays, covered with preglacial alluvial sediments, fluvioglacial sands, and glacial till from the Sanian 2 (Elsterian) Glaciation. In the Subcarpathian Pradolina near Jasionka at the elevation of 210-213 m a.s.l. fluvioglacial deposits and washed glacial till cover an interstadial organic series from the Sanian 2 Glaciation (Laskowska-Wysoczańska, 1971). The bottom of the Wisłok River valley is terraced and filled with alluvia of the thickness up to 20 m. Between Rzeszów and Trzebownisko, a slightly inclined terrace plain ranges at

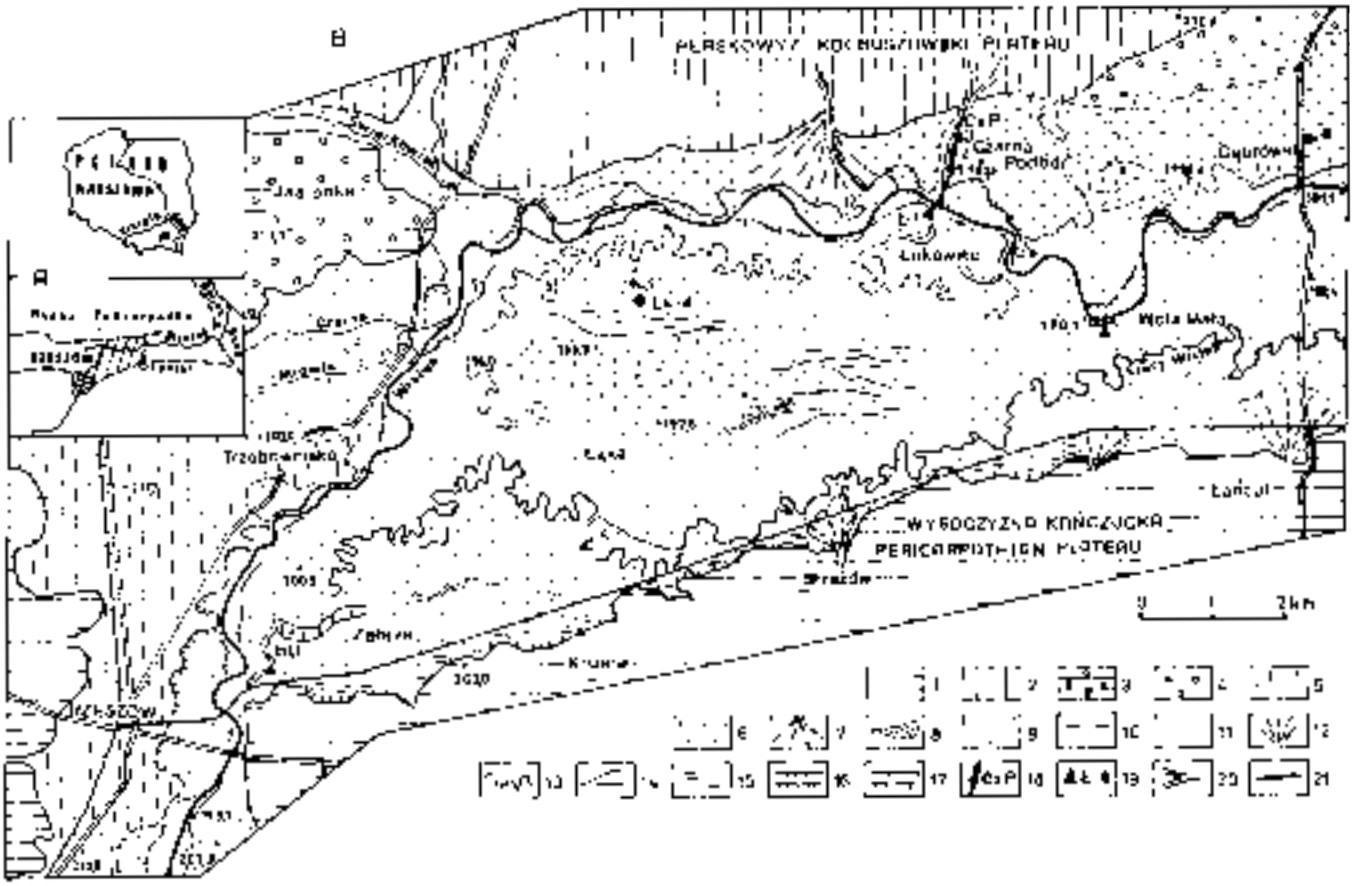

Fig. 1. *Geomorphological map of the Wisłok River valley between Rzeszów and Łańcut:*
1 – PeriCarpathian Loess Plateau, 2 –- Kolbuszowski Plateau, 3 – fluvioglacial level from the Sanian 2 Glaciation, 4 – alluvial terrace from the Middle Polish Glaciation?, 5 – loess-covered terrace plain from the Vistulian Glaciation, 6 – sandy terrace 8-10 m high, 7 – alluvial fan of the Vistulian age, 8 – dune ridges, 9 – higher floodplain (rendzina terrace) 7-10 m high, 10 – flatbottomed depressions (floodbasins), 11 – lower floodplain 3-5 m high, 12 – alluvial fan of Holocene age, 13 –- paleochannel system, 14 – traces of braided river (Late Vistulian age), 15 – peatbogs, 16 – erosional edges below 10 m, 17 – erosional edges above 10 m, 18 – geological transect with borehole numbers, 19 – excavations, 20 – roads, 21 – railway.

the elevation about 20 m above the Wisłok River level. Its upper part consists of dozen-metre-thick loess, and its lower part contains alluvial sands with organic mud insets and gravels lying on the Miocene clays. These deposits are 20 m thick and they date to the Vistulian Glaciation (Jahn, 1957). Along the left border of the valley, at the height of 8-13 m above the Wisłok River channel, a sandy terrace stretches, 0.5 to 1.5 km wide, with a wind-blown sands on the top. In places, undercut by paleomeanders, it is separated from the rendzina terrace by a 1-2 m high edge. Circular, wet depressions (thermokarstic?) and natural levees with wind-blown sands on the top have been profiled on the terrace surface. The contemporary bottom of the Wisłok River valley, 4-6 km wide, is occupied by a Holocene rendzina terrace, which is cut 10 m deep in the vicinity of Rzeszów and 7-8 m deep near Łańcut (**Fig. 1**). It forms a higher level of a floodplain that currently is not flooded even during the highest freshets. It forms an alluvial fan beyond Rzeszów, with several abandoned (due to avulsion processes) palaeomeander systems of the Wisłok River and its tributary Czarna River. The best known is a narrow and sinuous paleochannel system called Stary Wisłok abandoned after one of catastrophic floods in the half of the 18th century (Strzelecka, 1958). The rendzina terrace is built of gravels with sands in the lower part, and sands with alluvial loams and 2-4 m thick clays in the upper part. In the Łąka locality a Pleistocene sandy terrace occurs in isolated patches and it rises 1-3 meters above the floodplain (**Fig. 1**). This is probably a fragment of an alluvial fan formed by the Wisłok River during the Vistulian time, which is indicated by an archaeological findings of Mesolithic settlements (Czopek and Podgórska-Czopek, 1995). The lower level of the floodplain makes narrow bench of swampy meadow terrace at the elevation of 3-5 meters above the river channel, being several tens to 500 m wide. It is covered with meadows and brush and it is flooded almost every year during higher freshets. It is mainly built of sandy loams overlying sands with gravel. It has probably been formed during the last 150-200 years, similarly like the swampy meadow terrace of the San River (Szumański, 1986). The channel of the Wisłok River underwent partial regulation in the beginning of the 20th century, but it is not embanked. The present width of the river is about 25-35 m.

3. SITE DESCRIPTIONS

Łukawiec-1

A very interesting profile, exposing two series of alluvial deposits (**Figs 1** and **2**), was found during the geomorphological mapping of the 7 m high terrace on the right bank of the Wisłok river. The lower series consisted of fine sands covered with alternately stratified silt and yellow-olive sand. In the upper part of the sequence sand distinctively graded into blue silty clays which in turn gradually graded into organic silts and peaty mud of 0.6 metre thickness. At the contact between the organogenic layer and the underlying silts and sands numerous sedimentary involutions and cryogenic fissure structure filled with organic material, had developed. The top of organogenic series has been truncated and covered with the younger series of alluvial sediments of 5 m thickness. This younger series consists mainly of sands with coarse gravel (channel deposits) and sets of cross-bedded sands with sandy silt insets (meander point bar deposits) and of overbank alluvial loams in the top. The peaty mud sample taken at the elevation of 2 m above the present water level in the river channel yielded the radiocarbon age >38,500 BP (Gd-15157). Pollen analyses made on eight samples taken from peaty mud organic silts in the profile Łukawiec-1 (**Fig. 3**) revealed large amounts of herbaceous plants (NAP), particularly *Cyperaceae* and grasses (*Poaceae*). Tree pollen percentage reaches almost 25% of the total pollen count only in the top sample; in other samples it varies between 9.8% and 20.2%. The taxonomic composition of samples is not much diversified. Among the trees only pollen of common pine (*Pinus silvestris*) and of stone pine (*Pinus cembra*) are abundant in all samples. Among the bushes relatively high scores have been recorded for dwarf birch (*Betula nana*). A few pollen grains of willow (*Salix*), sporadic pollen grains of alder (*Alnus viridis*) and abundant colonies of *Pediastrum* algae have been found. They indicate the presence of shallow water depressions, at least periodic. The results enable stating that the most characteristic feature of the landscape of the area surrounding this site was a prevailing number of open communities of herbaceous plants. Most of all they were communities of wet and waterlogged habitats. There were probably some other types of plant communities, besides grass-sedge ones, where dwarf birch shrubberies, alder, willow and brown moss grew together with other plants of dry non-forest steppe-tundra sites (*Artemisia*, *Chenopodiaceae* and *Helianthemum*). Trees could by found, if any, sparsely in small assemblages or in the Wisłok River valley. Palynological data and results of radiocarbon dating suggest that sediments were deposited in cool climatic conditions during the older part of Pleniglacial of the Vistulian glaciation. Łukawiec yielded yet another radiocarbon date made on peat sampled by L. Starkel from the layer forming rapids in the Wisłok River bed, exposed on the right edge of the terrace (Starkel, 1980). It is difficult now to point the place from which the dated sample derived. The age of peat, as obtained in 1975 by M. Geyh and equal to 43.9±2.1 ky BP (Hv-6388), is indicative of the interstadial series (interpleniglacial) of the last glaciation (Gradowski and Nalepka, 1985; Starkel, 1980).

Czarna-Podbór

At the distance of some 0.5 km NNE of Łukawiec profile, at the border of Czarna-Podbór hamlet, there are several open sand pits. Sand pits are located on the terrace plain elevated about 8-9 m above the river bed and up to 1.5 km wide. It is bordered on the floodplain by a distinct edge of the old paleochannel up to 2 m high (**Figs 1** and **2A**). The terrace surface is slightly undulated with flat swellings and depressions not higher, or deeper, than 2 m. Dune ridges, 5-10 m high, occur at higher elevations and low levees occur in places closer to the edge of the terrace. To the west of the biggest sand pit the terrace is

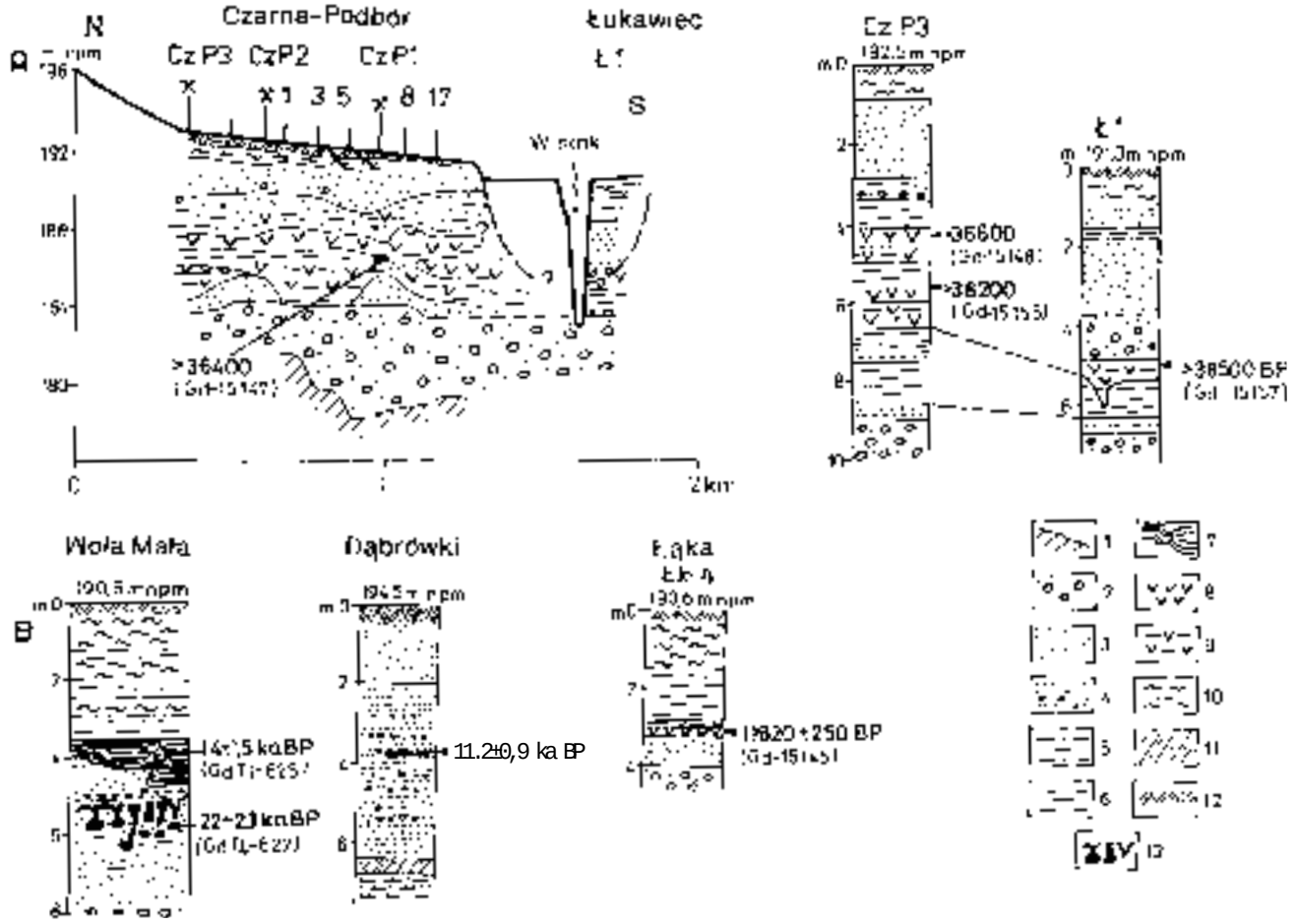

Fig. 2. *Radiocarbon dating results and the cross-section through the sandy terrace (8-10 m) in Czarna-Podbór and the right bank terrace (7 m) in Łukawiec site:*
1 – Miocene, 2 – sand with gravel, 3 – sands, 4 – stratified sands with fine gravels (eolian cover sands), 5 – sandy silts, 6 – muds and clays, 7 – stratified muds and sands disturbed by periglacial structures, 8 – peaty muds, 9 – organic silts, 10 – alluvial loams, 11 – fossil soil, 12 – Holocene soil 13 – involutions (drop soils) and frost wedges.

cut down by a valley of a small stream, the bottom of which is covered with flood muds. In the biggest sand pit belonging to Mr. Kazimierz Jeziorek from Medynia Łańcucka the layer of silt with organic matter was found at the depth of 5 m below the terrace surface. The structure of the terrace was documented by 23 archival drillings made on the sand pit area of 0.25 km^2. Sampling was made by three additional geological drillings using "Geomeres" derrick and samples for palynological and radiocarbon analyses were taken.

Four basic members of deposits have been recognised in the terrace structure (**Fig. 2A**). At the depth of 10-13 m a sandy gravel cover, 2-5 m thick, lies on Miocene clays. Above that there is a member of silty and sandy clays bedded with organic silts and peaty mud, 1.5 to 2 m thick, filling fossil depressions (paleochannels?) cut in the channel alluvia. The top of the terrace consists of dusty sands truncated by coarse sands with an admixture of gravel, 1-3 cm size, with a pavement in the bottom. The thickness of the upper members of the deposits is 3-4.5 m. Samples for dating have been taken from two selected drilling sites. A drilling core sample coming from an upper layer of peaty mud lying at the height of 4 m above the river bed in the Czarna-Podbór 3 profile, yielded an indefinite age >36.6 ka BP (Gd-15148), and the second sample of peaty mud from a layer lying 1 m below gave also an indefinite age >36.2 ky BP (Gd-15155). Another peaty mud sample taken from the Czarna-Podbór 1 drill core, 3.7-3.9 m above the Wisłok river bed was dated to >36.4 ka BP (Gd-15154). The age of the sampled deposits corresponds, probably, to the older part of the Middle Plenivistulian, similarly to the profile in Brzeźnica upon Wisłoka River (Mamakowa and Starkel, 1974; Mamakowa *et al*., 1997) or is much older.

Wola Mała

The site Wola Mała near Łańcut, on the right bank of a big southward bent meander of the Wisłok River, reveals an interesting sequence of sediments (**Figs 1** and **2B**). Below the overbank alluvial loams of Holocene age, sand and silt layers are exposed, part of it being disturbed. Holocene overbank deposits are represented by massive clays interbedded with silts of the total thickness of 3.5 m. A vertical profile exposes two sequences of deposits below the alluvial loams. The lowermost part of the profile, shows mixed sands with single gravels and silty sands with involutions (overbank deposits). The top of these sediments is cut and covered with another layer of cross-

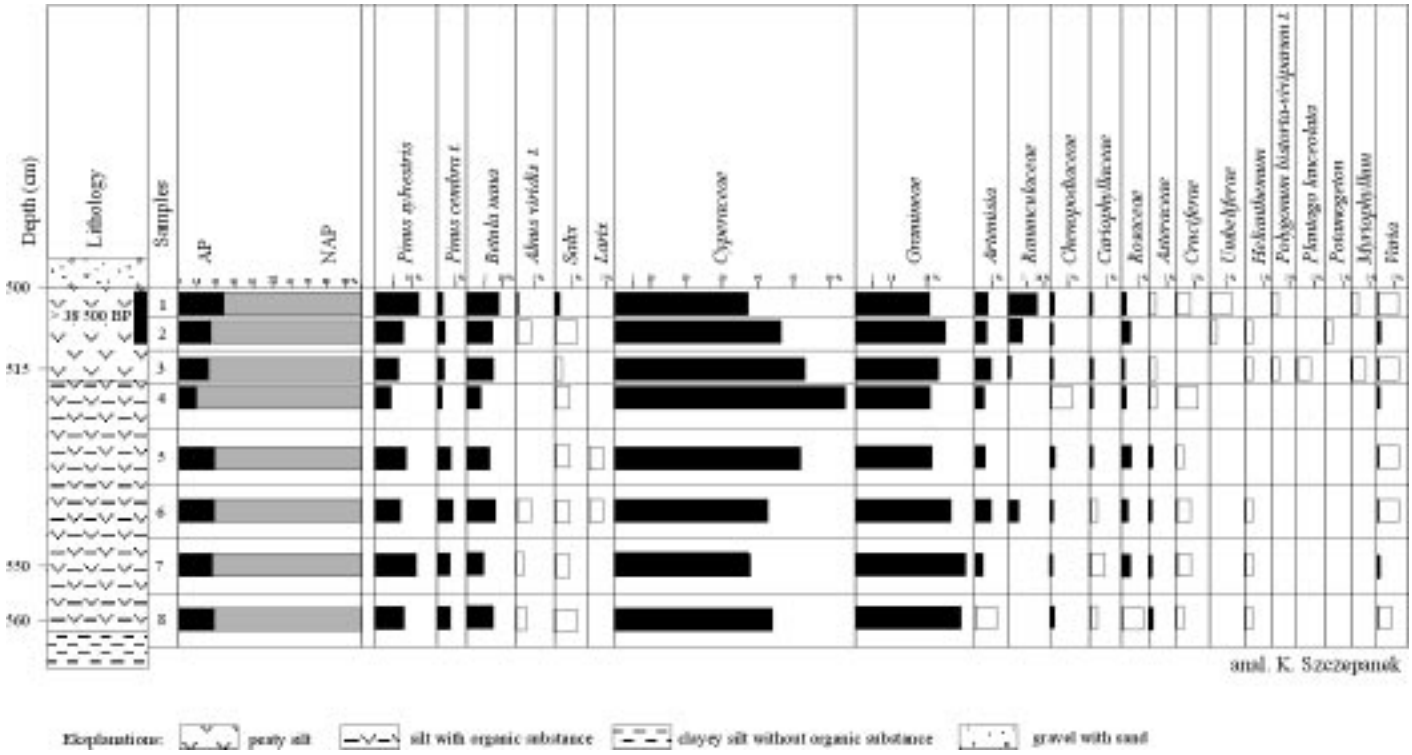

Fig. 3. *Pollen diagram from the Łukawiec-1 profile.*

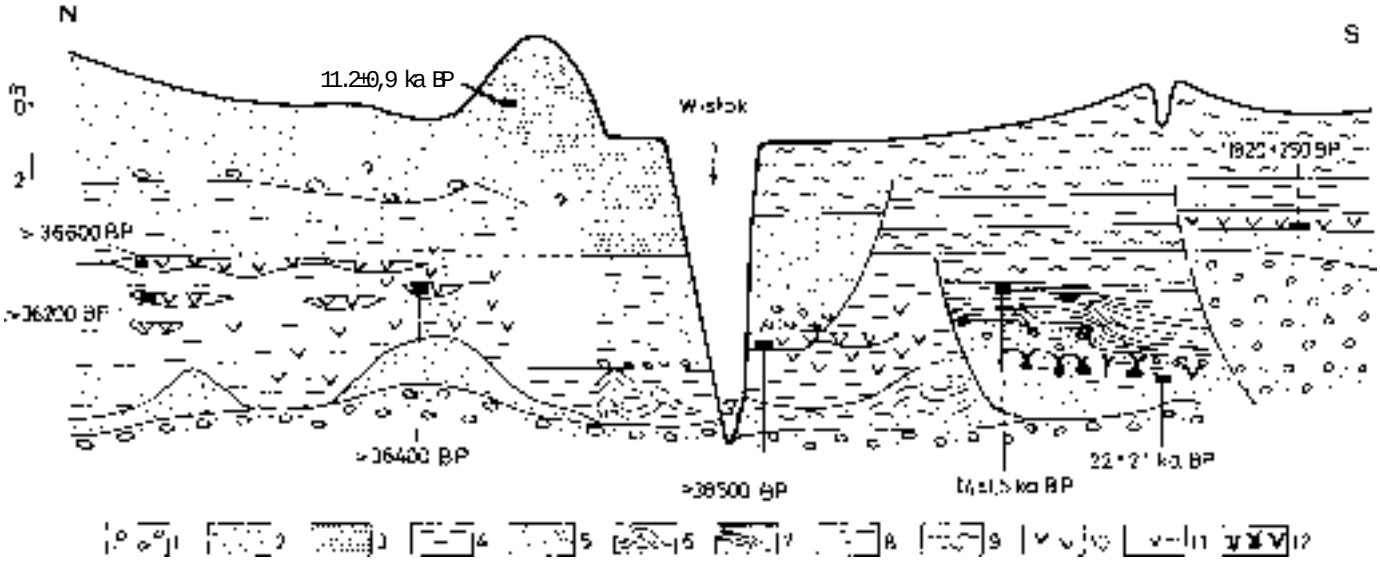

Fig. 4. *Schematic cross-section of the northern margin of the Wisłok River valley floor near Czarna and Łukawiec:*
1 – sands with gravels, 2 – fluvial sands, 3 – stratified fluvial sands with eolian cover sands in the top of the terrace, 4 – silty sands 5 – unstratified eolian sands, 6 – stratified sands and silts disturbed by involutions, 7 – laminated muds and sands, 8 – clays and muds, 9 – alluvial loams, 10 – peaty muds, 11 – organic silts, 12 – involutions and frost figures.

bedded sands with fine gravels and laminated silts (floodplain deposits). Layers of sands and silts in the top part are inclined and subjected to sliding.

