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Timing and style of deglaciation of northeastern Poland from cosmogenic ^{36}Cl dating of glacial and glaciofluvial deposits

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Determining the age of glacial and glaciofluvial deposits is necessary to better understand the deglaciation of northeastern Poland. Cosmogenic ^{36}Cl, accumulated in boulders and matrix, suggests that inheritance and erosion affect cosmogenic inventories and must be taken into account when calculating exposure ages of landforms. A simple approach to detect and distinguish between the two effects, by comparing the inventories of ^{36}Cl in boulders and matrix, allows us to compute appropriate corrections to apparent (uncorrected) ages and to determine model (corrected) exposure ages of the deposits. Apparent cosmogenic ^{36}Cl ages fall in the range between 11 ky and 28 ky (1 ky = 1000 calibrated ^{36}Cl years), pointing, correctly, to the end of the last glaciation, and correlate with oxygen isotope stage 2 (OIS 2). Model ages of glacial and glaciofluvial deposits fall into one of three time intervals. The oldest erratics, 27–28 ky (Kruszki and Bachanowo 1), date the advance of the Weichselian ice sheet. They are older than the surrounding surfaces, which confirms the existence of nunataks during later phases of the last glaciation. The main belts of recessional moraines formed 19.7 ± 1.0 ky ago (Gremzdy Polskie) and 17.9 ± 1.3 ky ago (Łopuchowo 2 and Gulbieniszki), and the last ice melted 14.4 ± 1.0 ky ago (Łopuchowo 1). Erosional terraces in the Czarna Hańcza valley were formed 14.7 ± 0.9 ky ago (Bachanowo 2) and 14.4 ± 1.0 ky ago (Bachanowo 3), probably by the melt waters from the last ice in the area. Our results suggest that different parts of the southern margin of the Fennoscandian Ice Sheet advanced and retreated independently, supporting the idea that the deposits at the southern margin of the Scandinavian Ice Sheet are not synchronous.

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INTRODUCTION

The Suwałki Lakeland, NE Poland, shows characteristics of a young glacial landscape such as large changes of elevation (up to 140 m), freshness and diversity of glacial forms, and common glaciofluvial deposits. Maximum elevations reach 300 m above sea level (a.s.l.). In areas of morainic plateaux, forms of active ice (end moraines, often pushed) and of dead ice (kames, dead-ice moraines) are well-developed. Associated with them are multidirectional glacial channels and sandur surfaces, which to the south of the studied area form the Augustów Plain (Fig. 1). Numerous large erratics occur both individually and in groups. The modern landscape of the Suwałki Lakeland was shaped primarily by the ice sheet