Single sand wedge being up to 0.5 m long and truncated at the top, frost fissure and small faults caused probably by ground subsiding, were observed in the dusty sands. Abundant involutions, described as drop soils were found at the border between silts and sands. This type of structures usually develops as a result of differences in sediment density and processes of gravitational liquidation of plastic masses of water-saturated sediment and probably takes place during permafrost degradation (French, 1996; Eissmann, 1997). Two samples taken from this profile have been dated by the single aliquot optical dating (SAR OSL) method. The sample WM-1 taken from an undisturbed sands lying at the height of 2 m above the water level in the Wisłok River channel, and below the previously described involution structures, gave an age of 22.2±2.1 ka BP (GdTL-627). The second sample WM-2, taken from laminated silt lying directly below Holocene alluvial loams, 4 m above the river water level, was dated to 14.0±1.5 ka BP (GdTL-628). Thus, the dated alluvial series corresponds to the Upper Plenivistulian and it is younger than sediments described in Łukawiec and Czarna localities.

Dąbrówki

On the left bank of the Wisłok River, in the village of Dąbrówki, there is a small, sandy hillock developed on a sandy plain. Its relative height is 3.5-4 metres and 13.5 meters above the Wisłok River bed (**Fig. 1**). To the north of this hillock, and slightly higher, there are dune ridges up to 20 meters high. Due to exploitation of sands, the western part of the hillock and the top part of the terrace plain have been exposed, enabling insight into the structure of both forms down to the depth of 7 m (**Fig. 2B**). The lower part of the terrace is built of sands, gravels and silts, while the upper one consists mainly horizontally laminated silty sands. The hillock consists mostly of somewhat coarser material, mainly fine- and medium-grained sands, alternately laminated with thin layers of coarse-grained sand and gravel up to 0.5 cm diameter. The lamination ceases towards the top of the hillock and sands become better sorted, with a Holocene soil developed in the top. The small size of the hillock and alternating layers of sand grains makes it similar to hillocks made of eolian cover sands found on the Polish Lowlands (Nowaczyk, 1976). Structures described above have been recorded in eolian sands of contemporaneously developing dunes (Fryberger *et al*., 1992) as well as in Pleistocene cover sands (Schwan, 1986; Goździk, 1998). The sample of sand taken from the bottom layer of the hillock, about 10 m above the Wisłok River level, has been dated by SAR OSL method to 11.2±0.9 ka BP (GdTL-626). This result points the Late Vistulian (Younger Dryas ?) when eolian processes intensified and sand was reworked by strong winds. These date correlates well with numerous eolian series of dune and cover sands dated in Poland (Nowaczyk, 1986).

Łąka

On the rendzina terrace, to the south of the present Wisłok River bed, several boreholes gave insight into the structure of the flat-bottomed depression surrounding the sandy patches of Pleistocene terrace near Łąka (**Figs 1** and **2B**). The structure of the wide depression consists of peat, lying on sands with silts, clays, and alluvial loams in the top. The radiocarbon dating of a sample from the Łąka-4 borehole (sample from the bottom of the peat layer at the depth 3.25-3.30 m) gave the result 11,820±250 BP (Gd-15146). This means that the infilling of the depression started in Alleröd, and peat, probably, covers a fragment of a Late Vistulian alluvial plain of a braiding river.

4. DISCUSSION OF ^{14}C DATING RESULTS

The measurements of ^{14}C concentration have been performed in the Gliwice Radiocarbon Laboratory by the gas proportional counting method (except for the Hv-6388 result which was obtained in the Hannover Radiocarbon Laboratory). Conventional radiocarbon age of each sample has been normalised to $\delta^{13}C$ = -25‰, following the Stuiver and Polach's procedure (1977). One definite ^{14}C date (sample Łąka-4, Gd-15146) was calibrated using the Gliwice Calibration Program GdCALIB (Pazdur and Michczyńska, 1989) and the calibration curve of Stuiver *at al*. (1998). **Table 1** contains the results of radiocarbon dating as conventional radiocarbon ages (^{14}C Age, BP) and results of the calibration procedure in the form of the narrowest 68% confidence intervals (Cal. Age, BP).

The results of radiocarbon dating fell at or behind the limit of the applied method, except for Łąka-4 sample, which yielded a definite age. Considering the stratigraphical division of the Vistulian glaciation (Kozarski, 1991), radiocarbon dates obtained for Łukawiec and Czarna-Podbór profiles (older than 38.5 ka BP and older than 36.0 ka BP, respectively) mean that the respective organic sediments from the two sites were deposited during the older part of the Middle Plenivistulian (interpleniglacial). The probable candidate is the Hengelo interstadial (warm) period and an immediately earlier stadial period. Palynological data suggest that studied sediments were deposited under relatively stable conditions, during a period without significant climate fluctuations. The low percentage of tree pollen, reaching 25% at the best, together with the domination of open sets of herbaceous plants may be interpreted as a result of relatively stable climatic conditions of the colder period (stadial) immediately preceding the Hengelo interstadial. Numerous involutions and small frost wedges found at the contact between organic deposits and underlying layers developed under periglacial conditions are the other proofs supporting this hypothesis. It is also congruent with results of other studies of Middle Plenivistulian fluvial series in the southern part of Poland (Jersak and Sendobry, 1991; Superson, 1996) and in eastern part of Germany (Eissman, 1997; Mol, 1997).

Table 1. *Description of the samples and their radiocarbon and luminescence ages. Calibrated age range (Gd-15146) has been determined at 68% confidence level using GdCALIB program.*

Sample name **type of sediment**	**Stratigraphy**	**Lab. No.**	**^{14}C Age** [BP] **Cal. Age** [BP]	**OSL Age** [BP]
Łukawiec-1 peaty mud	top layer of peaty mud, 2 m above channel water level	Gd-15157	> 38,500	
Łukawiec peaty mud	Peat from a bank forming a riverbed bar	Hv-6388	$43{,}900^{+2100}_{-1650}$	
Czarna Podbór-3 peaty mud	top layer of peaty mud, 5 m above channel water level	Gd-15148	> 36,600	
Czarna Podbór-3 peaty mud	Layer lying 4 m above channel water level	Gd-15155	> 36,200	
Czarna Podbór-1 peaty mud	Layer lying 4 m above channel water level	Gd-15154	> 36,400	
Wola Mała WM-1 sand	Layer lying 2 m above channel water level	GdTL-627		22,200 ± 2100
Wola Mała WM-2 laminated mud	Layer lying 4 m above channel water level	GdTL-628		14,000 ± 1500
Dąbrówka sand	Layer lying 10 m above channel water level	GdTL-626		11,200 ± 900
Łąka-4/3.25-3.30 m peat	lower layer of peat	Gd-15146	11,820 ± 250 [14,050 ÷ 13,530]	

5. DISCUSSION OF RESULTS OF OSL DATING

Luminescence dating of three sediment samples has been made in the Luminescence Dating Unit of the Department of Radioisotopes, Institute of Physics, Silesian University of Technology, Gliwice, Poland. The OSL measurements have been done on coarse quartz extracts (125-200 μ) applying a single aliquot regenerative dose protocol (SAR) to obtain values of paleodoses absorbed by grains. The respective dose-rate values have been calculated from radioactivity of the sediment samples measured by means of high-resolution gamma spectrometry, making appropriate corrections for sediment water contents, etching of quartz grains in concentrated hydrofluoric acid, and taking into account the cosmic dose-rate.

OSL of quartz aliquots have been measured with Daybreak 1150 automated reader equipped with a green light source (halogen lamp based) and a beta source for "in-place" irradiations. Irradiations, preheating and OSL measurements were executed automatically in a one continuous run. A typical SAR measurement protocol was employed with the following parameters:

- aliquot mass: *ca* 3 mg;
- test dose: 1.9 Gy;
- preheat after test dose: 0 s at 160° C;
- regenerative doses: 9.6, 19.1, 38.3 Gy;
- Preheat after regenerative dose: 10 s at 220° C;
- OSL taken at 125° C during 1 s of green light (514±17 nm wavelength) excitation followed by 58 s long bleaching and then 1 s excitation for recording a background signal (a total of 60 s of green light exposure)

Equivalent dose (ED) values have been calculated by interpolation of the non-linear saturated exponential fit to the laboratory growth points. Results of the laboratory measurements and OSL dating are presented in **Tables 2** and **3**.

The single aliquot method is usually applied to a number of aliquots making it possible to investigate the distribution of luminescence ages of quartz grains within the sediment. In this case aliquots consisted of many individual grains so the interpretation of the distribution is less straightforward. Nevertheless, it was shown that only a few grains give actually rise to luminescence observed from an aliquot, so the distribution should have similar

Table 2. *Depth, water content, radioactivity and effective dose-rate for three samples.*

Sample	**Depth** [cm]	**Water content** (assumed) [%]	**Activity [Bq/kg]** ^{238}U	^{232}Th	^{40}K	**Dose rate** [Gy/ka]
Wola Mała WM-1	600	12±3	5.18±0.86	3.76±0.29	249.2±4.3	0.99 ± 0.08
Wola Mała WM-2	400	12±3	18.12±1.48	15.10±0.58	420.9±7.4	1.93 ± 0.14
Dąbrówki D-1	400	12±3	5.38±0.77	3.32±0.26	182.1±4.1	0.90 ± 0.03

Table 3. *Equivalent dose (ED) and OSL age values obtained for the dated samples.*

Sample	**Number of aliquots**	**EDOSL** [Gy]	**OSL Age** [ka]
Wola Mała WM-1	10	22 ± 1	22.2 ± 2.2
Wola Mała WM-2	10	27 ± 2	14.0 ± 1.5
Dąbrówki D-1	40	10.1 ± 0.7	11.2 ± 0.9

features as the individual grain distribution but broader and with larger "background". **Figs 5** to **7** show the results for individual aliquots transformed in such a way that each point represents a single date. The abscissa of a point is inversely proportional to the dating error ΔT_i and its ordinate is proportional to the age value T_i less an arbitrary value (usually chosen to be an average of obtained ages) and inversely proportional to dating error. This transformation leads to that points representing same age lie on a straight line going through the point of origin (0, 0) and the larger the distance from the origin, the more accurate the date is. This type of plot helps better judgment of dominant features of the age distribution and its interpretation.

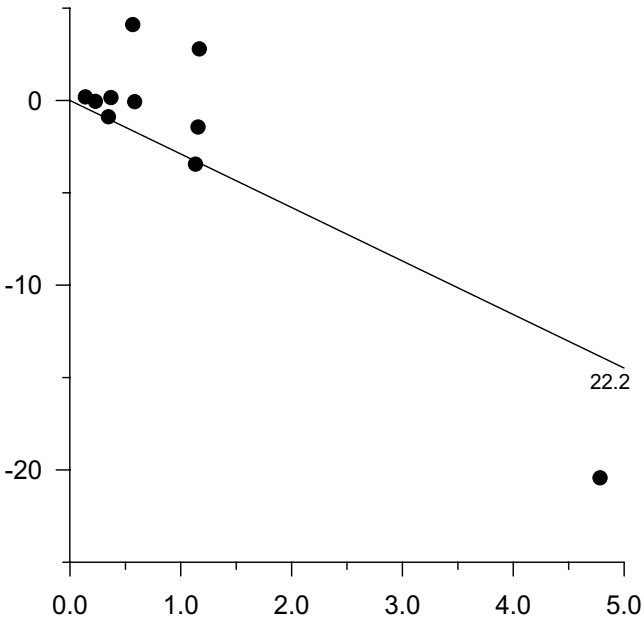

Fig. 5. *Results of the SAR method dating of the sample WM-1. The plot presenting single dates is constructed in such way that "equal age" points lie on the ray coming out of the point (0, 0). The distance along the horizontal axis is equal to* $\frac{1}{\Delta T_i}$ *while the distance along the vertical axis is* $\frac{T_i - \overline{T}}{\Delta T_i}$. *The ray shows an age of 22.2 ka.*

Samples WM-1 and WM-2 have relatively simple distributions meaning that deposition of the sediment took place after a moderately long exposure to light. The sample D-1, on the contrary, shows a quite complex distribution (being the reason why we decided to repeat dating for 40 aliquots). The most probable reason for this is that in the history of this sediment several episodes of reworking and re-deposition occurred. The OSL date stated for this sample cannot be interpreted as the age of the whole form. It is rather the last episode of more intense reworking. This site will be a subject of further investigations, including OSL dating of more samples with an aim to shed more light on the origin and age of the form.

6. CONCLUSIONS

Radiocarbon and luminescence dating (OSL) confirm complexity of alluvial series of deposits of Middle to Upper Plenivistulian age, occurring in the Subcarpathian pradolina section of the Wisłok River valley bottom between Łąka and Łańcut. A schematic section shows locations of dated alluvial series and their probable spatial extension along the bottom of the valley (**Fig. 4**). The distinguished Vistulian series of sediments occupies mainly the northern zone of the Wisłok River valley. The contemporary channel of the Wisłok River cuts into this series.

The thick series of InterpleniVistulian sediments forming a sandy terrace, 8-10 m high, has been dated to be older

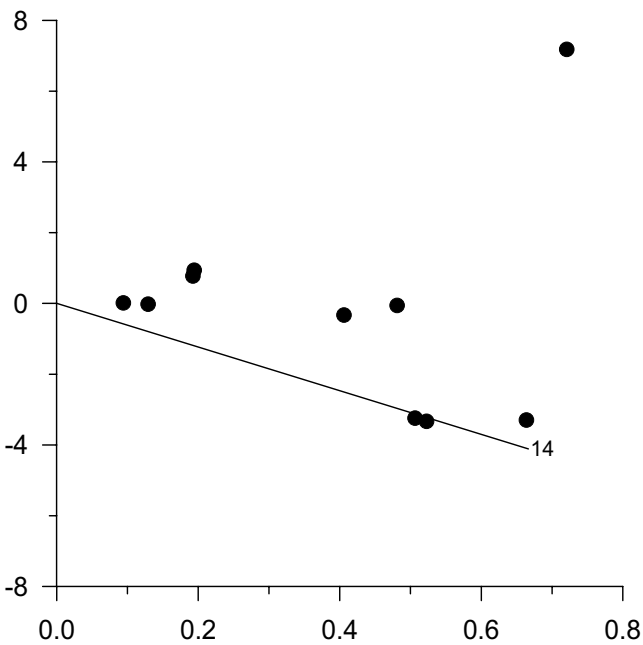

Fig. 6. *Results of the SAR method dating of the sample WM-2. The ray shows an age of 14 ka.*

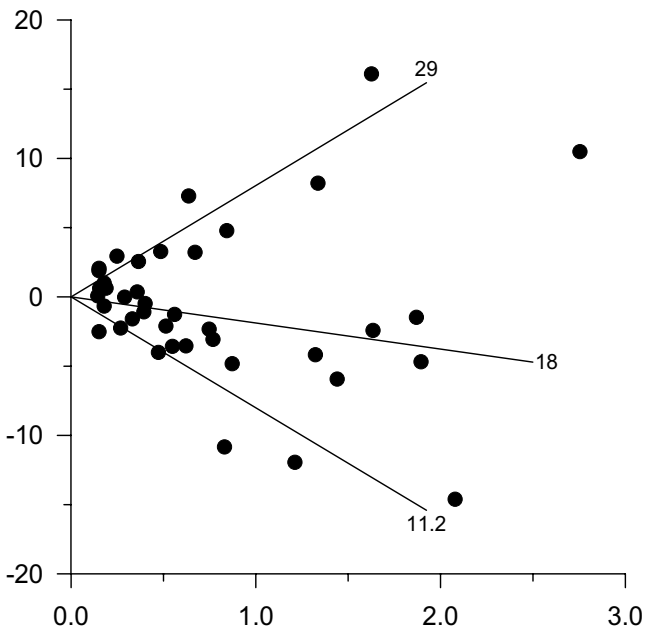

Fig. 7. *Results of the SAR method dating of the sample D-1. The three rays show ages of 11.2 ka, 18 ka and 29 ka.*

than 36 ka BP. The oldest links of this series occurring in the floor of the 7 m terrace have been dated to be older than 38 ka BP. The problem that needs further research are the genesis and age of the sandy formations covering the InterpleniVistulian series. Undoubtedly, a part of the uppermost formations of the sandy terrace is of eolian origin; besides dunes, low hillocks are found, that are built of eolian cover sands. A single OSL date obtained for these sands points to the end of the Late Vistulian.

The alluvial series, built of sediments dated back to 22-14 ka BP is covered with Holocene alluvial loams. Further to the south of the contemporary Wisłok River bed fragments of the Late Vistulian alluvial plain are found side by side with younger alluvial fills of fluvial sediments connected with abandoned paleochannel system of the Wisłok River. This feature may be related to migration of the river bed towards the left edge of the valley bottom.

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RADIOCARBON DATED WOOD DEBRIS IN FLOODPLAIN DEPOSITS OF THE SAN RIVER IN THE BIESZCZADY MOUNTAINS

JÓZEF KUKULAK[1], ANNA PAZDUR[2] and TADEUSZ KUC[3]

[1]*Department of Geography, Pedagogical University, Podchorążych 2, 30-084 Cracow, Poland (e-mail: jkukulak@wsp.krakow.pl)*
[2]*Department of Radioisotopes, Institute of Physics, Silesian University of Technology, Krzywoustego 2, 44-100 Gliwice, Poland (e-mail: pazdur@polsl.gliwice.pl)*
[3]*Department of Physics and Nuclear Techniques, University of Mining and Metallurgy, Al. Mickiewicza 30, 30-059 Cracow, Poland (e-mail: kuc@novell.ftj.agh.edu.pl)*

Key words: WOOD DEBRIS, ALLUVIUM, RADIOCARBON DATING, HOLOCENE, CARPATHIANS

Abstract: Tree logs and smaller fragments of wood debris occur in floodplain alluvium (1-3 m above the river level) of the San river in the Bieszczady Mountains (Polish East Carpathians). The greatest accumulations of wood debris occur in the lower part of the alluvium, beneath a layer of sandy muds. The wood debris in these accumulations was dated by radiocarbon method. The dates fall within the time interval 3270±70 BP to 103.7±1.1 pMC, but most of them are from 17th to 19th century. The abundance of the wood debris in the alluvium is the result of its intense supply to the river channel, caused by deforestation and large floods. The age of the wood accumulations corresponds to the phase of settlement in the upper San valley in the 16th to 17th centuries. The older wood debris could be redeposited to the young alluvium from older alluvial terraces.

1. INTRODUCTION

Wood debris is usually a subordinate component in alluvial sediments and it usually widely varies in size. Large buried logs and other coarse wood fragments (branches, roots) usually focus the attention of researchers. Less visible is fine debris (leaves, bark, fruits and seeds) and this is usually omitted in descriptions of alluvial sediments. Dating of wood debris of all size provides an important insight into the age of alluvium and the evolution of river terraces. The most common methods used to date wood debris are radiocarbon (^{14}C) dating and dendrochronology.

Wood debris in alluvium of the Carpathian rivers occurs mainly in depositional covers of Holocene terraces. These are better preserved in foothill sections of valleys, not so common in the mountain zone. They are most common immediately below the outlets of the valleys from the Carpathians, e.g. in the valleys of the Wisłoka, Wisłok and San rivers (Starkel, 1960 and 1996; Klimek, 1974; Kalicki and Krąpiec, 1991; Krąpiec, 1992; Kalicki, 1997; Nogaj-Chachaj *et al.*, 1999). Their presence is commonly considered as indication of climate fluctuations and occurrence of floods in the Carpathians or lateral migration of fluvial channels (Środoń, 1952; Alexandrowicz *et al.*, 1981; Starkel, 1996 and 1999; Kalicki and Krąpiec 1991; Kalicki, 1991).

Geological studies in the Bieszczady Wysokie Mountains (Polish East Carpathians) have revealed the presence of abundant wood debris also in the mountane section of the San river (Haczewski *et al.,* 1998 and 2001). This is accumulated only in floodplain sediments of the San river and its tributaries, far upstream from the margin of the Carpathians. They form a continuous horizon in floodplain sediments, on the top of older gravels and at the base of the younger sandy mud (Kukulak, 2000). The accumulation of this wood debris seems to be not exclusively caused by a climatic factor.

This paper presents a description of wood debris in Upper San river floodplain alluvium and presents the results of its dating by the ^{14}C method. An attempt at explaining the causes of rich supply of wood debris to the river channel is also presented. The dated wood was collected from its rich accumulations in the alluvium in the headwater section (about 20 km long) of the San river, between its source at the Uzhok Pass (863 m a.s.l.) and the junction with the Muczny Stream (upstream from the Kiczera Dydiowska).

2. CHARACTERISTICS OF THE STUDY AREA

This part of the San river watershed has mountane relief near the water divide (long and steep slopes of the Pasmo Połonin Range) and foothill relief in the valley part (low altitude differences and gentle gradients). Most of the watershed is wooded (*ca*. 85%), only the highest parts of the Pasmo Połonin Range and the bottom of the San river valley (especially the Dźwiniacz Depression) are not forested. The dominant species of trees are beech (*ca* 46% in the Tarnawa forestry area), less abundant are spruce (*ca* 27%) and fir (*ca* 20%; Krygowski, 1975). The high percentage of forests in the slope areas retards the surface runoff from the abundant precipitation (*ca* 1100 mm per year) and reduces flood waves in the streams. The sediment load in the streams is now small during high water

Fig. 1. *Extent of the lower fluvial terrace along the San river and its tributaries.*

states, as intense farming has ceased in the Polish part of the San river watershed (*ca* 80% of the total) half a century ago.

The floodplain is the lowermost level of alluvial deposition in a valley, older terraces lie higher and are arranged in steps. The height of the floodplain above the river level gradually increases downstream, from 0.5 m to 2 m, locally even to 3 m. At places it consists of two horizons (1.5-3 m, 0.5-1.5 m). The width of the terrace is greatest (50 m) in the Dźwiniacz Depression, where the vertical gradient of the river is lower than 0.5 % and the channel is meandering. The floodplain extends along the San river from its very source, and penetrates into valleys of bigger tributaries (Niedźwiedź, Sychłowaty, Halicz, Litmirz and Muczny streams). The sedimentary cover of the terrace differs from the older covers in its finer-grained sediments and a large content of wood debris. Fossil wood is only sporadically found in the sediments of the older terraces. The main horizon with wood debris has a constant stratigraphic position in the floodplain sections. It extends in the lower part of the alluvial cover, at the boundary between the lower gravels and the overlying sandy muds. The wood debris lies in layers or lenses of a few centimetres to 0.5 m thick. Meso-scale fragments of wood debris usually form one thick layer; the finer debris lies in two to five thin, laterally extensive layers. The higher, fine-grained part of the alluvial cover contains much less and finer wood debris. Only locally it fills erosional channels at different levels in the vertical sections or is dispersed in mineral deposits.

3. MATERIAL AND METHODS

Accumulation of plant debris in exposures of floodplain deposits have been studied and documented in years 1996-2000. Determined were forms of the accumulations, their state of preservation; the remains have been identified in selected sections of the terrace (Haczewski *et al.*, 1998). Wood from several debris accumulations was collected for radiocarbon dating (Sianki, Beniowa, Bukowiec, Tarnawa Niżna, Łokieć and Dydiowa). One or two samples were taken from each of the selected accumulations, all from the lower part of the vertical sequence (boundary between gravel and sandy mud).

All datings were done in years 1997-2000; most of them in the Gliwice (A. Pazdur), a part in the Cracow Radiocarbon Laboratories (T. Kuc). ^{14}C concentration in the samples was measured in the Gliwice Radiocarbon Laboratory by gas proportional counting and in the Cracow Radiocarbon Laboratory by liquid scintillation counting. $\delta^{13}C$ was determined in mass spectrometer, thus conventional radiocarbon age was normalised to $\delta^{13}C$ = -25‰, according to the Stuiver and Polach's procedure (1977). ^{14}C dates were calibrated by use of the Gliwice calibration Program GdCALIB (Pazdur and Michczyńska, 1989), except for some dates of radiocarbon age less than 300 BP, which were calibrated by OxCAL (Ramsey, 1995). In both cases the calibration curve of Stuiver *et al.* (1998) was used. **Table 1** shows the results of radiocarbon dating as conventional radiocarbon ages (^{14}C Age, BP) and after calibration procedure, as the intervals of the highest probability at confidence level 68% (Cal. Age, AD/BC).

Geological, archaeological and historical data have been compiled for the period indicated by the radiocarbon dates, including results of palaeobotanical analyses of local peat-bogs (Pałczyński, 1962; Marek and Pałczyński 1962; Zarzycki, 1963; Ralska-Jasiewiczowa, 1969, 1980 and 1989). These mainly record changes in a vegetation cover of the Bieszczady Mountains during the Holocene, thus indirectly they reflect the phase of a climatic change and early human activity. Archaeological findings are few in the studied area and they suggest rather migrations than settlement in pre-historic times (Reyman, 1958; Parczewski, 1991). Historical data on the San river valley have been collected from archival maps, cadasters, chronicles and published studies (Kummerer, 1855; Akta, 1868; Stadnicki, 1848; Fastnacht, 1962). History of forests and their management during the last five centuries are well documented in the above sources.

4. RESULTS

Meso-scale components of fossil wood in the floodplain sediments are logs and their fragments, branches, roots and sporadic polypores. The accumulation of fine debris consist mainly of leaves, bark, fruits and seeds. Noteworthy is the large proportion of bark, branches and tree tops. The wood debris is accompanied by fragments of peat, herbaceous plants and their fruits and seeds, fungal sclerotia and insect remains. Microscope studies of the fine alluvium reveal a significant admixture of microscopic plant detritus in all size fractions. Coarse logs are usually found in shallow erosional troughs dissecting gravels (Beniowa) or in channel sediments at palaeochannel bends (Tarnawa Niżna). They are buried in sand and fine gravel, some logs are completely buried in gravel (Bukowiec and Tarnawa Niżna). The finer wood debris occurs only in the sandy mud, in sections of flat ancient river bottom.

Most logs are well preserved. They lack large fragments of bark, but all have cambium preserved. Stumps complete with roots and branches are rare. Locally rotten logs with still visible internal structure also occur. A few logs at Beniowa and Bukowiec bear traces of working with tools (wedge-shaped axe-made incisions and saw-made cuts). A wooden board, symmetrically cut on both sides and perforated, apparently a household object, is exposed at the bottom of the mud layer at Sianki. Many finer wood fragments at Sianki and Tarnawa Niżna are partly impregnated or coated with iron oxides, which makes them more resistant to decay. Some of the wood fragments are charred or scorched (Kukulak, 2000).

Each of the wood debris accumulations is a separate assemblage of size classes, usually composed of several similar classes. The accumulations of coarse wood debris usually lack finer detritus or have only a small proportion of it. The areally more extensive wood debris accumulations display a lateral trend in grain size, depending on the form of accumulation. Besides size sorting (layers of leaves or branches), weight sorting also occurs (e.g. fruits,

bark). These features are better visible in the accumulations of plant detritus in low-gradient segments of the valleys (Beniowa and Łokieć). Wood in each of the eight radiocarbon-dated samples, has a different conventional radiocarbon age (**Table 1**). The obtained dates cover a wide time interval: from 3270±70 BP (Tarnawa Niżna I) to modern - 103.7±1.1 pMC (Sianki). Half of the dated samples represent wood that died at modern times (18th-19th centuries). The dates of wood from Beniowa (122±60 BP), wattle made from thin stems and twigs at Łokieć (150 ±60 BP) and a layer of beech leaves at Dydiowa (140±60 BP) fall within a very narrow time interval. The other half of the samples consisted of much older wood, and the differences in their ages attain 500-700 years. Only at Tarnawa Niżna, wood from a thick log (I) and fir cones (II) buried in the same horizon, have similar ages (terminal part of the Subboreal Epoch of the Holocene).

Dating of the studied wood debris indicate that wood debris of various age has been buried in the floodplain alluvium. Very young is the debris that fills an erosional channel at Sianki, older are artificial wattle reinforcements at Łokieć. The logs buried in the basal gravels at Bukowiec are from the beginning of the Common Era, and those at Tarnawa Niżna are as old as Subboreal. The presence and predominance in the alluvium of wood debris dated at the last three centuries, proves that most of the debris was accumulated at times close to, or only slightly later than, its radiocarbon dates. It could occur in the 18th or 19th century. The dates of these samples do not determine the age of the main wood debris horizon over the whole length of the San valley. Also the presence of the oldest wood in this horizon (Tarnawa Niżna) may be the result of its redeposition from older terraces.

5. DISCUSSION AND CONCLUSIONS

The times of plant death indicated by the radiocarbon dates of wood are related to events of both climatic (the older dates) and anthropogenic (the younger dates) nature in the natural environment of the Bieszczady Mountains. The age of the buried logs at Tarnawa Niżna corresponds to the phase of frequent floods in the watershed of the upper Vistula River towards the end of the Subboreal time (Starkel, 1977 and 1994). Also the age of the logs at Bukowiec is isochronous with floods in the Carpathian rivers in Roman times, and the fragments from Beniowa – with floods in early Mediaeval times (**Fig. 2**). The flood sediments of the upper Vistula river laid down at those periods include numerous buried logs (Awsiuk *et al.*, 1980; Kalicki and Krąpiec, 1991 and 1996; Krąpiec, 1992). The older dates from the studied wood debris fit well within the phases of the San river floods and may be related to climatic conditions. The number of older dates is, however, too small to exclude that the coincidence is only accidental.

The accumulations of the younger wood debris have been also laid down during floods, but the cause of their deposition seems to be mainly anthropogenic. It is related to the phase of settlement and onset of farming in the part of the Bieszczady Mountains during late Mediaeval and early Modern times. Many permanent settlements of farmers and wood workers have been founded here on inhabited grounds during the second half of the 16th and at the beginning of 17th century. These have evolved later into agricultural villages (Fastnacht, 1962). The settlements were located in areas that were already partly deforested as pasture grounds at valley bottoms (Ternowe

Table 1. *Description (name, depth, material) and conventional and calibrated ages of the samples. Calibrated age range has been determined with confidence level 68% using the GdCALIB programme, developed in the Gliwice Radiocarbon Laboratory and Oxford programme OxCal for very young samples.*

Sample name/depth **Dating material**	**Lab. No.**	**^{14}C Age** [BP]	**Range of Cal. Age** [AD/BC]
Sianki/0.95-1.05 m Twigs, cones	Gd-15166	103.7±1.1pMC (*)	MODERN
Beniowa I/0.7 m Charcoal	KR-168	122±60	[1800, 1950] AD
Beniowa II/1.45-1.55 m Leafs, twigs, bark	Gd-11555	1380±50	[636, 686] AD
Bukowiec/2.6-2.8 m Wood	Gd-7860	1940±50	[21, 91] AD
Tarnawa Niżna I/1.1-1.2 m Wood	Gd-12136	3270±70	[1621, 1491] BC
Tarnawa Niżna II/1.60-1.65 m Twigs, cones	Gd- 15194	2680±70	[1002, 762] BC
Łokieć/2.5 m Wood	KR-167	150±60	[1720, 1820] AD
Dydiowa/0.7 m Leaves, twigs	KR-172	140±60	[1800, 1890] AD

Cal. Age = calibrated age, Lab. No.= laboratory number, Gd- = Lab. No. of ^{14}C dates from Gliwice Radiocarbon Laboratory, KR- = Lab. No. of ^{14}C dates from Laboratory of the University of Mining and Metallurgy, Cracow , (*) = pMC-percent of modern carbon.

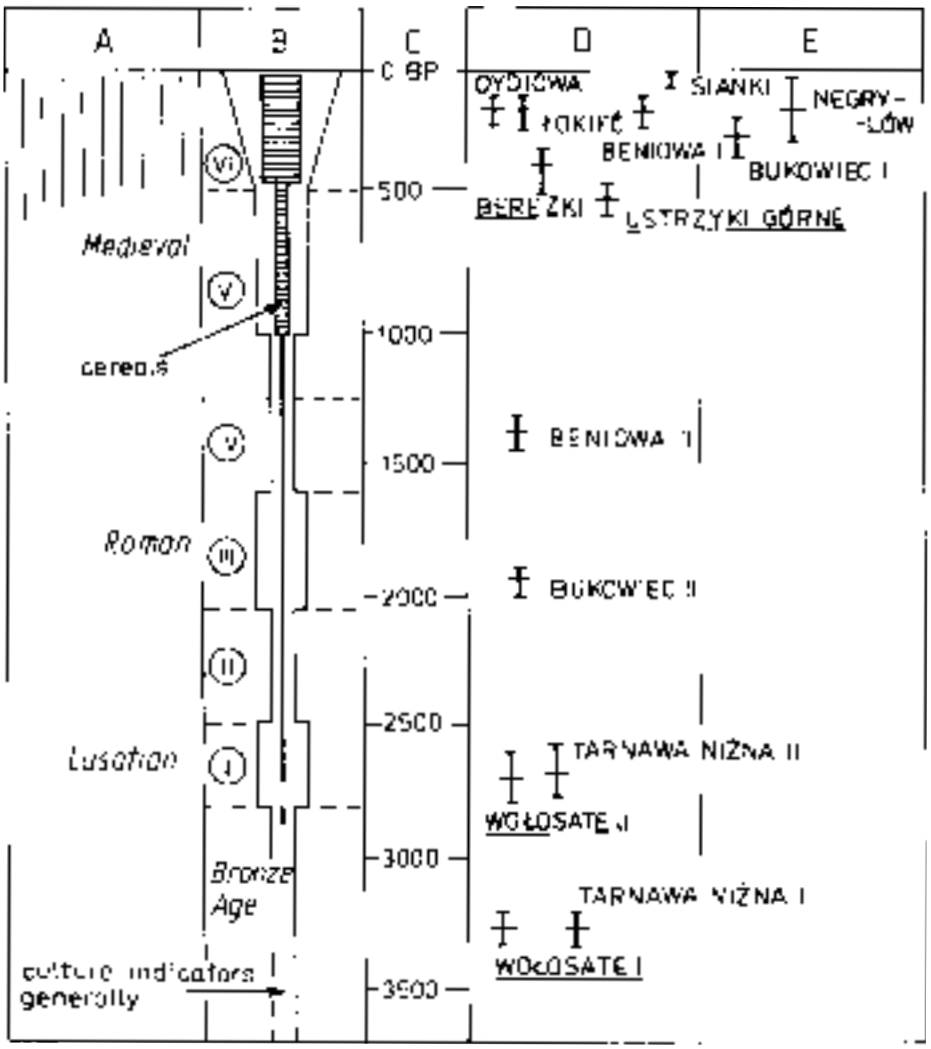

Fig. 2. *Corelation of phases of settlement in the Bieszczady Mountains with the age of wood debris in the lowest (1-3 m) terrace. A – period of permanent settlement and farming in the Bieszczady Mountains; B – record of human influence on environment in pollen diagrams of peat-bogs (after Ralska-Jasiewiczowa, 1989); C – radiocarbon dates; D – dated wood fragments at the bottom of the fine-grained; E – dated wood fragments from the fillings of erosional thoughs in the alluvial terrace. Archaeologic periods: I – Hallstatt, II - La Tène, III – Roman, IV – Migration, V – Medieval, VI – Modern times. Underlined are dates from San tributary situated off the west margin of* ***Fig. 1****.*

Pole, Beniowe Pole and Pole Bukowiec). The glades were mainly the work of the Valachian herders who were coming here seasonally from the 14th to 16th century, with their herds of cattle and sheep (Kubijowicz, 1926; Parczewski, 1991).

The first villages were located in the Dźwiniacz Depression: Dźwiniacz Górny (before 1529), Tarnawa Niżna and Tarnawa Wyżna (1537). The expansion of settlements reached the Uzhok Pass in the end of the 16th century: Bukowiec (1580), Beniowa (1580) and Sianki (1580). The economy of these villages was based on cattle herding and grain growing, activities that required wide expansion of farmland. Clear cutting of forests began on great scale, providing areas for arable fields and meadows. The clearcuts were not limited to the areas around villages but also included widening of natural mountain meadows on the mountain crests (so called poloninas). Tax registers from the 16th and 17th centuries (Spisy, 1787), land cadasters from the 18th. (Akta, 1868) and old maps from the 18th-19th centuries (Liesganig, 1824; Kummerer, 1855) prove a nearly complete deforestation of the valley bottom, a large reduction in the forest area on slopes and lowered timberline around the poloninas.

The clearing of forest was done mainly by fire clearance. Initially, this was the easiest way to gain farmland, then also to fertilise it (Kubijowicz, 1926; Broda, 1952; Pałczyński, 1962). The settlers usually did not perform complete clearcutting and did not clear the area of branches, tree tops and bark. This wood debris was burnt in place or thrown away to stream channels (Szwab, 1956). The rapid re-growing of woods in non-cultivated ground and repeated cutting in the same places favoured accumulation of large amounts of wood debris in nearby stream channels. The initial phase of settlement in the San river valley had to be the most productive in wood litter.

The increased runoff due to deforestation of slopes resulted in more violent flooding of the streams and enabled transport of the wood debris to the San river channel. This supply had to be rich, as the debris formed thick accumulations in the channel sediments and erosional troughs on terraces. The deposition of wood debris was accompanied by increased load of slope-derived sediments in flood waters. This increased supply of clay from arable fields resulted in a tendency to alluvial aggradation in the San river channel. The alluvial aggradation was the fastest along reaches with low vertical gradient (below 0.5%). It was also at those places where the greatest amount of wood debris was laid down. The burnt and charred wood found in this debris may be the product of fire clearance. The radiocarbon dates from the burnt wood

at Beniowa correspond to the period of the greatest activity of local wood-burning industries (potash-making facilities, blacksmithery and steam-powered sawmills). A large part of the buried logs may have come from undercutting of river banks, as conditions for lateral channel migration existed during the greater floods.

All the wood debris, dated at various periods of the late Holocene, is now buried in the alluvial cover of the same terrace. The interpretation of time of their deposition in the alluvium is thus not unequivocal. One may assume that the floodplain consists of fragments of different age, so that older wood is buried in the older fragments, and younger wood in the younger ones. The division of the terrace into fragments of different age is, however, expressed in its stratification (gravels at bottom, mud above) rather than in the presence of laterally adjacent segments of different age (due to lateral aggradation). Only a part of the fine-grained alluvium (the upper part of the cover) includes fills of linear erosional troughs. The main horizon of wood debris forms a layer in the terrace and it seems to be isochronous. It is thus more likely that the older wood debris was redeposited to the young alluvium from the older terraces of the San.

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CHRONOLOGY OF THE VISTULIAN (WEICHSELIAN) GLACIAL EVENTS IN THE LOWER VISTULA REGION, MIDDLE-NORTH POLAND

WOJCIECH WYSOTA[1], KRZYSZTOF R. LANKAUF[2], JACEK SZMAŃDA[2], ALICJA CHRUŚCIŃSKA[3], HUBERT L. OCZKOWSKI[3] and KRZYSZTOF R. PRZEGIĘTKA[3]

[1]*Department of Geology and Hydrogeology, Institute of Geography, Nicholas Copernicus University, Sienkiewicza 4, 87-100 Toruń, Poland (e-mail: wysota@cc.uni.torun.pl)*
[2]*Laboratory of Sedimentology and TL Dating, Institute of Geography, Nicholas Copernicus University, Fredry 6/8, 87-100 Toruń, Poland (e-mail: szmanda@geo.uni.torun.pl)*
[3]*Thermoluminescence and Dating Laboratory, Institute of Physics, Nicholas Copernicus University, Grudziądzka 5/7, 87-100 Toruń, Poland (email: przeciu@phys.uni.torun.pl)*

Key words: NORTH POLAND, VISTULIAN GLACIATION, TL DATING

Abstract: **Stratigraphy of the Vistulian glacial events in the southern part of the Lower Vistula region in the north Poland is presented. Lithostratigraphic units and TL dating of Vistulian deposits exposing along the Vistula valley between Toruń and the Chełmno Lakeland are described in detail. The obtained results indicate that the Vistulian sequences in the Lower Vistula region were deposited during five palaeogeographical episodes. Three glacial events were distinguished: the first at the beginning of the Middle Vistulian (~65–70 ka) and two younger ones during the Late Vistulian. The Middle and Late Vistulian glacial events were separated by a long ice-free period, between 65 and 30 ka.**

1. INTRODUCTION

The studies of the Vistulian Glaciation stratigraphy in the southern part of the Lower Vistula (**Fig. 1**) region have been carried out for several recent years (Wysota, 2002; Wysota *et al.*, 1996 and 2000). Thick and not deformed Vistulian stratigraphic sequences exposed along the scarp of the Vistula Valley between Toruń and Chełmno have been the subject of detailed examinations.

Lithostratigraphical and sedimentological researches have been carried out at seven key sites: Rzęczkowo, Łążyn, Unisław, Kiełp, Starogród 1, Starogród 2 and Chełmno (**Fig. 1**). They included: (1) identification and lithofacial analysis of sedimentary units, (2) analysis of directional elements (palaeocurrents, till fabric and kinematic indicators), (3) lithologic and petrographic investigations (grain size composition, carbonate content, quartz grain roundness, pethrographic composition of gravels and heavy mineral composition), (4) TL dating of deposits, and (5) spatial analysis of stratigraphic units. Some results of the studies conducted at Rzęczkowo and Łążyn sites have already been published (Wysota *et al.*, 1996 and 2000).

The paper presents the synthesis of the Vistulian Glaciation stratigraphy in the southern part of the Lower Vistula region. The new ideas of chronology and palaeogeography of the Vistulian glacial events have been also put forward.

2. STRATIGRAPHIC UNITS

The lower limit of Vistulian deposits has not been satisfactorily recognized yet. It is supposed that upper fluvial series of the Lower Vistula formation, which so far has been connected entirely with the Eemian (Makowska, 1979 and 1980), represents preglacial period of the Early Vistulian (**Fig. 2**).

The sequence of Middle and Late Vistulian deposits, that overlies the Early Vistulian fluvial sediments, has the thickness of 25–70 m here. Three main stratigraphic units have been distinguished: Chełmno clays formation, Rzęczkowo formation and Starogród formation (**Fig. 2**).

Chełmno clays occur at the bottom of the Middle Vistulian succession. They comprise varved clays and silts up to 20m in thickness, which fill the upper part of the Eemian/Early Vistulian palaeovalley. Overlying it,

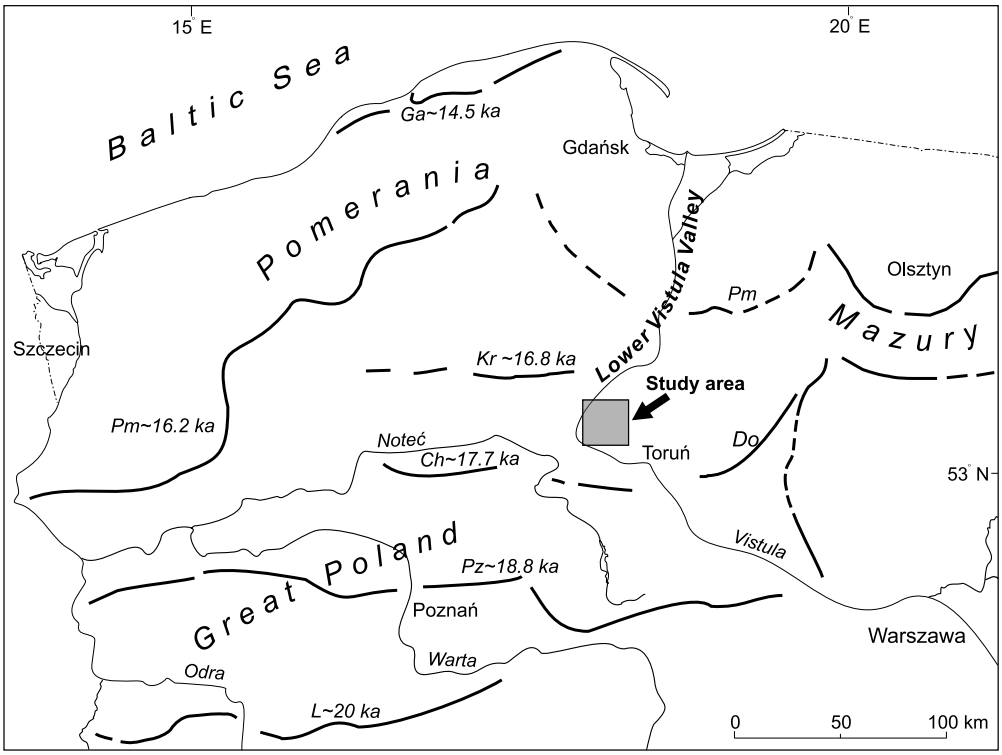

Fig. 1. *Study area against the ice sheet margins of the Vistulian Glaciation in the mid-western Poland.*
L – *Leszno phase,* Pz – *Poznań phase,* Ch, Do – *Chodzież, Dobrzyń readvance,* Kr –*Krajna subphase,* Pm – *Pomeranian phase, and* Ga – *Gardno phase.*

Rzęczkowo formation is 15–25 m thick, and composed mostly of fluvial sands. Lithofacies of planar cross-bedded sands, parallel laminated sands and ripple-laminated sands are predominant.

Starogród formation occurs at the top of the Vistulian sequences. Two separate till units have been distinguished: the lower till member – Łążyn till and the upper till member – Starogród Zamek till. Łążyn till is 1.5–10m thick and combines sandy and clay-rich massive and stratified diamictons. It comprises three genetic types of subglacial facies: deformation till, melt-out and decoupling till and melt-out till. Till fabric shows NE and NNE ice movement directions. Unisław clays, 2–6 m thick, of glaciolacustrine origin and lying underneath Łążyn till can be found in places. Glaciolacustrine sediments of up to 18-m thickness (Kiełp clays) overlie the lower till member. Glaciofluvial series occur below and above them locally.

Starogród Zamek till constitutes the highest unit of Starogród formation. It consists of massive brownish clay-rich diamicton up to 8–10m thick. The diamicton usually comprises two facies: lodgement till and melt-out till. Till fabric shows N and NNE ice movement directions.

3. RESULTS OF TL DATING

Two sets of samples were dated by TL method. The first one consisted of four samples related to Kiełp clays: R-4, R-5, St1-1 and St1-2. The other seven samples: K-2, K-3, Ch-1, Ch-2, R-6, Sa2-1 and Sa2-2 were related to Rzęczkowo formation.

The material taken for TL analysis was cleaned and afterwards the quartz grains of specified size were separated and then etched, appropriate to the procedure described earlier (Przegiętka, 1999; Oczkowski *et al.*, 2000a). The bleaching of natural TL signal was performed in a specially designed chamber with sunlight simulator (Oczkowski and Przegiętka, 1998a). The bleached samples were used for equivalent dose estimation by the regenerative method. The *plateau* test was applied to choose the best temperature region. The additive method was also applied for the majority of the samples. The Risø System comprising the calibrated ^{90}Sr source (Oczkowski and Przegiętka, 2000) was used for beta dose irradiation and TL measurements. Details of equivalent dose determination procedures were presented earlier (Oczkowski and Przegiętka, 1998a; Przegiętka, 1999; Wysota *et al.*, 2000). The annual dose rates were determined on the basis of high-resolution gamma spectrum measured with HP germanium detector and Canberra MCA-100 analyser. Details of measurement and computational procedures were published previously (Oczkowski and Przegiętka, 1998b; Oczkowski *et al.*, 2000b). Results are presented in the **Table 1**.

Previously four samples related to Rzęczkowo formation were dated (Wysota *et al.*, 2000). Those dates were analysed together with seven new ones. The mean age value T= 42.9 ka with standard uncertainty $\sigma = \pm 1.7$ ka were obtained by the weighted averaging method. The histogram showing the distribution of the eleven TL dates is presented in **Fig. 3**.

Apparently these dates represent rather a continuous process stretched over a certain period of time than a single event (**Fig. 4**). Hence the mean age value is not suitable parameter for describing such a process. We assumed that the set of eleven investigated samples was good enough for the representation of Rzęczkowo formation. The shape of the histogram (**Fig. 4**) may suggest that the deposition lasted for the period of *ca*. 35 ky. Hence, we concluded that sedimentation of Rzęczkowo formation deposits started *ca*. 65 and ended about 30 ka ago.

Table 1. *TL dates of deposits from southern part of the Lower Vistula region.*

No Section	Stratratigraphic Unit	Sample Name	Lab. No.	Material	Age [ka]	Equivalent Dose [Gy]	Dose Rate [Gy/ka]
1. Rzęczkowo	Kiełp clays	R-4	TOR-35	Glaciolacustrine silts	19 ± 3	35 ± 6	1.863
	Kiełp clays	R-5	TOR-36	Glaciolacustrine silts	20 ± 2	36 ± 4	1.805
	Rzęczkowo Fm.	R-6	TOR-37	Fluvial sands	33 ± 3	34 ± 3	1.023
	Rzęczkowo Fm.	R-2*	TOR-25	Fluvial sands	49 ± 6	51 ± 6	1.045
2. Łążyn	Rzęczkowo Fm.	L-3*	TOR-28	Fluvial silts	50 ± 8	104 ± 17	2.078
	Rzęczkowo Fm.	L-2*	TOR-27	Fluvial sands	63 ± 20	126 ± 40	2.000
	Rzęczkowo Fm.	L-1*	TOR-29	Fluvial sands	65 ± 20	130 ± 40	2.000
3. Kiełp	Rzęczkowo Fm.	K-2	TOR-31	Fluvial sands	39 ± 6	61 ± 9	1.564
	Rzęczkowo Fm.	K-3	TOR-32	Fluvial sands	57 ± 7	57 ± 7	1.008
4. Starogród 1	Kiełp clays	St1-2	TOR-41	Glaciofluvial sands	21 ± 3	41 ± 5	1.931
	Kiełp clays	St1-1	TOR-40	Glaciofluvial sands	27 ± 5	36 ± 6	1.329
5. Starogród 2	Rzęczkowo Fm.	Sa2-1	TOR-38	Fluvial sands	47 ± 7	62 ± 9	1.325
	Rzęczkowo Fm.	Sa2-2	TOR-39	Fluvial sands	49 ± 5	60 ± 6	1.221
6. Chełmno	Rzęczkowo Fm.	Ch-1	TOR-33	Fluvial silts	45 ± 5	76 ± 8	1.685
	Rzęczkowo Fm.	Ch-2	TOR-34	Fluvial sands	46 ± 5	47 ± 5	1.028

**) The data obtained prior to the present project and published in Wysota et al. (2000).*

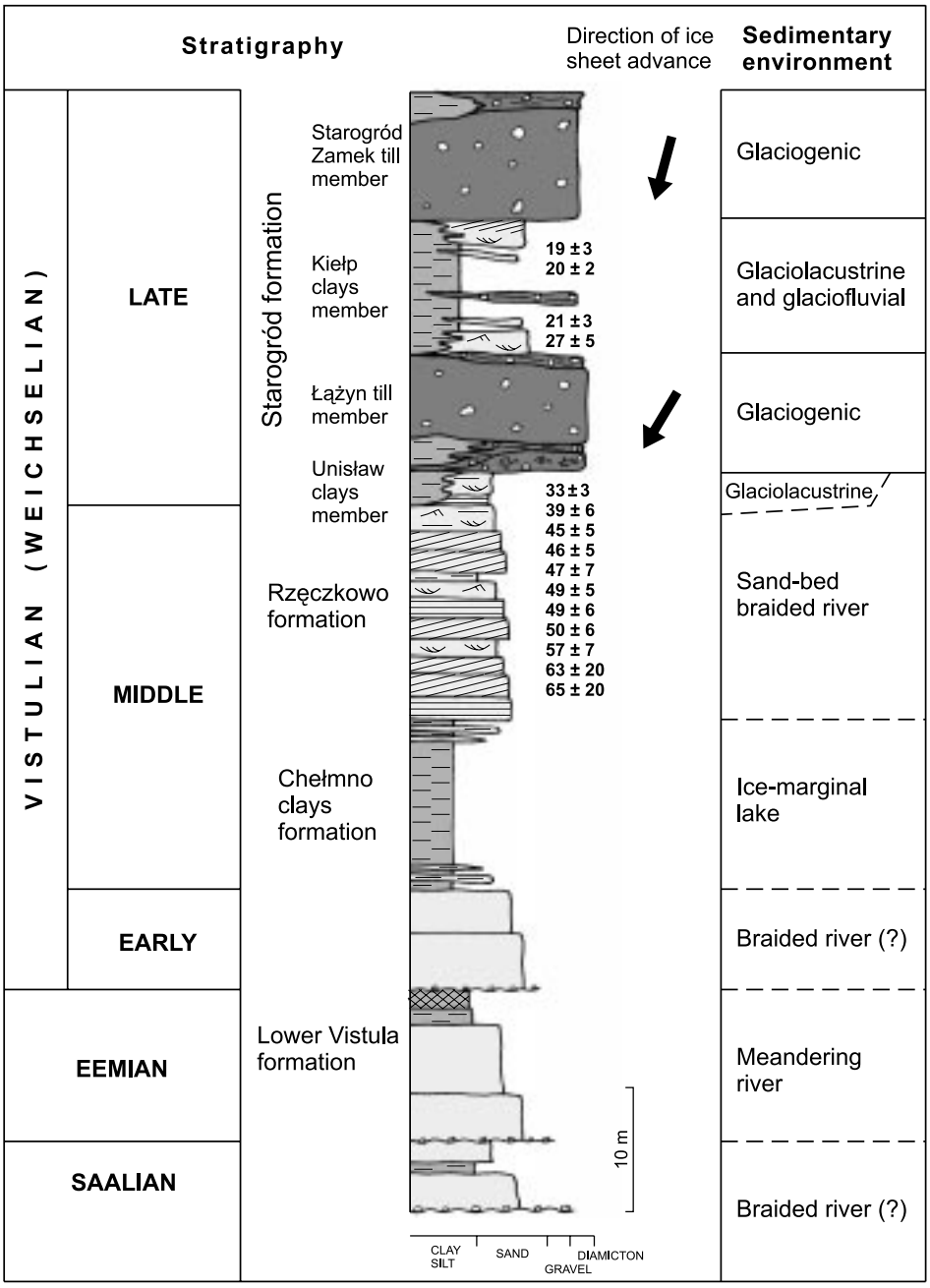

Fig. 2. *Synthetic section and sedimentary environments of Vistulian deposits in the southern part of the Lower Vistula region. The numbers column means TL dates in ka.*

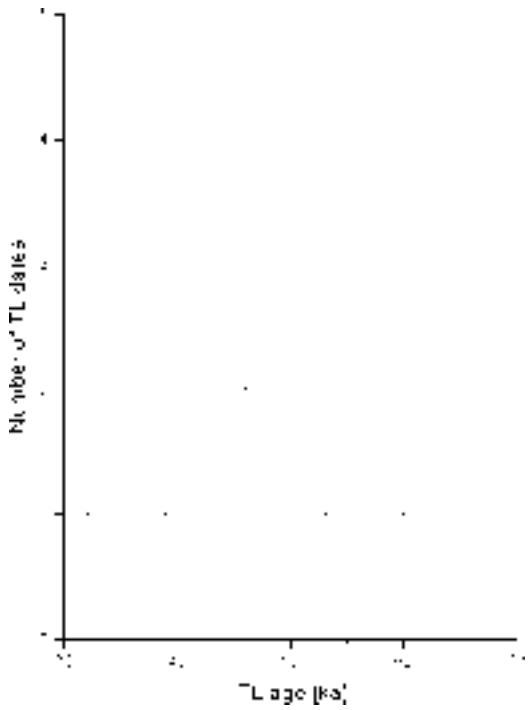

Fig. 3. *Histogram of eleven TL dates obtained for samples representing Rzęczkowo formation, the bar width is 7 ka.*

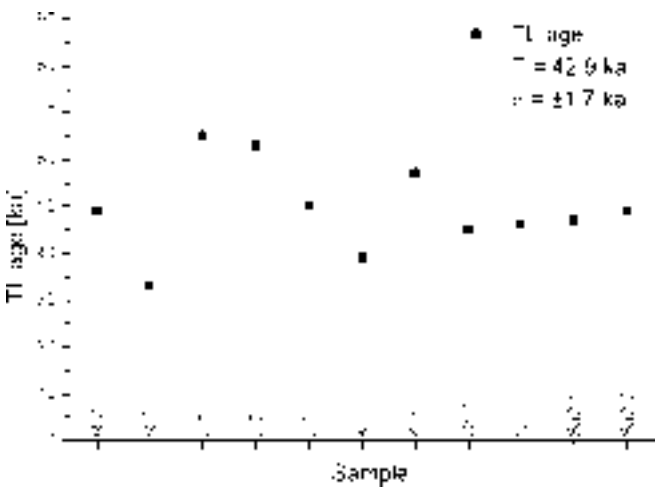

Fig. 4. *The set of eleven TL dates obtained for Rzęczkowo formation and the weighted average value with its uncertainty, $T \pm \sigma$.*

4. PALAEOGEOGRAPHIC EPISODES

The Vistulian deposits in the Lower Vistula region were deposited during five palaeogeographical episodes (**Fig. 2**). During the preglacial period of the Early Vistulian Upper fluvial series of the Lower Vistula Formation was accumulated. Deposition of deposits was developed in a braided river environment.

During the next stage Chełmno clays were formed. Sedimentary processes took place in a glaciolacustrine environment. The environment was formed as a result of the first ice sheet advance in the Lower Vistula region at the beginning of the Middle Vistulian (~65–70 ka). It is supposed that the ice sheet reached the Grudziądz Basin.

As the ice sheet was retreating, depositional processes were gradually changing their character from glaciolacustrine sedimentation to fluvial deposition. Rzęczkowo formation was deposited in the environment of a sand-bed braided river (Wysota *et al.*, 1996 and Wysota, 2002). The obtained TL dating suggests that the deposition of Rzęczkowo formation developed during a long ice-free period of the Middle Vistulian, between 65 and 30 ka.

Glacial, glaciolacustrine and glaciofluvial sedimentation characterised the succeeding depositional episodes. They were connected with two ice sheet advances, which covered the studied area during the Late Vistulian. The older glacial event was related to the first Late Vistulian maximum, *ca* 22–20 ka (the Leszno Phase). The younger one represented ice sheet readvance connected with the second Late Vistulian maximum, *ca* 19–18 ka (the Poznań Phase).

5. CONCLUSIONS

The obtained results of the studies indicate that there was no glacial event in the southern part of the Lower Vistula region during the Early Vistulian as it had previously been assumed (Makowska 1980, 1992 and 1994). Pelaeogeographical and especially palaeoclimalological conditions recently recognized in the Polish Lowland, also deny ice sheet existence on the Lower Vistula at that time (Mojski, 1999).

The first glacial advance in this area occurred as late as at the beginning of the Middle Vistulian. This advance corresponds to the Toruń glacial horizon distinguished earlier by Makowska (1979, 1980, 1992 and 1994) in the Lower Vistula region. The collected lithostratigraphic data have not confirmed that the ice sheet reached Toruń, as she presumed. The Middle Vistulian ice sheet anvanced to the northern, and probably to the middle part of the Lower Vistula region. Only proglacial deposits (Chełmno clays) are related to this advance in the southern part of the Lower Vistula region.

The obtained TL dates substantiated higher chronostratigraphic position of the younger Vistulian units than it had previously been stated (Makowska 1980, 1992 and 1994; Wysota *et al.*, 1996). It is presumed that Rzeczkowo Formation linked before to the Gniew Interstadial of the Early/Middle Vistulian period, represents a younger warm unit – the Grudziądz Interstadial of the Middle Vistulian. Overlying it, the lower glacial horizon of Starogród formation (Łążyn till), which formerly has been interpreted as the Middle Vistulian glacial episode unit (the Świecie stadial), is related to the first Late Vistulian maximum (ca. 22–20 ka). The ice sheet readvance connected with the second Late Vistulian maximum (ca. 19–18 ka) has not been recognized in the Lower Vistula region yet.

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SOME PROBLEMS IN THE STUDY OF THE CHRONOLOGY OF THE ANCIENT NOMADIC CULTURES IN EURASIA (9TH - 3RD CENTURIES BC)

A.YU.ALEKSEEV[1], N.A.BOKOVENKO[2], YU.BOLTRIK[3], K.A.CHUGUNOV[4], G.COOK[5], V.A.DERGACHEV[6], N.KOVALIUKH[7], G.POSSNERT[8], J.VAN DER PLICHT[9], E.M.SCOTT[10], A.SEMENTSOV[2], V.SKRIPKIN[7], S.VASILIEV[6] AND G.ZAITSEVA[2]

[1] *The State Hermitage Museum, St.Petersburg, Russia*
[2] *The Institute for the History of Material Culture of Russian Academy of Sciences, St.Petersburg, Russia*
[3] *The Institute of Archaeology of the National Academy of Sciences of Ukraine, Kiev, Ukraine*
[4] *The Institute of Cultural and Natural Heritage, St.Petersburg, Russia*
[5] *Radiocarbon Laboratory, SUERC, East Kilbride, Scotland*
[6] *The Physical-Technical Institute of the Russian Academy of Sciences, St.Petersburg, Russia*
[7] *State Scientific Centre of Environmental Radiochemistry of National Academy of Sciences of Ukraine, Kiev, Ukraine*
[8] *Svedberg Laboratory of Uppsala University, Uppsala, Sweden*
[9] *Radiocarbon Laboratory of Groningen University, Groningen, the Netherlands*
[10] *Department of Statistics, University of Glasgow, Glasgow, Scotland*

Key words: NOMADS, SCYTHIAN TIME, EURASIA, RADIOCARBON DATES

Abstract: This research is focused on the chronological investigations of ancient nomads belonging to the Scythian cultures which occupied the steppe and forest-steppe zones of Eurasia during the 9th-3rd centuries BC. The ^{14}C dates for the pre-scythian and early scythian time in both Europe and Asia are presented and compared to their chronological position based on archaeological evidence. The first ^{14}C dates have been produced for the Scythian time monuments located in the Lower Volga River basin, Urals and Transurals regions. Their chronological positions are compared with the position of the monuments of Southern Siberia and Central Asia. It was shown that the nomadic cultures belonging to the Scythian culture began to exist over the wide territory of Eurasia from the 9th-8th centuries cal BC and there are some monuments which may be synchronous to the Arzhan royal barrow (the oldest monument known). A list of new ^{14}C dates and a map of the monuments are presented.

1. INTRODUCTION

The chronology of the nomadic tribes, which occupied the steppe and forest-steppe zones of Eurasia during the 1st millennium BC is very important. The tribes are traditionally connected with the Scythian cultures which have different names in different regions of Eurasia: the Scythians in Europe, the Suoromathian in the Lower Volga River Basin and Southern Ural regions, the Tasmola in the Transural regions and the different mosaic cultures in Altai, Southern Ural and Central Asia. The majority of sites associated with these cultures are located between ~ 40 °-55°N and 30°-110°E. The connections between European and Asian Scythian cultures, and their interaction is testified by the similarities between both European and Asian Scythian artefacts, the dynamics of these interactions can be solved on the basis of chronological research.

For a long time, the chronology of the Eurasian Scythian cultures was based on a variety of different archaeological approaches due to a lack of ^{14}C dates for the European monuments. Recently the first radiocarbon dates for these monuments have been produced by AMS dating.

It is necessary to note that about 20 years ago, M.P.Gryasnov picked out 11 geographical zones in the history of Early Scythian cultures (9-7 centuries BC): 1) Northern Black Sea region, 2) the Northern Caucasus region, 3) the Aral Sea region, 4) Central and Northern Kazakhstan, 5) Semirech'e, Tien Shan and the Pamirs, 6) steppe and forest-steppe zones to the North and West from Altai Mountains, 7) Altai Mountains, 8) South Siberia, 9) Tuva, 10) Mongolia, 11) Ordos (Gryasnov, 1983).

It was found that these local zones contained features of later chronological periods, but it was necessary to add two additional geographical zones – the Lower Volga and

Southern Urals regions – to the list of zones. These latter additions may be considered as distinctive intermediate points for cultural and ethnic pulses between the two main macro-regions of the Scythian World – Western and Eastern.

One should also not forget that the Lower Volga nomads have close relations with European Scythians to the west, on one hand, and that Southern Urals barrows have many similar features with the Aral Sea region, Kazakhstan, and Southern Siberia materials to the east, on the other hand (Ochir-Gorayeva, 1988).

Such conclusions have been drawn on the basis of archaeological evidence. Now we have produced the first ^{14}C dates for the monuments in these regions and can compare the radiocarbon chronology of the key Scythian monuments for Eurasia focusing special attention on determining the first appearance of the Scythian culture.

2. RESULTS

In total, samples for dating have been collected from about 40 Eurasian Scythian monuments, many of them having not been previously dated. As well, additional ^{14}C dates were produced for some well-known Scythian monuments: Oguz, Solokha, and Chertomlyk, the Pazyryk group barrows, Arzhan, Dogee-Baary-2 and others. The map of monuments dated is presented in **Fig. 1**. The ^{14}C dates produced during the last two years and dates which were not published previously now are presented in **Table 1**. Earlier there was a broad sweep of territory in which the Scythian monuments had not been dated including the Lower Volga River basin and the Southern Ural regions. Now this gap has begun to be filled. There have also been a considerable number of samples collected for Scythian time monuments in Southern Siberia. It is important to note that before the end of 1990»s, only the elite barrow Arzhan, Dogee-Baary-2 and Kopto barrows had been ^{14}C dated (Alekseev *et al.*, 2001). Now there are about 10 Scythian-time monuments in this region dated by ^{14}C. Discussion of the interpretation of these results now follows.

3. DISCUSSION

Steppe and Forest-steppe regions of Europe

For the prescythian time of European Scythia, the monuments of the so-called Chernogorovka culture dated by archaeological finds to pre-scythian time play the most important role. Until recently there were no ^{14}C dates for this culture. In 1971 the Vysokaja Mogila barrow (graves number 2 and 5) was excavated in the Lower Dnieper River basin (steppe area). At first this monument was dated by archaeological materials. Grave number 5 dates to the late Chernogorovka period (900-750 BC according to Terenozhkin, 1976) and grave number 2 to the younger Novocherkassk period (750-650 BC). There are contradictory opinions on the absolute chronology of these two monuments: for example, 25 years ago A.I.Terenozhkin dated them both to *ca* middle 8th century BC, but S.A.Skory together with other archaeologists now date Vysokaja Mogila, grave 2 from the late 8th to the early 7th centuries BC (Skory, 1999). ^{14}C dates of both graves

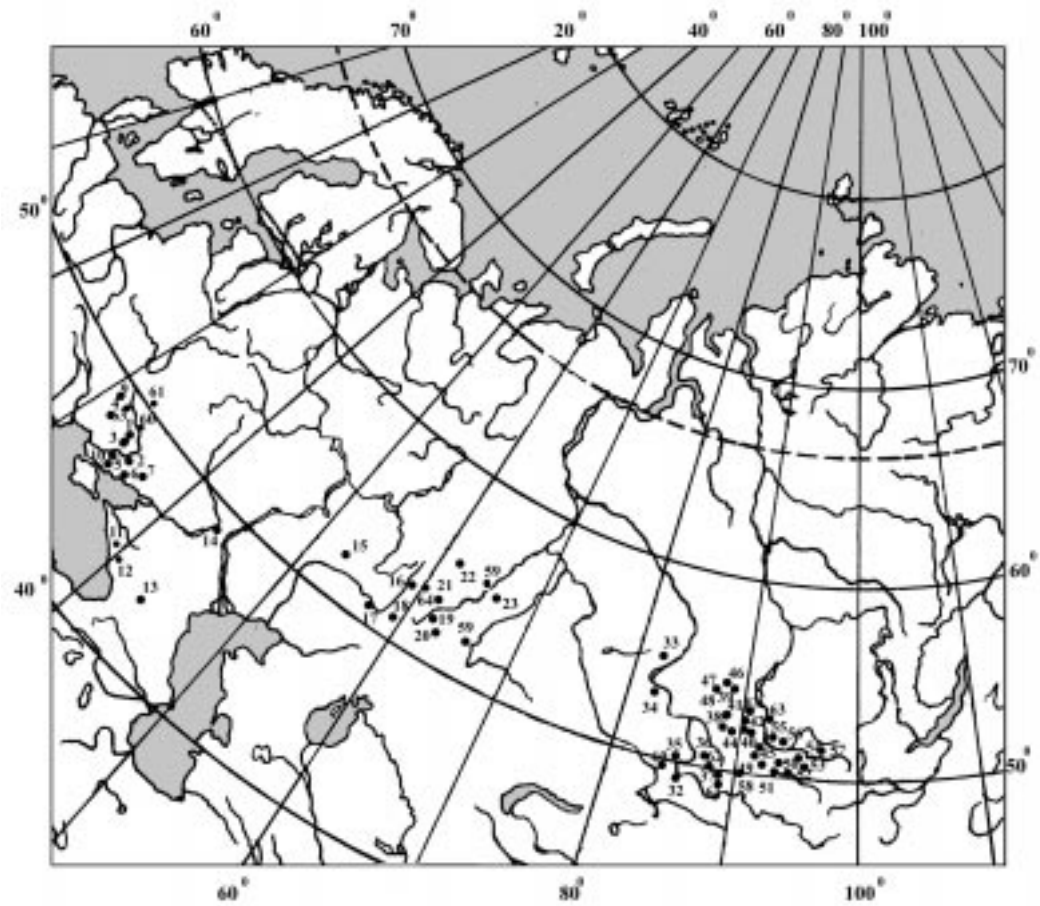

Fig.1. *Map of location of the Scythian time monuments dated by ^{14}C.*

produced recently are very close and give earlier results: grave 5, Ki –8425, 2765±50 BP (calibrated 1007-815 cal BC, 2σ), and grave 2, Ki-8424, 2740±50 BP (calibrated 997-805 cal BC, 2σ). This evidence would suggest that the modern archaeological "short" chronology is not quite correct.

Another important monument for European Scythia also dated to the early period is barrow 15 of the Steblev group located in the forest-steppe area. This was established as the oldest Scythian grave and dated by archaeologists to the late 8th century BC (Klochko and Skory, 1993). The ^{14}C dates produced for this barrow (2620-2580 BP) testify to the earlier Scythian association (the late 8th century cal BC).

For a long time, the oldest monument for all Eurasia was the royal barrow Arzhan (Central Asia and Tuva Republic). About 30 ^{14}C dates were produced which lay in the interval from 2800-2666 BP, testifying that this monument was erected during the 9th century cal BC (Zaitseva *et al*, 1998). Now there is the possibility to compare the radiocarbon chronology of the Arzhan barrow and European prescythian time monuments (Vysokaja Mogila and Steblev, grave 15). One can unter the same time intervals for their existence (**Table 1**).

Very interesting results have been obtained for the classical Scythian royal tomb Solokha, one of the four greatest Scythian barrows in the northern Black Sea region. Because the construction of any tomb occurred over a rather short time, it was very important to obtain a precisely calibrated calendar interval for ^{14}C dates and to compare the archaeological data and radiocarbon chronology. According to archaeological data, this barrow can be dated to 400-375 BC (Alekseev, 1992). Eleven ^{14}C dates for this famous barrow have been produced. Taking into account the complicated character of the calibration curve, which has a wide plateau for the intervals 2600-2400 BP, and impossibility of using in this case the wiggle matching method to establish the more precise calendar time of this tomb construction, we used the combine dates obtained by the OxCal calibration program. The combined ^{14}C date from the eleven individual dates is 2333±15 BP which corresponds to 400-395 cal BC (1σ) and to 403-390 cal BC (2σ) (**Fig. 2**). These results are generally in good agreement with the archaeological dates.

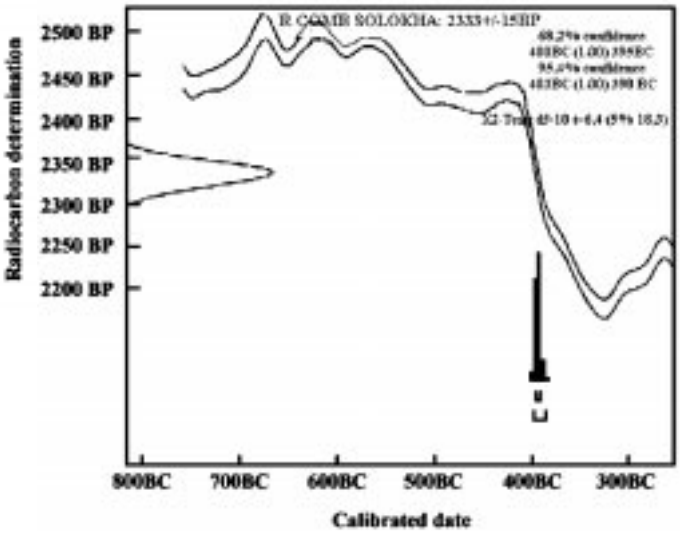

Fig. 2. *Combined ^{14}C date for the Solokha barrow and its position on the calibration curve.*

The Lower Volga River basin

The Lower Volga nomads have close relations with European Scythians to the West. They also have many similarities with the nomads of the Aral Sea region, Kazakhstan and Southern Siberia to the East. Now we present the first ^{14}C dates for the monuments in these regions (**Table 1**).

There are numerous nomadic graves of the Scythian era in the Lower Volga River region belonging to the so-called "Sauromatian" culture and one of them is the Aksenovski burial ground discovered in 1966 by V.P. Shilov (Shilov, 1997). According to archaeological data, the dates of all Aksenovski barrows and graves lie in the range of *ca* 450 – 375 BC.

Barrow number 10 (grave number 1, where two women were buried) also dates back to this time. Two bronze mirrors were found, however, which according to archaeological data belong to an earlier time – the 7th-6th centuries BC and what is more, one of these mirrors belongs to a special group of so-called "indicators" of the Early Scythian culture (Alekseev, 1992).

A sample for AMS radiocarbon dating was taken from wooden fragments of one of the mirror-cases. One of the ^{14}C dates (Ua-16869) gave us the general chronological period from the 9th to 5th centuries cal BC (2σ). In more detail, the calibration intervals are the following: 9th-6th century cal BC, early 5th century cal BC, or second half of the 5th century cal BC. Each of these intervals is in a good agreement with the known archaeological date. A second ^{14}C date (GrA-16832) is earlier – from the 9th to the beginning of the 8th century cal BC. It is important to note that combined date (2640±41 BP) gives also the same range. One explanation is that the samples perhaps came from the central part of the trunk. In any case, results of radiocarbon dating show that *terminus ante quem* of the construction of this wooden artifact is the late 5th century BC.

Southern Urals and Southern Transurals regions

The ancient nomadic culture in the Southern Urals was located in the centre of the "steppe belt" of the Scythian cultures and it was subjected to a certain influence from the nomads from the West (the Pontic Sea area) and from the East (Central Asia, Altai and Southern Siberia). The most important and famous barrow for the late prescythian and early Scythian periods is the Great Gumarovo barrow (grave number 3) excavated in 1980 by R. Ismagilov (Ismagilov, 1988). This monument can be archaeologically dated on the late 8th to the early 7th centuries BC. Samples for ^{14}C analyses (AMS) were taken from four leather fragments and one wooden fragment from the quiver.

The agreement between archaeological and ^{14}C dates is good, except sample Ua-16867, 2750±75 BP, which gave an earlier chronological age – from the late 12th to the

Table 1. *The ^{14}C dates produced for the Scythian time monuments of Eurasia.*

No	No on the Map	Lab. index	^{14}C Age [BP]	Monument	Material	C alibrated age [BC]	
						1	2
Ukraine							
Pre-Scythian time (Chernogorovskaya culture)							
1	60	Ki-8424	2740±50	Visoka mogila	Wood	910-826	990-806
2	60	Ki-8425	2765±50	Visoka mogila	Wood	978-834	1000-814
Earlier Scythian time							
3		Ki-7740	2490±50	Steblev, barrow 15	Animal bone	766-528	782-412
4	9	Ki-7741	2660±50	Steblev, barrow 15	Animal bone	892-794	906-778
5	9	Ki-8426	2620±60	Steblev, barrow 15	Wood	892-562	908-532
6	9	Ki-8427	2530±60	Steblev, barrow 15	Wood	794-534	804-414
7	9	Ki-8428	2580±60	Steblev, barrow 15	Wood	810-550	836-420
Scythian time							
8	63	Ki-8454	2180±60	Vishneva Mogila, barrow 11, grave 3	Organic remains	360-122	374-60
9	63	Ki-8454	2230±60	Vishneva Mogila, barrow 11, grave 5	Leather	368-202	396-120
10	63	Ki-8455	2210±60	Vishneva Mogila, barrow 11, grave 5	Wood	364-192	392-106
11	63	Ki-8456	2170±70	Vishneva Mogila, barrow 11, grave 5	Leather from shoes	358-110	382-44
12	63	Ki-8457	2250±70	Vishneva Mogila, barrow 11, grave 4	Leather	384-202	406-106
13	6	GrA-10163	2170±40	Oguz, grave 9	Grass,	354-118	364-66
14	6	Ki-7717	2230±50	Oguz	Skeleton bone	366-202	392-176
15	6	Ki-7718	2190±50	Oguz	Grass	360-178	380-100
16	7	GrA-10164	2330±50	Pastak, barrow 10	Wood from sword	476-214	750-202
17	10	GrA-10059	2180±40	Chertomlyk	Wood from arrows	356-166	368-106
18	10	GrA-10203	2320±50	Chertomlyk	Wood from arrows	408-210	516-200
19	10	GrA-10204	2350±50	Chertomlyk	Wood from arrows	514-368	756-208
20	10	Ki-7720	2290±50	Chertomlyk, embanment	Horse bone	398-210	404-200
21	10	Ki-7721	2170±80	Chertomlyk, embanment	Sheep bone	360-108	388-8
22	10	Ki-7722	2335±80	Chertomlyk, northern grave	Animal bone	520-206	762-192
23	10	Ki-7723	2130±70	Chertomlyk, northern grave	Sheep bone	348-44	366BC-10AD
24	10	Ki-7724	2210±70	Chertomlyk, northern grave	Horse bone	368-190	394-66
25	10	Ki-7725	2170±60	Chertomlyk	Wool from clothes	358-112	370-54
26	10	Ki-7726	2310±55	Chertomlyk	Skeleton bone	406-208	512-196
27	8	GrA-10060	2325±40	Solokha,	Wood from sword	406-264	484-206
28	8	GrA-10159	2270±50	Solokha	Wood from sword	390-208	398-200
29	8	GrA-10160	2350±50	Solokha	Wood from sword	514-368	756-208
30	8	Ki-7742	2370±55	Solokha	Wood from sword	746-380	762-254
31	8	Ki-7743	2295±55	Solokha	Wood from sword	400-208	474-192
32	8	Ki-7744	2310±55	Solokha	Wood from sword	406-208	512-196
33	8	Ki-7745	2350±55	Solokha	Wood from artefact	516-266	758-204
34	8	Ki-7746	2320±55	Solokha	Wood from artefact	410-208	522-198
35	8	Ki-7747	2380±55	Solokha	Grass rope	750-386	762-266
36	8	Ki-7748	2425±60	Solokha	Leather	756-402	764-394
37	8	Ki-7749	2300±55	Solokha	Wood from artefact	402-208	482-192
Northern Caucasus, Russia							
38	11	Ki-7769	2510±50	Uashkhitu, barrow 1	Wood	780-530	796-416
39	11	Ki-7770	2570±50	Uashkhitu, barrow 1	Wood	806-554	816-526
Lower Volga River Basin							
40	14.	Ua-16869	2595±75	Aksenovski	Wood from mirror	826-546	902-418
41	14	GrA-16832	2660±50	Aksenovski	Wood from mirror	892-794	906-778
Southern Ural and Transural regions (Orenburg, Chelyabinsk oblasts, Bashkartostan)							
42	15	GrA-15862	2320±50	Filippovka	Wood from the gold deer	408-210	516-200
43	15	GrA-15860	2940±50	Filippovka	Wood from the gold deer	1250-1046	1304-994
44	17	Ua-16866	2430±70	Gumarovo	Leather	758-402	766-394
45	17	Ua-16867	2750±75	Gumarovo	Organic	982-816	1112-796
46	17	GrA-12895	2500±70	Gumarovo	Organic	774-524	792-412
47	17	GrA-16829	2500±50	Gumarovo	Leather	770-530	792-414
48	17	AA-40434	2623±44	Gumarovo	Wood from arrow bow case	822-780	898-554
49	18	Ua-16870	2590±85	Solonchanka	Wood of shaft	830-536	900-414
50	64	AA-40432	2454±58	Small Klimovski	Wood from shaft	760-410	766-404
51	21	GrA-16831	2250±50	Temir	Wood	378-206	392-194
52	21	Ua-16868	2250±75	Temir	Bark-birch	386-202	408-64

Altai							
53	35	Le-5788	2200±40	Bashadar dendro- sampl, 80 tree-rings	Wood, 1-10 tree-rings	358-192	378-126
54	35	Le-5789	2200±20	Bashadar dendro- sampl, 80 tree-rings	Wood, 11-20 tree-rings	355-195	359-191
55	35	Le-5790	2175±20	Bashadar dendro- sampl, 80 tree-rings	Wood, 21-30 tree-rings	345-182	356-130
56	35	Le-5791	2145±25	Bashadar dendro- sampl, 80 tree-rings	Wood, 31-40 tree-rings	194-118	342-64
57	35	Le-5792	2160±50	Bashadar dendro- sampl, 80 tree-rings	Wood, 41-50 tree-rings	354-10	364-50
58	35	Le-5793	2152±25	Bashadar dendro- sampl, 80 tree-rings	Wood, 51-60 tree-rings	198-118	350-68
59	35	Le-5794	2170±20	Bashadar dendro- sampl, 80 tree-rings	Wood, 61-70 tree-rings	343-176	354-120
60	35	Le-5795	2190±40	Bashadar dendro- sampl, 80 tree-rings	Wood, 71-80 tree-rings	358-184	372-116
61	36	GU-8355	2340±60	Pazyryk-2	Wood, all tree rings	516-254	758-200
62	36	GU-8356	2360±50	Pazyryk-2	Wood, all tree rings	516-376	760-210
Southern Siberia							
63	40	Le-5838	2780±30	Tiger-Taidzhen, barrow1	Wood	980-848	992-838
64	43	Le-5646	2640±120	Kazanovka-3, barrow 2A, grave 2	Bone of skeleton	920-530	1030-400
65	45	Le-5669	2570±30	Taplaya, barrow 1, grave 2	Charcoal	802-610	806-552
66	46	Le-5679	2370±20	Cheremshino, barrow, grave 1, log, 4 layer from the centre	Wood	406-397	473-390
67	46	Le-5678	2400±20	Cheremshino, barrow, grave 1, log, 3 layer from the centre	Wood	484-401	516-399
68	46	Le-5677	2540±40	Cheremshino, barrow, grave 1, log, 2 layer from the centre	Wood	794-552	802-526
70	46	Le-5676	2710±60	Cheremshino, barrow, grave 1, log, 1 layer from the centre	Wood	900-812	990-796
71	46	Le-5680	2435±25	Cheremshino, barrow 1, grave 1, outside rings	Wood	746-410	756-404
72	46	Le-5670	2470±30	Cheremshino, barrow 1, grave 3	Wood	762-420	764-412
73	46	Le-5668	2530±25	Cheremshino, barrow 1, grave 2	Wood	786-554	792-542
74	46	Le-5671	2610±50	Cheremshino, barrow 1, grave 3	Wood	828-606	894-540
75	46	Le-5672	2660±60	Cheremshino, barrow 1, grave 1, outside rings	Wood	898-792	980-556
76	46	Le-5675	2700±50	Cheremshino, barrow 1, grave 1, central rings	Wood	898-808	926-796
77	47	Le-5651	2480±50	Pechische, barrow 3, grave 3	Bone of skeleton	764-518	770-412
78	48	Le-5652	2490±80	Sarala, barrow 2, grave 1	Bone of skeleton	770-516	790-410
Central Asia (Tuva)							
79	49	Le-5848	2440±30	Aldy-Bel,branch grave	Wood	752-410	760-402
80	49	GU-9181	2470±50	Aldy-Bel,branch grave	Wood	762-418	766-412
81	50	Le-5446	2880±120	Arzhan	Horse teeth	1210-910	1380-820
82	50	Le-5645	2750±35	Arzhan	Wood, fragment of upper log, 22 tree-rings	908-842	982-816
83	51	GU-8351	2310±60	Arzhan-Tarlag	Wood, fragment of upper log, 20 tree-rings	406-208	520-192
84	51	GU-8354	2360±50	Arzhan-Tarlag	Wood, fragment of upper log, 20 tree-rings	516-376	760-210
85	51	GU-8352	2410±70	Arzhan-Tarlag	Wood, fragment of upper log, 20 tree-rings	758-396	768-384
86	51	GU-8353	2470±60	Arzhan-Tarlag	Wood, fragment of upper log	762-418	768-408
87	51	Le-5450	2455±25	Arzhan-Tarlag	Wood, fragment of upper log	756-416	762-408
88	52	Ua-12968	2425±45	Dogee-Baary-2, barrow 10	Leather	752-404	762-396
89	52	Ua-12969	2435±45	Dogee-Baary-2, barrow 3	Textile	754-408	762-400
90	52	Ua-12970	2490±45	Dogee-Baary-2, barrow 1	Textile	764-528	782-414
91	52	Ua-12971	2420±45	Dogee-Baary-2, barrow 6	Textile	752-402	762-394
92	52	Ua-12972	2450±45	Dogee-Baary-2, barrow 15	Textile	758-410	764-404
93	54	Le-5603	2800±200	Suglug-Khem-1, part of artefact	Wood	1260-790	1430-410
94	55	Le-5566	2300±50	Saryg-Bulun, barrow 1, grave 5	Wood	402-210	408-200
95	56	Ua-15270	2190±70	Ust'-Khadynnyg-1- barrow 37	Bone	366-162	384-58
96	56	Ua-15229	2635±70	Ust'-Khadynnyg-1, barrow 4, grave 3	Wood from arrow	902-606	926-528
97	56	Ua-15228	2805±70	Ust'-Khadynnyg-1, barrow 4, grave 3	Leather from quiver	1016-844	1154-810
98	57	Ua-12973	2360±45	Chinge-2, barrow 22, grave 2	Textile	510-380	756-256

early 8th century cal BC, but it turns out that all the dates result in very wide calibrated intervals and so do not allow a more accurate age definition. The combined date (2562±25 BP) gives a "narrower" calibrated range: 798-766 cal BC (1σ), 802-760, 676-662, 632-590 and 584-554 cal BC (2σ), and there is evidence that the quiver can be attributed to the period *ca* 800-750 BC or to the period from the 7th to the first half of the 6th century BC.

As one of the most famous monuments of this period we can identify the so-called Filippovka "royal" burial ground which was excavated in 1986-1989 by A. Pshenichniuk (2000). The most important site is barrow number 1 which is of 7 m height. Different weapons, horse bridles, golden plaques on wooden vessels, several gold and silver Iran vessels and 26 large, extraordinary wooden sculptures of deer which were covered by gold and silver were found. The majority of these objects are unique but at the same time, they demonstrate stylistic similarity with objects from other regions of the Scythian world – South Siberia, Altai Mountains, Central Asia, and Northern Caucasus (Korolkova, 2000). According to the archaeological data there are two similar dates proposed for the Filippovka burial ground – the 5th century BC (Korolkova (Chezhina), 1992) and the early 4th century BC (Pshenichniuk, 2000). Samples for ^{14}C analyses (AMS) were taken from wooden fragments from inside the base of the deer sculptures.

Radiocarbon dates give different chronological ranges (GrA-15860, 2940±50 BP; GrA-15862, 2320±50 BP). GrA-15862 date is in perfect correlation with archaeological evidence. The combined ^{14}C date 2630±35 BP, calibrated to 832 – 774 cal BC (2σ) is earlier than the archaeological dating.

The comparison of the radiocarbon age for the Scythian time monuments of the Lower Volga River basin and the Southern Ural regions with the monuments of the Sayan-Altai (the Arzhan and Pazyryk group) presented in **Table 1** shows, that the radiocarbon age of these monuments is significantly younger than the Arzhan barrow but closer to the Pazyryk group barrows.

Southern Siberia and Central Asia (Tuva)

As mentioned above the oldest monument for all Eurasia is the royal barrow Arzhan (Central Asia and Tuva Republic). In 2000 the first radiocarbon dates were produced for other monuments belonging to the prescythian and early Scythian time.

The most interesting new date has been produced for the monument Tigir-Taidzhen, barrow 1: 2780±30 BP (Le-5838). It is very important that, according to this date and to the archaeological finds, this barrow is synchronous with the Arzhan barrow and can be dated to the 9th cal BC.

Another interesting monument of the Tagar culture in the Southern Siberia (Minusinsk valley) is the Cheremshino barrow. According to the archaeological classification, this monument dates to the early stage of the Tagar culture. Now the first radiocarbon dates have been produced for this monument from the wooden barrow construction and have been used in the "wiggle matching" method to produce a precise determination of the calendar interval. According to these data this barrow can be dated to the beginning of the 8th cal BC.

The so-called "aldy-bel" culture (Grach, 1983) existed in Central Asia (Tuva). One should note that the earliest Scythian barrow Arzhan is located in Tuva too. For a long time only this monument was dated by ^{14}C. Now ^{14}C dates have been produced for the Ust'-Khadynnyg-1 barrow. Dates 2635±70 BP, wood from arrow (Ua-15229) and 2805±70 BP, leather from quiver (Ua-15228) for barrow 4, grave 3 excavated by A.D. Grach in 1980 (Grach, 1983) can be correlated with the dates for the Arzhan barrow.

The key monument of the late stage of Scythian time, the so-called the uyuk-saglynsk culture, is the Dogee-Baary-2 barrow. A long series of ^{14}C dates have been produced for this monument and the "wiggle matching" method has been used to determine its position on the calendar scale (Alekseev *et al*., 2001). The results confirmed the archaeological ideas about the existence of this monument during the 5th-4th centuries BC. ^{14}C dates for the Arzhan-Tarlag (Gu-8351-8354) and the Chinge (Ua-12973) barrows testify to their synchronicity. The Aldy-Bel' burial mound according to the ^{14}C dates produced from the wooden barrow construction (Le-5848, and GU-9181) can be related to this time.

The first ^{14}C dates produced for the monuments belonging to the pre-scythian and early scythian time of Southern Siberia and Central Asia testify that some monuments existed in this territory at the same time as the Arzhan barrow.

4. CONCLUSIONS

Since the 9th-8th centuries BC the Scythian cultures began to appear on the wide territory of the steppe and forest-steppe zones of Eurasia. Now there are some monuments, which, according to the radiocarbon dates, can be demonstrated to be synchronous to the Arzhan royal barrow. The ages of monuments located in the Lower Volga River basin, the Urals and Transurals regions are more synchronous to the Pazyryk group barrows.

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RADIOCARBON DATING OF THE NASCA SETTLEMENTS LOS MOLINOS AND LA MUŃA IN PALPA, PERU

JOCHEN GÖRSDORF[1] and MARKUS REINDEL[2]

[1]*Deutsches Archäologisches Institut, Eurasien-Abteilung, Postfach 330014, D-14191 Berlin, Germany (e-mail: 14C@dainst.de)*

[2]*Kommission für Allgemeine und Vergleichende Archäologie des Deutschen Archäologischen Instituts, Endenicher Straße 41, D-53115 Bonn, Germany (e-mail: reindel@kava.dainst.de)*

Key words: RADIOCARBON DATING, NASCA CULTURE, CHRONOLOGY, NASCA LINES

Abstract: The Palpa Archaeological Project PAP investigates the relationship between the famous Nasca lines and ancient settlements in the Palpa region, in the desert of the south coast of Peru. Chronology will be fixed in absolute terms by radiocarbon dating of sites of Los Molinos and La Muńa. As a first approximation we get for the Nasca 3 culture 60-280 cal AD and for Nasca 4/5 and 5 culture 320-430 cal AD. That means the transition from Early to Middle Nasca is in the range between 280-320 cal AD.

1. INTRODUCTION

The Palpa Archaeological Project of the German Institute of Archaeology and the Swiss-Liechtenstein Foundation for Archaeological Research Abroad investigates the relationship between the famous Nasca lines and ancient settlements in the Palpa region, in the desert of the south coast of Peru (Reindel, 1997; Reindel and Cuadrado, 1998 and 2000; Reindel *et al.*, 1998a,b). The Nasca culture is known mainly from undocumented museum materials excavated by grave looters. There have been few excavations which produced well documented archaeological contexts. The Palpa project aims to enlarge the archaeological data base concerning the cultural history of the Nasca region with emphasis on settlement studies, large scale excavations and stratigraphic investigations. Chronology will be fixed in absolute terms by radiocarbon dating. Field work includes a detailed photogrammetric and terrestrial mapping of the geoglyphs of the pampas, their associated archaeological features, an exhaustive survey of archaeological sites, test excavations and large scale excavations in several settlements. More than 500 archaeological sites have been recorded in the valleys of Rio Grande, Rio Palpa and Rio Viscas (**Figs 1** and **2**), dating from Middle Formative (600 BC) to Inca times (1530 AD). The archaeological evidence indicates that the geoglyphs originated from petroglyphs at about 400 BC and reached their apogee in Nasca times (200 BC – 600 AD). No later geoglyphs were identified (**Fig.3**).

The sites of Los Molinos and La Muńa functioned as administrative centres in the early and the middle Nasca period (0 – 400 AD). This chronological assessment could be confirmed by several radiocarbon dates, which we present. Settlement patterns, architecture, burial practices, the ceramic findings as well as botanical and faunistic remains show that the Nasca society was well organised and stratified. Religious specialists must have been in charge of the rituals concerning the nearby geoglyphs. Small shrines directly associated with the geoglyphs, where offerings of crop fruits, textiles and considerable amounts of Spondylus shells were found, demonstrate that water and fertility rites were practised in a sacred landscape which was constantly modified by the modelling of new geoglyphs. Our aim is to show the radiocarbon dating results in the frame of archaeological context.

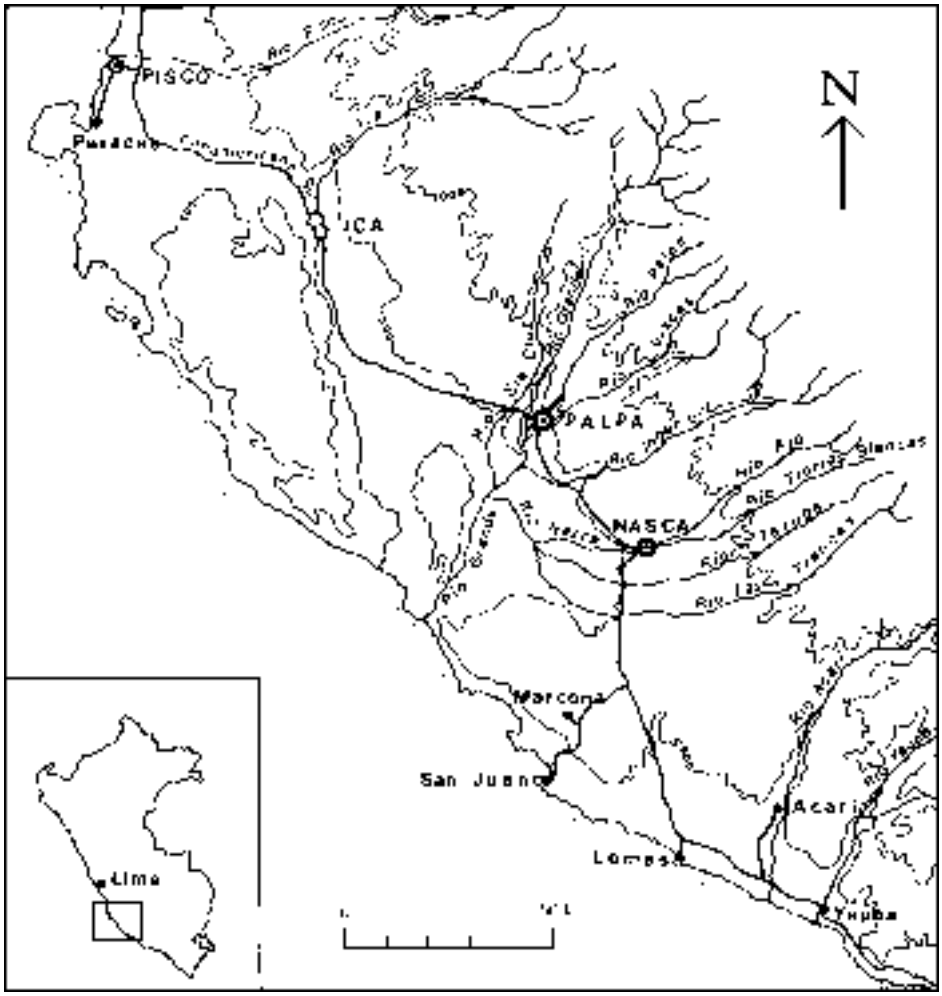

Fig. 1. *The Nasca region at the south/west coast of Peru.*

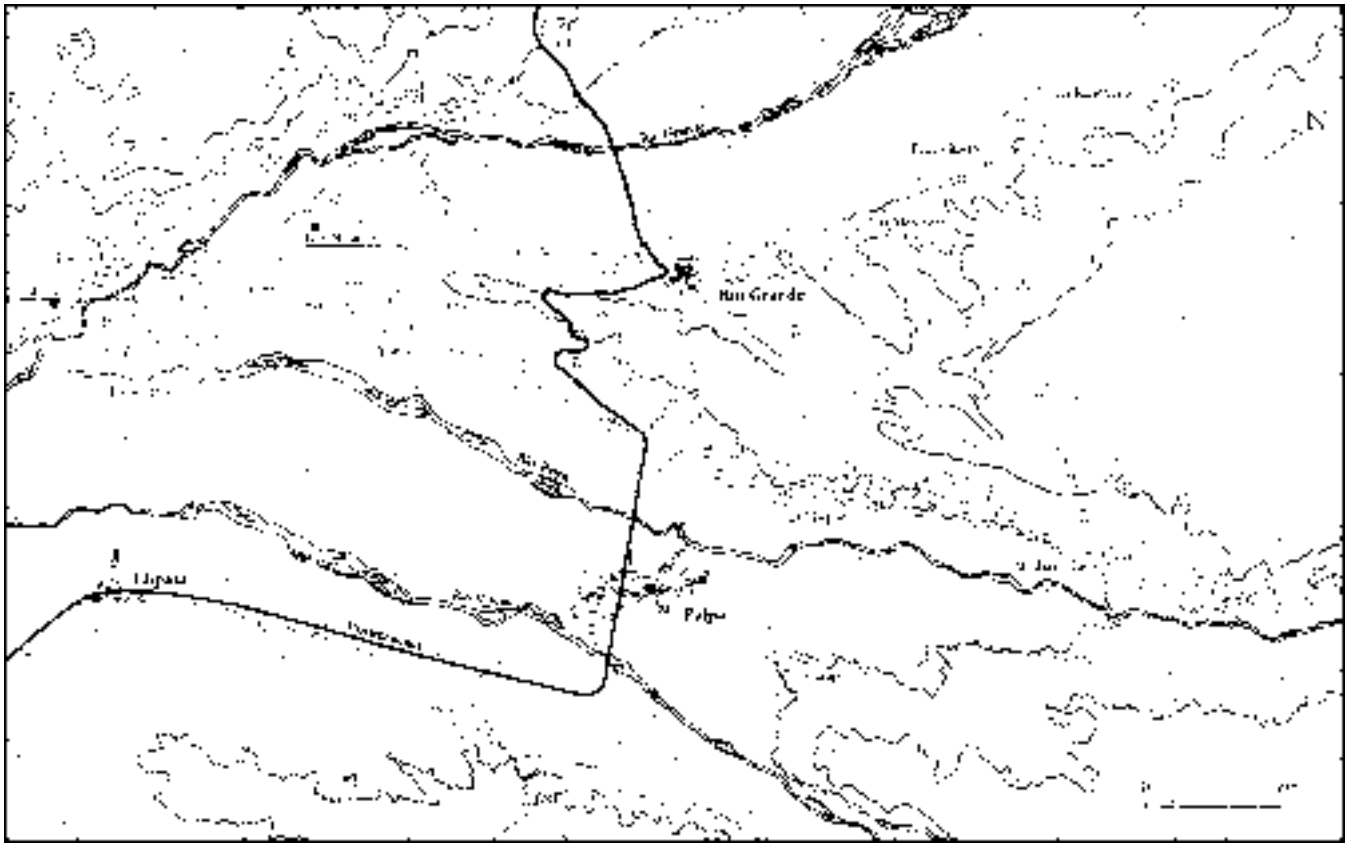

Fig. 2. *Map of the investigation area with PAP numbers of the archaeological sites.*

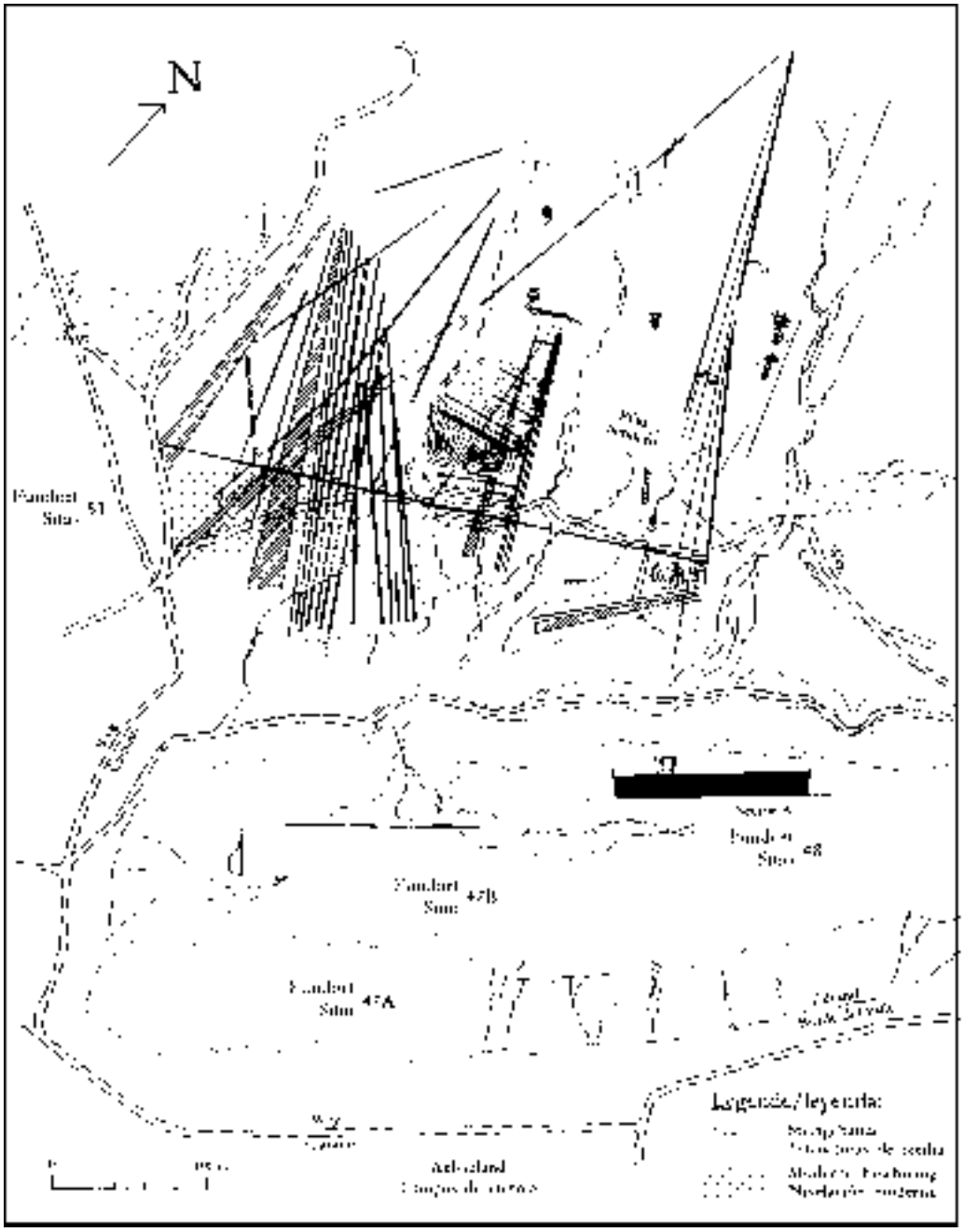

Fig. 3. *Investigation area near the sites PAP 47,48 and 53 with geoglyphs.*

2. METHODS

The bigger samples were dated in the Berlin Laboratory (Bln). Chemical pretreatment of samples was done by AAA treatment (Mook and Streurman, 1983). The dating was performed with gas proportional counters of the Houtermans-Oeschger type, using methane at 133.3 kPa pressure as filling gas. Measurement control and data processing were done using computer controlled system (Görsdorf, 1990; Görsdorf and Bojadžiev, 1996). A modern electronics is used. The preamplifier, pulse amplifier, comparator, pulse shaper and anti-coincidence unit are located in a box (19cm x 10cm x 5cm), which is directly connected to the counter. The detection of variation of the environmental radiation and the inspection of the long time stability of the electronics were required in order to reach the measurement accuracy (Görsdorf, 2000). The $\delta^{13}C$-measurements were done at the Leibniz-Labor, University of Kiel, Germany and are reported in permil relative to PDB-standard.

The smaller samples were dated in the Accelerator Mass Spectrometry Laboratory in Erlangen (Erl).

3. RESULTS

The results with sample numbers, site names and dating materials are shown in **Table 1**. The datings are corrected for isotopic fractionation using the measured $\delta^{13}C$ values. The ^{14}C ages are calibrated using the program Ox Cal v.3.5 (Ramsey, 1995, 1998 and 2000) and employing

the decadal calibration curve (Stuiver *et al*., 1998) as a first approximation for all samples. A Southern Hemispheric offset of 24±3 ^{14}C yr was taken into consideration (Stuiver *et al.,* 1998). The calibration intervals were presented for a confidence of 68.2 % and are rounded off to 10 years. **Fig. 4** shows the calibration results of the datings in chronological order.

4. COMMENTS AND CONCLUSIONS

The calibration results of the radiocarbon datings agree with the general chronological table of the Palpa area (based on Menzel, 1977), which is shown in **Table 2**. Only the dating results of the samples Bln-5239 seems to be too young. No explanation was found for that up to now.

Table 1. *Radiocarbon samples of the Palpa Archaeological Project and dating results.*

Sample no.	Site	Sector	Unit	Architectural Unit Tomb*	Layer	Context	Ceramic Phase	Material	Weight [g]	Lab. No.	δ^{13}C [‰]	^{14}C Age [BP]	Calibrated Ages (68,2%) [cal AD]
1	La Muña	C	2	R. N	C	Hearth	5	Charcoal	120	Bln-5234	- 25.0	1711 ± 30	290 - 420
2	La Muña	C	2	R. S	A	Hearth	5	Charcoal	160	Erl-3090	- 28.0	1816 ± 43	150 - 270
3	La Muña	B	5	R. 2	C	Hearth	5	Charcoal	105				
4	La Muña	B	5	R. 1	E	Tomb	5	Wood	350	Erl-3091	- 26.0	1685 ± 39	340 - 440
5	La Muña	B	5	R. 1	C	Hearth	5	Charcoal	80	Bln-5235	- 26.1	1691 ± 27	350 - 430
6	Los Molinos	A	1	T1	D	Tomb	4?	Cane	90				
7	Los Molinos	A	2	T1	B	Tomb	3	Wood	575	Bln-5236	- 24.4	1774 ± 25	250 - 340
8	Los Molinos	A	2	T1	B	Tomb	3	Cane	175	Erl-3092	- 25.0	1999 ± 40	20 cal BC - 80 cal AD
9	Los Molinos	A	2	T1	B	Tomb	3	Charcoal	95				
10	Los Molinos	A	2	R. 1	C	Hearth	4/5	Charcoal	100	Bln-5237	- 25.9	1694 ± 27	350 - 430
11	Los Molinos	A	2	R. 1A	J	Arch. Fill	3	Bean	10	Erl-3093	- 24.8	1858 ± 38	130 - 240
12	Los Molinos	A	2	Pass.	H	Arch. Fill	3	Bean	10	Erl-3094	- 24.6	1934 ± 39	50 - 140
13	Los Molinos	A	3	LT6	A	Tomb	4/5	Wood	345	Bln-5238	- 23.4	1727 ± 30	270 - 390
14	Los Molinos	A	3	AU4	F	Floor	4?	Cane and Wood	60				
15	Los Molinos	A	3	AU4	I	Arch. Fill	3/4	Maniok	140				
16	Los Molinos	A	3	AU2	B	Refuse	3	Seed of Huarango-tree	10				
17	Los Molinos	A	3	AU1	D	Layer	4?	Seeds	10				
18	Los Molinos	B	1	AU2	C-D	Post	3	Wood	275	Bln-5239	- 23.5	1634 ± 30	400 - 490
19	Los Molinos	B	1	AU2	D	Hearth	3	Charcoal	100	Erl-3095	- 26.4	1836 ± 39	150 - 250
20	Los Molinos	A	4		E	Arch. Fill	8	Bean	10				
21	Los Molinos	A	4		D	Arch. Fill	8	Bean	10	Erl-3096	- 29.2	1482 ± 35	570 - 650
22	Sitio PAP-11	A	1	T1	C	Tomb	Oc8	Wood	25				

R. =Room, AU =Architectural Unit, T =Tomb, LT =Looted Tomb, Pass. =Passage.

Table 2. *Chronological Table of the Palpa area (based on Menzel, 1977).*

Absolute Dates	Chronology Ica-Valley			Chronology Palpa-Valley
	Periods	Cultures		
1532 AD	LATE HORIZON	INKA		Inka
1476 AD	LATE INTERMEDIATE PERIOD	ICA		Poroma Carrizal
1000 AD	MIDDLE HORIZON	WARI		Chakipampa Loro (Nasca 8)
600 AD	EARLY INTERMEDIATE PERIOD	NASCA	Late	Nasca 6/7
			Middle	Nasca 4/5
			Early	Nasca 2/3
BC 0 AD	TRANSICIONAL	Initial Nasca		Ocucaje 10/Nasca 1
200 BC	EARLY HORIZON	PARACAS	Late	Ocucaje 8/9
			Middle	Ocucaje 5/6
800 BC			Middle	Ocucaje 3

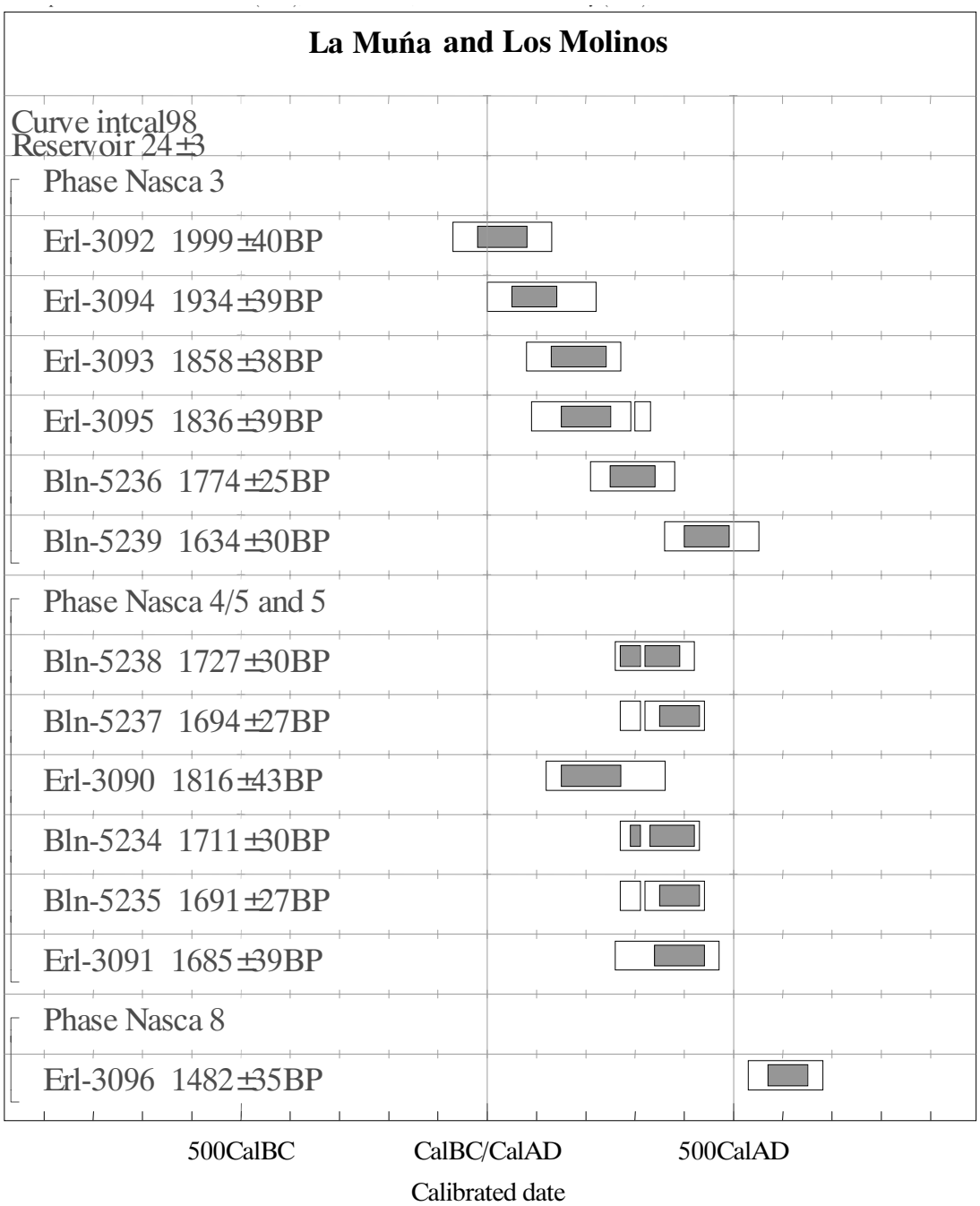

Fig. 4 *The calibration results of the dates from Los Molinos and La Muńa sites.The confidence limit of the hatched boxes is 68.2% and of the broader boxes 95.4%.*

A recalculation of the calibration intervals, take into account the cultural order, with the help of the Gibbs Sampling Method (Ramsey, 1995) gives the results in **Fig. 5**. The sum of calibration results date the cultures in a first approximation. For the Nasca 3 sum (probability of 68,2 %) we get 60-280 cal AD and for Nasca 4/5 and 5 (probability of 68,2 %) we get 320-430 cal AD. That means the transition from Early to Middle Nasca is in the range between 280-320 cal AD.

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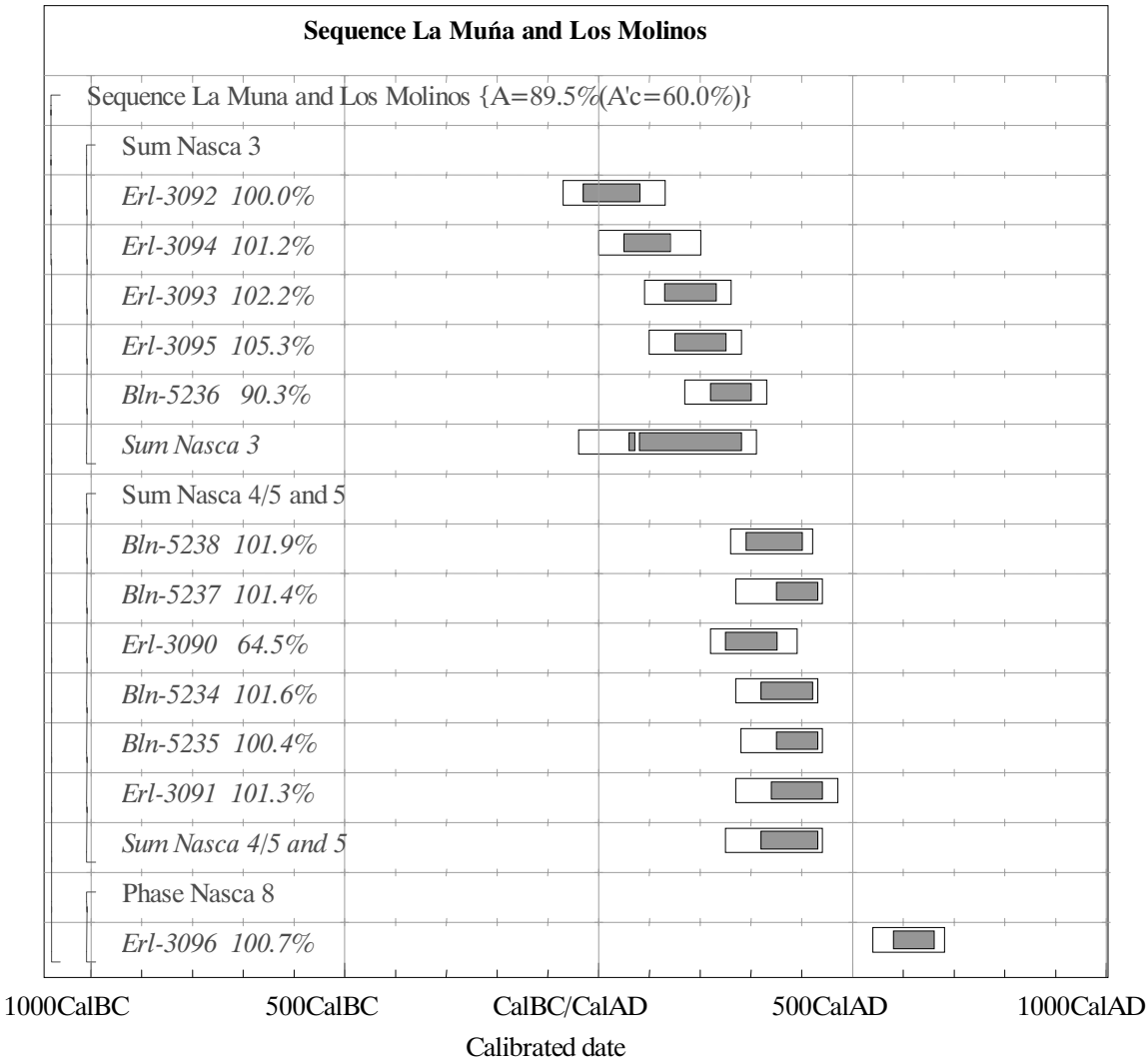

Fig. 5 *The calibration of dating results with the Gibbs Sampling Methode. The confidence limit of the hatched boxes is 68.2% and of the broader boxes 95.4%.*

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DATING OF THE GRAVE COMPLEX IN DACHARZÓW, MAŁOPOLSKA

HALINA TARAS[1], NIKOLAJ KOVALJUKH[2] and VADIM SKRIPKIN[2]

[1]*Institute of Archaeology University of Lublin, Curie-Skłodowska 4 square, 20-031 Lublin, Poland*
(e-mail: koliber@klio.umcs.lublin.pl)
[2]*State Scientific Centre of Environmental Radiogeochemistry, Palladin 34, 142 Kiev, Ukraine*

Key words: RADIOCARBON DATING, BONES, DACHARZÓW SITE, MAŁOPOLSKA

Abstract: Radiocarbon dating has confirmed the division of the period when the grave complex in Dacharzów was used into two stages, between which there was a distinct gap. In the second stage the graves appeared in cycles, after longer breaks (100 years or more). The cemetery was used from the end of the 17th to the 10th or 10th/9th centuries BC.

1. INTRODUCTION

Dacharzów (Sandomierz district) is situated in the north-eastern part of the Sandomierz Upland (**Fig. 1**). In 1991 one barrow was discovered here, marked as site 1 (Florek, 1994). It is situated on the edge of the Opatówka river valley, rising 50 metres above the flat bottom of the valley. In the years 1994-1995 archaeological excavations were carried out on the barrow and its surroundings (Florek and Taras, 1996). As a result, a whole complex of graves was uncovered, dating from the Bronze Age, from the period of the Trzciniec Culture (Florek and Taras, 1997; Florek, 1998).

In the central part of the barrow was found a stone structure consisting of two chambers (**Fig. 2**). They had a wooden rafter structure, which supported the walls, and a wooden (oak) floor; the remains of the wood have been used in radiocarbon dating.

Inside the bigger chamber there were bone remains of six people – four women and two children. The skeletons, badly-preserved, were not lying in the anatomical order, and some of the bones in the northern part were burnt out. In the smaller chamber there were scattered less burnt bones of, most probably, a man. The bone material coming from all the people buried here was radiocarbon-dated.

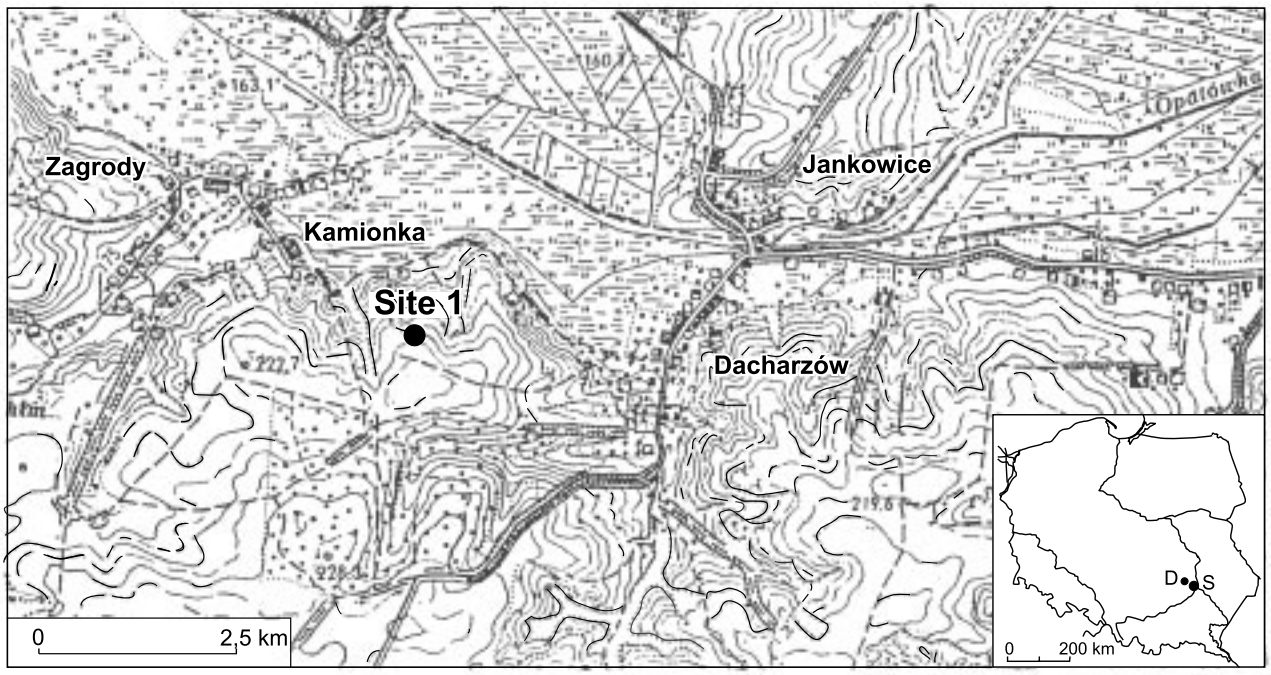


Fig. 1. *Dacharzów, site 1. Location of the site (S – Sandomierz, D – Dacharzów).*

The stone graves with their immediate surroundings were covered with an earthen mound; earth for the mound was taken mainly from the area north of the barrow, where, as a result, a semi-circular basin was created.

On the south-western part of the mound there was observed a semicrescent-like ditch (**Fig. 2**). On the circumference of the mound, in its southern and eastern parts, eight graves were discovered (No. 2, 5, 8-12, 14) containing inhumation burials. The skeletons are poorly-preserved, in some cases there are only single bones preserved. The bone remains from all the graves but one – No. 14 – have been radiocarbon-dated.

2. METHODS OF RADIOCARBON DATING OF BONE SAMPLES

In the research was used the technology developed in Kiev Radiocarbon Laboratory. This technology makes it possible to produce lithium carbide production from collagen or bone without preliminary deposition of them in a pure kind (Skripkin and Kovaljukh, 1998). The bones for this purpose are reduced to fragments, and after washing with trisodium phosphate solution they are processed by 1-3% hydrofluoric acid. This acid transforms carbonate and partly calcium phosphate into fluoride. Calcium fluoride practically does not dissolve in weak acids, but change of CO_3^{-2} and PO_4^{-3} volumetric anions for compact F^- leads to genesis of mineral matrix which is porous and cleaned from organic-silicate complex. Collagen in this case exists in semi-bound non-hydrated state. The essential advantage of hydrofluoric acid is its ability to dissolve silicates and humic acids as well as products of bacteria vital activity absorbed on them. It makes it possible to remove introduced organic substances and carbonic carbon, to wash and dry the processed sample easily and qualitatively. As a result of running processes the collagen is converted into volatile organic combinations and into bone coal. The addition of manganese dioxide plays an important role. When the temperature is above 550°C the manganese dioxide disintegrates with active oxygen liberation all over the volume of mixture. Oxygen liberation runs quietly, under the broad range of temperatures (550-940°C). Fine-dispersed bone coal therewith is oxidised till carbon oxide and dioxide,

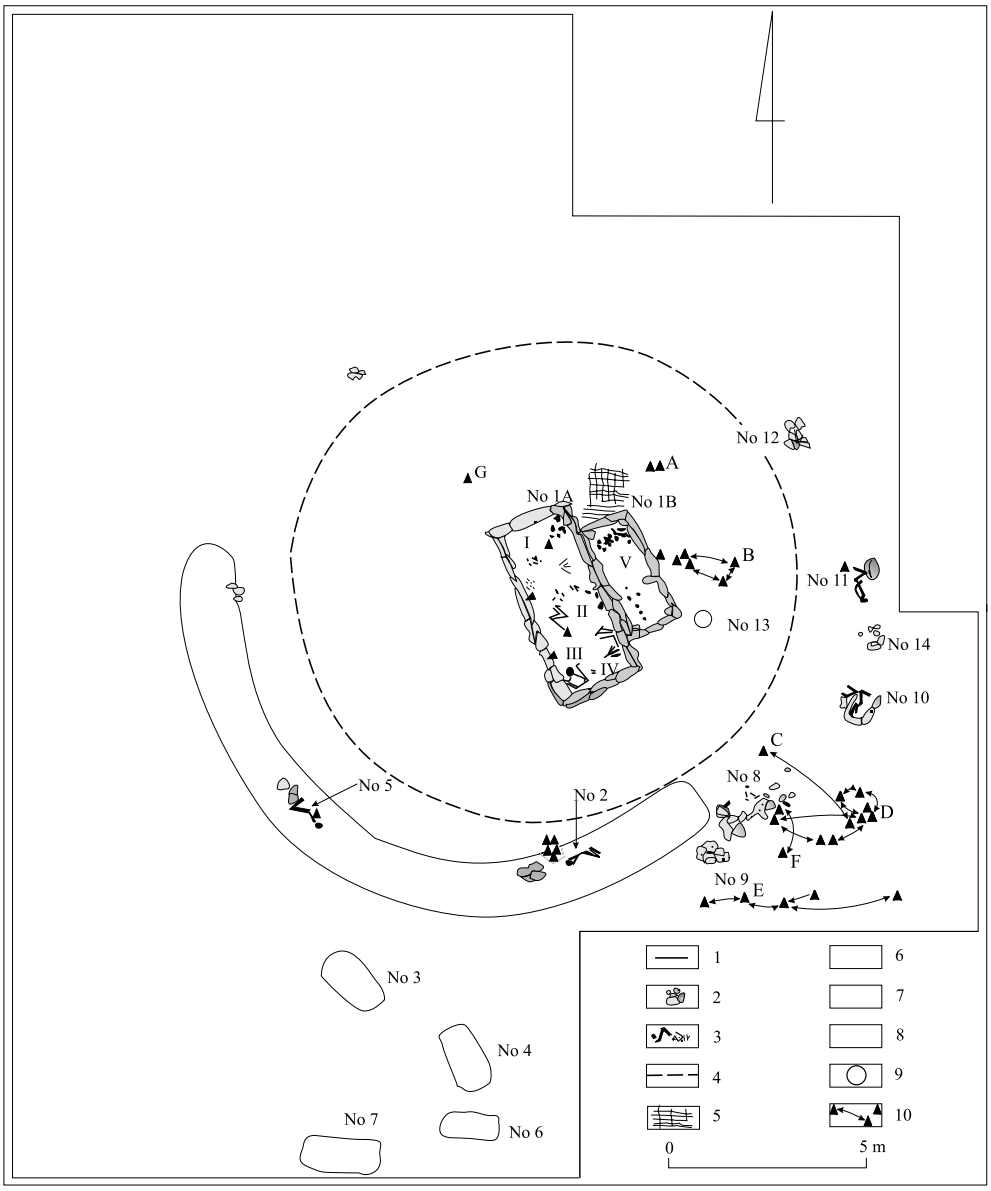


Fig. 2. Dacharzów, site 1. Grave complex of the Trzciniec Culture: 1 - boundaries of the investigated area, 2 – stones, 3 - human bones, 4 – original circumference of the base of the barrow, 5 – traces of ploughing, 6 - range of the basin created after taking earth for erecting the mound, 7 – ditch, 8 – pits, 9 – hole left by a post, 10 - pottery; I-V - bones of individual people buried in the graves; No 1-13 – features; A-G - pottery (after Florek and Taras 1996).

and in such a kind it is absorbed by melted metallic lithium. An essential feature of manganese oxides is their ability to link phosphorus and sulphur in thermal stable combinations. This allows getting lithium carbide of high quality, and what is more - practically from the whole carbon content of bone organic substances. Lithium carbide is subjected to hydrolysis, and gassing acetylene is converted into benzene on vanadium catalyst. The vacuum system for benzene syntheses is made from materials, which adsorb not all acetylene and benzene. Constructive particularities mentioned above allow one reach 95-97% benzene output to the total exclusion of the memory effect. As a result of summation of new complex technology advantages there appears a possibility for bone samples dating carried-out with collagen total contents up to 250-300 mg.

Measurement of benzene is carried out into the specially developed vials with the help of "Quantulus" - low-background spectrometer.

As a result of biological processes, which have been going on within the system bone - soil microorganisms, the natural relation between three main carbon isotopes (^{12}C, ^{13}C and ^{14}C) undergoes certain changes. In evaluating radiocarbon age the correction is being taken in account for biological isotopic fractionation. Undertaking such an operation is possible due to well-defined relationship between the deflection of ^{13}C isotope concentration and the degree of ^{14}C isotope fractionation. For this aim the determination is made on variation in concentrations of ^{13}C isotope in the ready benzene by mass-spectrometric method. This factor usually falls within the limit $-20.7 < \delta^{13}C < -18.5‰$. Correction entering for the isotopic fractionation is currently central for bone samples.

3. STATISTICAL APPROACH

For receiving reliable dates of bone material from the Dacharzów settlement the statistical approach of the radiocarbon dating was used. Big separate bones were cut to several parts and then all necessary procedure steps were made quite separately. The received dates were calculated for average value. Averaged dates are much more reliable and may be used for good evaluation of the main historical periods.

4. ARCHAEOLOGICAL DATING RESULTS

The site in question has clear, stratigraphically confirmed stages of use:

1. Construction and use of the stone graves and their surroundings. The smaller chamber, situated on the then ground level, was added to the already existing larger one, slightly sunk in the loess.
2. Building the mound.
3. Construction and use of the ditch surrounding the barrow from the south-west. The ditch cut into the western periphery of the basin created by digging earth for the construction of the mound, thus pointing to the sequence of the events.

The area around the ditch continued to be used, however, there is no stratigraphic evidence that would point to the chronological order of the following events:

– filling the ditch and using it for two burials,

– the appearance of further graves on the circumference of the mound that together with the ditch formed a ring.

The only certain thing that was found was that graves No. 11 and 12 – just like No. 2 and 5, that were uncovered in the ditch – appeared after the mound was made because they are situated in the eastern part of the basin created as a result of erecting the mound (**Fig. 2**). Since the flat graves form a regular ring on the circumference of the mound, the logical conclusion is that all of them were built after the barrow was made.

It has been assumed that the ditch was filled at one go. The claim is supported by the homogenous character of the filling material, both in its colour and texture, and the absence of clear pit contours as in the case of grave No. 2, which would point to a later digging of the grave in the filled ditch. As far as grave No. 5 is conserved, the situation is more complex: the contour of a rectangular, shallow pit is visible only on the level and it not possible to see the contour. Under the circumstances, it seems that graves No. 2 and 5 were built during the using (grave No. 5) and filling (grave No. 2) of the ditch.

The objects found in graves 1A and 1B and in their surroundings are connected with the first stage of using the cemetery, namely the period before the mound was built. The identical style of their production enables one to date them to the first half of phase II of the Bronze Age (16th – $16^{th}/15^{th}$ centuries BC) and also suggests that the period in which they were being deposited in the graves did not last too long.

The second stage in the use of the cemetery is connected with material coming from the graves built after the erection of the mound, on its circumference. The material consists of the equipment from graves No. 2, 5 and 11. The formal features of the pottery found in these graves are typical of the late or terminal stage of the Trzciniec Culture, both in Małopolska (Górski, 1994) and in other regions (Taras, 1995), which are dated to the end of phase II and phase III of the Bronze Age ($14^{th}/13^{th}$ – 12th centuries BC), and in eastern Poland even longer (Górski, 1998; Taras, 1998).

The analysis of the objects found in individual graves shows that between the stage of using the stone graves and the appearance of graves on the circumference of the mound there was a considerable time gap, possibly even 200 – 300 years.

5. RADIOCARBON DATING RESULTS

Radiocarbon dating was carried out in the Kiev Laboratory. The calibrated age was obtained using three calibrations programs worked out in: Groningen (Van der Plicht, 1993), Oxford (OxCal, v. 3.5) and Cologne (Weninger, 1986 and 1993). In the case of well-preserved material (remains of wood from the central graves, skeletons in good condition) between 2 and 5 samples were dated, in other cases single dating were done. The obtained dates

Table 1. *Age of samples from Dacharzów, site 1.*

Lab. Code (material)	**Place of origin**	**^{14}C Age** [BP]	**Cal Age [BC]** (van der Plicht, 1993)	**Point dating [BC]** (Weninger, 1993)	**Cal Age [BC]** (Ox Cal v.3.5)
Ki-8548 (wood)	Feature 1A	3340±60	1σ 1685-1599 1587-1577 2σ 1747-1495	1595±73	68.2% 1690-1520 95.4% 1770-1490
Ki-8106 (wood)	Feature 1A	2830±70	1σ 1053-899 2σ 1131-829	958±95	68.2% 1130-890 95.4% 1220-820
Ki-8610 (wood)	Feature 1A	3335±45	1σ 1587-1581 2σ 1693-1523	1580±62	68.2% 1690-1580 95.4% 1700-1510
Ki-8614 (wood)	Feature 1A	3350±50	1σ 1687-1601 1585-1583 2σ 1699-1521	1599±66	68.2% 1690-1580 95.4% 1750-1510
Ki-8615 (wood)	Feature 1A	3450±80	1σ 1829-1683 2σ 19451-1599	1745±109	68.2% 1890-1680 95.4% 1950-1520
Ki-8089 (bone)	Feature 1A-I (women)	3445±90	1σ 1833-1681 2σ 1957-1523	1740±120	68.2% 1890-1630 95.4% 1980-1520
Ki-8090 (bone)	Feature 1A-I (child)	3340±160	1σ 1775-1435 2σ 2035-1260	1604±187	68.2% 1780-1430 95.4% 2150-1200
Ki-8091 (bone)	Feature 1A-II (women)	2800±80	1σ 1023-891 2σ 1131-805	923±90	68.2% 1050-840 95.4% 1220-810
Ki-8092 (bone)	Feature 1A-II (child)	2820±80	1σ 1051-895 2σ 1133-823	937±100	68.2% 1080-890 95.4% 1220-810
Ki-8314 (bone)	Feature 1A-III	3270±70	1σ 1621-1491 2σ 1689-1411	1521±79	68.2% 1630-1490 95.4% 1690-1400
Ki-8315 (bone)	Feature 1A-III	3220±70	1σ 1527-1411 2σ 1639-1375	1465±75	68.2% 1530-1410 95.4% 1690-1370
Ki-8316 (bone)	Feature 1A-III	3310±70	1σ 1641-1519 2σ 1699-1435	1566±82	68.2% 1690-1510 95.4% 1750-1430
Ki-8094 (bone)	Feature 1A-IV	3340±70	1σ 1593-1525 2σ 1773-1491	1593±81	68.2% 1690-1520 95.4% 1780-1440
Ki-8317 (bone)	Feature 1A-IV	3415±70	1σ 1775-1679 2σ 1833-1597	1679±99	68.2% 1780-1620 95.4% 1890-1520
Ki-8318 (bone)	Feature 1A-IV	3360±70	1σ 1693-1599 2σ 1777-1497	1605±84	68.2% 1700-1580 95.4% 1780-1490
Ki-8549 (wood)	Feature 1B	3320±70	1σ 1643-1521 2σ 1745-1437	1579±81	68.2% 1690-1520 95.4% 1750-1430
Ki-8107 (wood)	Feature 1B	3390±200	1σ 1925-1445 2σ 2205-1255	1674±241	68.2% 1940-1440 95.4% 2300-1100
Ki-8611 (wood)	Feature 1B	3280±45	1σ 1621-1515 2σ 1641-1489	1537±61	68.2% 1630-1500 95.4% 1690-1440
Ki-8616 (wood)	Feature 1B	3300±50	1σ 1623-1521 2σ 1689-1491	1554±63	68.2% 1630-1510 95.4% 1690-1440
Ki-8095 (bone)	Feature 1B-V	3340±60	1σ 1587-1577 2σ 1747-1495	1594±73	68.2% 1690-1520 95.4% 1770-1490
Ki-8319 (bone)	Feature 1B-V	3270±70	1σ 1621-1491 2σ 1689-1411	1521±79	68.2% 1630-1490 95.4% 1690-1400
Ki-8096 (bone)	Feature 2	2840±60	1σ 1051-915 2σ 1131-891	975±85	68.2% 1120-900 95.4% 1220-830
Ki-8320 (bone)	Feature 2	2820±60	1σ 1049-897 2σ 1127-831	942±80	68.2% 1050-890 95.4% 1130-830
Ki-8097 (bone	Feature 2	2790±70	1σ 1003-891 2σ 1127-811	907±78	68.2% 1010-830 95.4% 1130-800
Ki-8098 (bone)	Feature 5	3270±70	1σ 1621-1491 2σ 1689-1411	1521±79	68.2% 1630-1490 95.4% 1690-1400
Ki-8321 (bone)	Feature 5	3160±70	1σ 1517-1387 2σ 1537-1261	1408±80	68.2% 1520-1380 95.4% 1610-1250
Ki-8322 (bone)	Feature 5	3180±70	1σ 1521-1393 2σ 1617-1295	1438±75	68.2% 1530-1390 95.4% 1620-1290
Ki-8617 (bone)	Feature 5	3290±60	1σ 1637-1515 2σ 1689-1435	1544±72	68.2% 1640-1510 95.4% 1690-1430
Ki-8099 (bone)	Feature 8	2940±70	1σ 1217-1043 2σ 1319-973	1116±107	68.2% 1260-1010 95.4% 1320-970
Ki-8100 (bone)	Feature 9	6980±70	1σ 5913-5785 2σ 5927-5727	5806±83	68.2% 5920-5770 95.4% 5930-5720

Ki-8101 (bone)	Feature 10	2770±80	1σ 977-831 2σ 1127-801	897±80	68.2% 1000-830 95.4% 1130-790
Ki-8102 (bone)	Feature 10	2980±70	1σ 1315-1125 2σ 1325-1005	1175±111	68.2% 1320-1110 95.4% 1400-1000
Ki-8323 (bone)	Feature 10	3070±70	1σ 1411-1259 2σ 1463-1185	1311±92	68.2% 1420-1250 95.4% 1500-1120
Ki-8324 (bone)	Feature 10	2995±70	1σ 1317-1187 2σ 1405-1041	1196±112	68.2% 1320-1120 95.4% 1410-1010
Ki-8103 (bone)	Feature 11	2950±70	1σ 1261-1047 2σ 1321-995	1127±108	68.2% 1270-1040 95.4% 1320-970
Ki-8104 (bone)	Feature 11	2595±80	1σ 687-659 2σ 901-513	689±132	68.2% 700-540 95.4% 910-480
Ki-8325 (bone)	Feature 11	2800±70	1σ 1015-893 2σ 1129-815	916±82	68.2% 1020-890 95.4% 1130-810
Ki-8105 (bone)	Feature 12	3050±70	1σ 1405-1257 2σ 1445-1123	1293±98	68.2% 1410-1250 95.4% 1450-1050

Table 2. *Dacharzów, site 1. Average ^{14}C ages and calibration results.*

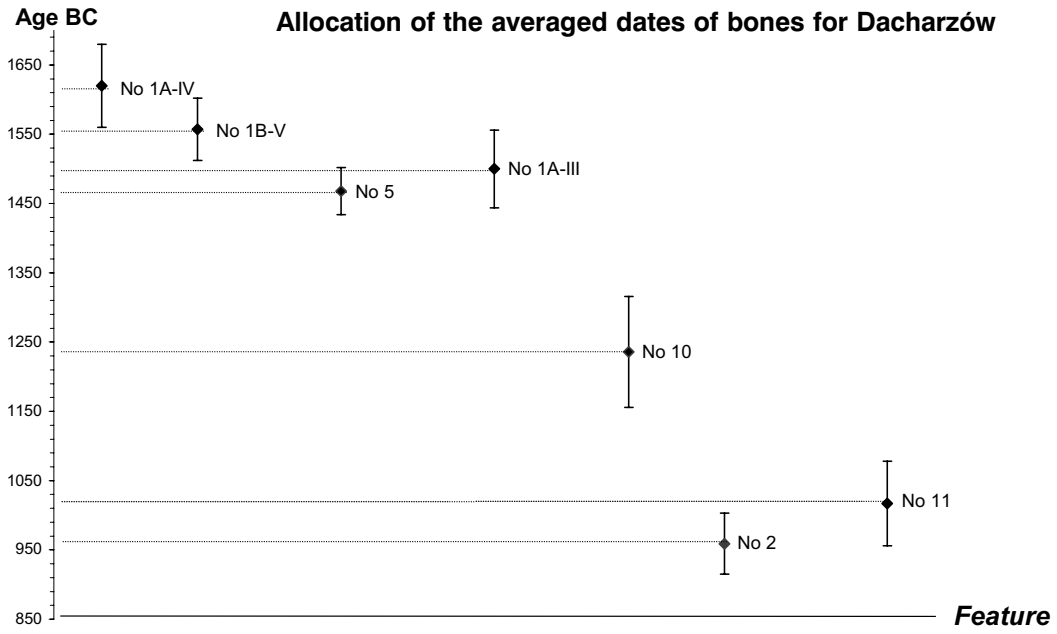
Lab. Code	**Place of origin**	**^{14}C Age** [BP]	**Cal Age [BC]** (van der Plicht, 1993)	**Point dating [BC]** (Weninger, 1993)	**Cal Age [BC]** (Ox Cal v.3.5)
Ki-8548/8610/ 8614/ 8615 (wood)	Feature 1A	3370±30	1σ 1673-1621 2σ 1695-1601	1636±52	68,2% 1690-1610 95,4% 1740-1600
Ki-8314-8316 (bone)	Feature 1A-III	3265±40	1σ 1537-1495 2σ 1623-1437	1500±56	68,2% 1610-1490 95,4% 1640-1430
Ki-8094/8317/8318 (bone)	Feature 1A-IV	3370±40	1σ 1693-1615 2σ 1741-1599	1620±62	68,2% 1700-1600 95,4% 1750-1520
Ki-8549/8611/8616 (wood)	Feature 1B	3300±30	1σ 1603-1525 2σ 1637-1519	1554±46	68,2% 1610-1520 95,4% 1690-1510
Ki-8095/8319 (bone)	Feature 1B-V	3305±30	1σ 1591-1525 2σ 1637-1521	1557±45	68,2% 1620-1525 95,4% 1690-1510
Ki-8096/8320 (bone)	Feature 2	2830±30	1σ 959-927 2σ 1049-903	959±44	68,2% 1050-900 95,4% 1130-890
Ki-8098/ 8321/8322/ 8617 (bone)	Feature 5	3225±35	1σ 1477-1455 2σ 1521-1437	1468±34	68,2% 1520-1440 95,4% 1540-1410
Ki-8102/8323/8324 (bone)	Feature 10	3015±40	1σ 1243-1213 2σ 1323-1207	1236±80	68,2% 1320-1210 95,4% 1400-1120
Ki-8103/8325 (bone)	Feature 11	2875±35	1σ 1055-999 2σ 1129-971	1017±61	68,2% 1130-990 95,4% 1130-920

confirm the division into an earlier period connected with the use of the stone chambers (dates from bone and wood samples) and a later one (graves on the circumference – dates from bone samples) and point to a distinct gap between the two stages. They do not, however, allow one to state clearly the order in which the individual graves on the circumference appeared, because the dates from single samples are not fully credible – an extreme case is here the date obtained from the bone sample from grave No. 9 (**Fig. 1**), while for another grave (No. 14) no date has been established due to the insufficient amount of bone material. The list of dates suggests that all the graves were built in cycles between 1450 and 950 BC. Thus, between the burials of people from graves 1A and 1B and the burials of those from grave No. 5 (or, to be precise, between the death of the last person to be buried in grave No. 5) approximately 50 years passed. During that time, the mound was erected and the ditch was dug. Between the burial in grave No. 5 and the next ones (graves No. 10 and 12) a maximum of 150 – 200 years passed.

6. DISCUSSION

Radiocarbon dating confirms the dating of the first stage of using the cemetery to the 16th century BC. The average dates obtained are generally within the years 1630 – 1500 BC; a couple of dates based on single samples do not fall into this period: the date obtained from the bone sample of woman I (**Fig. 2**, feature 1A-I) – second half of the 18th century BC – and that from woman and child II (**Fig. 2**, feature 1A-II) – second half of the 10th century BC. There is no justification for such dating in the stratigraphy of the site; the possibility of burying the bodies in the grave at a later time has also been excluded.

Another surprise was the dates from feature No. 5 – the grave located in the ditch, which, after calculating the average date, set the time of death of the person buried there (possibly also the time the grave was built) at approximately 1450 BC. The average date for feature No. 2, another grave from the ditch, is much later – approximately 950 BC. In the light of the above, the ideas about how the ditch was used and how it was filled should be revised. It may have been filled at one go (which view is



Fig, 3. *Dispersion averaged radiocarbon dates of bones from Dacharzów, site 1.*

supported by the character of the filling) as late as in the 10th century and that is when grave No. 2 appeared, while grave No. 5 (a secondary burial?) comes from the period of using the ditch. Another possibility is that the ditch was filled already in the 15th/14th century BC, after grave No. 5, was built and grave No. 2 was dug in the filling of the ditch at a later time. If so, the process of filling the grave pit must have been carried out in such a way that the earth dug out from the grave was not mixed with the earth from the area surrounding the ditch. There is a third possibility: both of the graves were dug in the previously filled ditch at different times and in such conditions that the earth from the graves and that of the surrounding area did not mix.

The youngest dates obtained for graves No. 2 and 11 could point to the fact that some enclaves of Trzciniec Culture settlement (or the religious tradition connected with the culture) survived in central and eastern Poland for a much longer time than was suggested by the hitherto available sources, that is even till the end of phase IV of the Bronze Age (Ha B1).

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DETERMINATION OF USAGE AND ABSOLUTE CHRONOLOGY OF A PIT FEATURE AT THE EARLY BRONZE I ASHKELON MARINA, ISRAEL, ARCHAEOLOGICAL SITE

D.I. GODFREY-SMITH[1] and S. SHALEV[2]

[1]*Department of Earth Sciences, Dalhousie University, Halifax, N.S., B3H 3J5, Canada (e-mail: DIGS@is.dal.ca)*
[2]*Institute for Maritime Studies and Department of Archaeology, University of Haifa, 31905 Haifa, Israel*

OSL AND TL DATING, BRONZE AGE, ASHKELON MARINA SITE

Abstract: A study of the luminescence properties of one of several pit features removed from the Ashkelon Marina EB1 (Early Bronze I) archaeological site during a 1998 excavation unequivocally determines their function in antiquity.

The features are shallow (Ł 50 cm) cup-shaped pits preserved in the ground. A hardened and reddened layer of earth Ł 3cm thick forms the shape of each pit, and a thin layer of white calcite is observed to lie upon the hardened earth. The pit is filled with soft buff coloured, quartz-dominated sediments, indistinguishable from the sediments which underlie it. This feature, and several others at the site, are suspected to be putative fire pit installations, over which crucibles for the melting of copper had been placed. However, the lack of any direct association of copper residues or artifacts found at the site with any of the pit features leaves this hypothesis unproven. Previous investigations, which included X-ray diffraction, differential thermal analysis, optical mineralogy studies, and FT-IR spectral measurements, have been unable to confirm the association of the pit features with fire. Calibrated radiocarbon dates place the use of the site at 5500-5300 BP.

We applied optical dating and thermoluminescence (TL) dating to the hardened red layer and the overlying fill sediments, in order to determine the last time of firing and/or exposure to sunlight of the two components of the feature. The premise driving our investigations is the fact that heated sediments will give the correct TL age. In contrast, unheated sediments will give an incorrect TL age far in excess of the depositional age, but will give a correct optical dating age. The TL analyses yielded ages of 5160 ±380 years for the hardened rim and 24,600 ±1600 years for the fill. Optical dating of the fill yielded an age of 5260 ±380 years, which is in excellent agreement with the TL age on the rim. These results fulfil the hypothesized results precisely. On this basis, we conclude that the pit features at the Ashkelon Marina archaeological site were fire pits used in early copper smelting technology.

1. SITE DESCRIPTION

Between 1996 and 1998 a rescue excavation uncovered an Early Bronze Age I (EB I) site at 18.5 m.a.s.l., above the Marina Beach in Ashkelon, Israel (**Fig. 1**). The remains of human activity included pottery shreds, animal bones, metal objects, amorphous small metal lumps and copper droplets, copper slag, and crucible fragments. The scattered archaeological material represents an intensive copper melting and refining activity and is the first metal workshop discovered in the Levant. The material remains clearly belong to the Early Bronze Age I cultural phase.

The major and almost the only architectural features unearthed were several small and empty shallow conical holes or pits ("installations") of hardened sediment in the ground.

No metals or any residues of metal activity, as well as no other archaeological remains nor any archaeological debris were found within or in connection with the installations in the ground. The slag and crucible fragments were found at a distance of at least 3 m from any of these installations. Thus, there is no archaeological proof that these totally clean and partially preserved installations were a part of the copper melting process. They are, however, the only man made features that could have served in this process.

Two AMS radiocarbon dates measured at the Instute of Physics, University of Aarhus, Denmark place the use

Fig. 1. Location of Ashkelon, Israel.

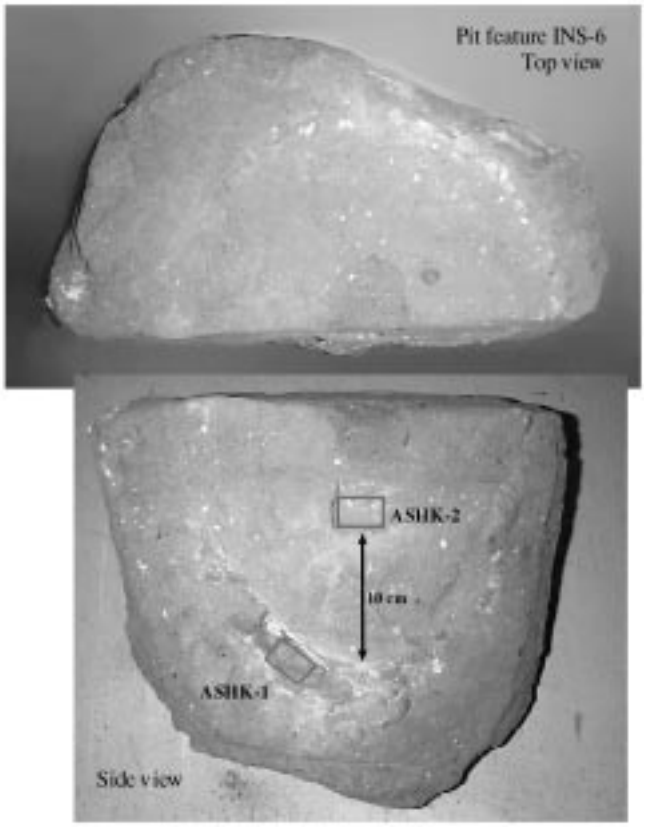

Fig. 2. The top and side outlines of pit feature INS-6, showing the locations of the samples collected for luminescence analyses.

of the site at 5580-5330 cal BP and 5450-5300 cal BP; both are 1 standard deviation ranges.

2. PIT FEATURES

The features are shallow (<50 cm) cup-shaped pits preserved in the ground (**Fig. 2**). A hardened and reddened layer of earth 3 cm thick forms the shape of each pit, and a thin layer of white calcite is observed to lie upon the hardened earth. The pit is filled with soft, buff coloured, quartz-dominated sediments that are indistinguishable from the sediments which underlie it. The installations appear in clusters; for example, three were found in a single excavation unit during the 1999 field season. All appear to be similar in composition. This suggests that all may have been deliberately constructed in the same manner, and/or that all served the same function.

The feature illustrated, and several others at the site, are suspected to be fire pit installations, over which crucibles for the melting of copper would have been placed. However, the lack of any direct association of copper residues or artifacts found at the site with any of the pit features leaves this hypothesis unproven. Previous investigations on seven installations which had been removed intact from the site included X-ray diffraction, optical mineralogy studies, differential thermal analysis, FT-IR spectral measurements, and phytolith analysis. These methods, however, have been unable to confirm the association of the pit features with fire (Palatnik, 1999).

3. MOTIVATION FOR THE ANALYSES

We undertook this study in an attempt to conclusively determine the origin of the pit features at this site. The premise driving our investigations is the fact that a heated sediment should give the correct TL age (Aitken, 1985). However, since the TL signal is not completely erased by exposure to light, an unheated sediment will always give a TL age well in excess of the depositional age. In contrast, the same unheated sediment should give a correct optical dating age, provided that the rate of sedimentation was sufficiently slow to allow complete zeroing of the optical signal (Godfrey-Smith, 1994).

We therefore applied optical dating (OSL) and thermoluminescence dating (TL) to quartz grains extracted from the hardened red layer and the overlying fill sediment, in order to determine the last time of firing and/or exposure to sunlight of the two components of the feature.

In addition to the principles generalized above, we also predicted that, if the rim sample had indeed been exposed to a high temperature, and if the infilling was reasonably rapid following the abandonment of the pits, as may be expected on the highly exposed coastal plain of the eastern Mediterranean Sea, then the optical age of the fill should closely match the TL age of the rim.

TL measurements

For each sample, six aliquots were prepared, each composed of ~5 mg quartz on a 1cm Al disk. Half of these were irradiated with a calibrated gamma dose of 10 Gy. After a few days of rest in complete darkness, the TL of all aliquots was measured at 3°/s to 450°C.

The TL glow curves were mass normalized. Thermally-shifted glow curves were aligned to the rest of the data set. For each 5° TL integral, a two-point De was computed using the least-squares linear fit, with the data points weighed inversely with respect to intensity. A plateau test was constructed for each sample using the TL and De data between the 200-375°C range.

Optical dating measurements

Single aliquot analysis on 15 aliquots of ~5mg was performed, using restricted green light stimulation, and detection in the near-UV region, a preheat of 230°C, held for 60 seconds, a shine of 0.5 s at 120°C, and cumulative radiation doses of 5,10, 20, 30, 40, 55, and 70 Gy. A post-additive preheat correction was applied.

The past dose De was deduced on the basis of the linear least squares fit to preheat-corrected data. The resulting De's were plotted against each aliquot's mass-normalized natural luminescence intensity.

4. DOSIMETRY

Bulk material was crushed to a fine powder using a tungsten carbide ball mill, and allowed to rest for 1 month prior to analyses. Th and U activities were measured on loose powders using thick source alpha counting. The values quoted are the averages of sealed and unsealed counts. K_2O concentrations were obtained by atomic absorption at a commercial laboratory (Bondar-Clegg of Vancouver, BC). Water contents were assumed based on known information on the site's location and typical moisture regimes in coastal Israel today.

Table 1. *Values used to compute dose rates.*

Sample	Depth [m b.s.]	K_2O [%]	Total α [ks^{-1} cm^{-1}]	Th α [ks^{-1} cm^{-1}]
ASHK-1 Rim	0.70	0.51	0.537 ± 0.011	0.220 ± 0.033
AASHK-2 Fill	0.58	0.27	0.585 ± 0.011	0.241 ± 0.035

Water content = 0.06±0.05.
Average grain size 120 mm, etched with concentrated HF.
b-value = 0.

5. RESULTS

Thermoluminescence

There is a clear distinction in the natural intensities and the glow curve shapes of the two samples, shown in **Fig. 3** and **4**. ASHK-1 has a peak TL intensity approximately one sixth as high as ASHK-2. ASHK-1 shows a maximum TL peak which falls at the nominal 325°C TL peak, and has a very low 375° C nominal TL peak, while ASHK-2 has its TL maximum at the nominal 375° C TL peak. Note that these peaks are shifted to 307°C and 345°C in our data due to a lower heating rate than that used to create reference TL curves for quartz, typically 10°/s. These shapes are typical of fired quartz (ex. from pottery) and unheated quartz (ex. from sediment), respectively.

The plateau tests, also shown in **Figs 3** and **4**, yield mean De's which differ by a factor 4.5 for the two samples. The mean De for ASHK-1 = 8.0±0.4 Gy (280-330°C plateau), while for ASHK-2 the mean De = 36.2±1.2 Gy (280-335°C plateau).

Single Aliquot Optical Dating

The data shown in **Figure 5** demonstrates that some aliquots represent grains which were more completely bleached by exposure to sunlight than others. The best De quoted below is based on the aliquots that were most completely bleached to light. Here, it is an average of the lowest four points on the graph, or 7.6±0.4 Gy.

Table 2. *Age results.*

Sample	Dose De [Gy]	Dose rate R [Gy/ka]	Apparent age [ka]
ASHK 1 Rim TL	8.0 ± 0.4	1.55 ± 0.08	5.18 ± 0.38
ASHK 2 Fill TL	36.2 ± 1.2	1.45 ± 0.08	24.9 ± 1.58
ASHK 1 Rim OSL minimum	7.2 ± 0.5	1.45 ± 0.08	4.93 ± 0.43
ASHK 2 Fill OSL best	7.6 ± 0.4	1.45 ± 0.08	5.26 ± 0.38

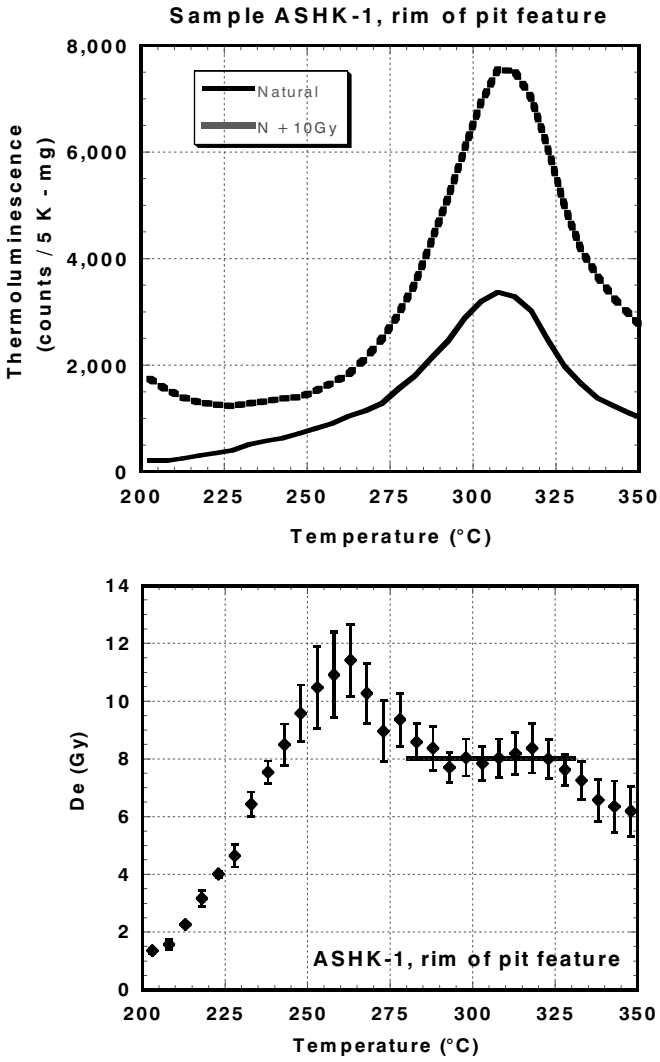

Fig. 3*. Thermoluminescence glow curves and plateau test for ASHK-1.*

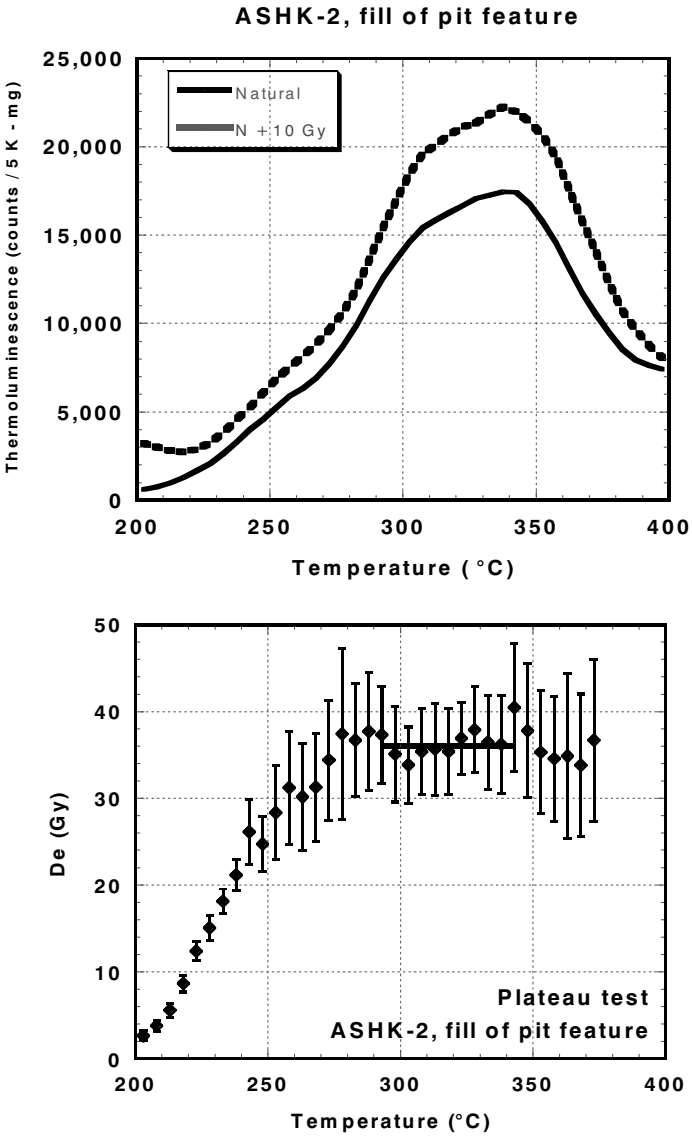

Fig. 4. *Thermoluminescence glow curves and plateau test for ASHK-2.*

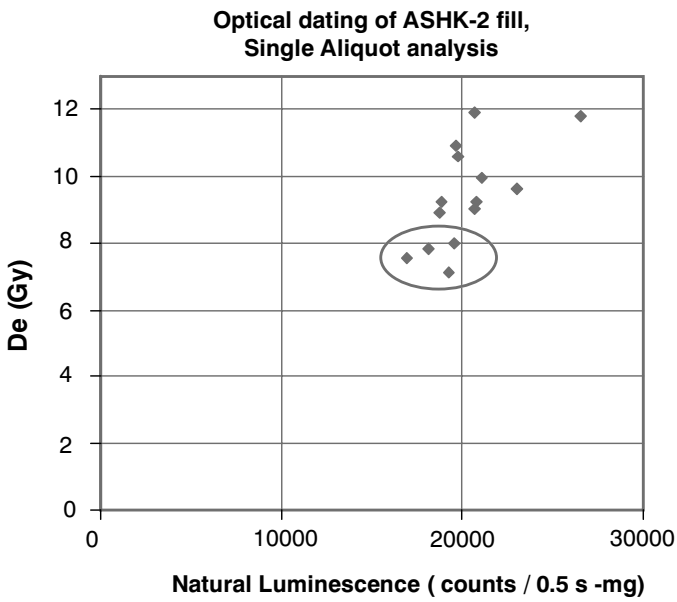

Fig. 5. *Single aliquot optical dating results for ASHK-2.*

6. SUMMARY

The apparent TL age of the fill is 4.5 times older than that of the underlying rim, even though their dose rates are nearly identical. Based on the simple natural laws of stratigraphic succession, such a result is clearly not a reasonable one if the two samples had identical thermal and depositional histories. Thus, we must conclude that sample ASHK-1 experienced a different thermal history than ASHK-2. While ASHK-1 has only the radiation dose De accrued since it was heated, sample ASHK-2, which has not been exposed to heat also carries a large residual dose of 28 Gy due to the unbleachable TL signal typical of unheated sediments. Optical dating of the fill yielded an age of 5260±380 years and is in excellent agreement with the 5180±380 years TL age of the rim, indicating that the infilling of the pit feature rapidly followed its creation and abandonment. These ages are also in an agreement with the radiocarbon chronology.

These results precisely fulfill our hypotheses. We conclude that the pit features at the Ashkelon Marina EB1 archaeological site originated as fire pits used in early copper smelting technology.

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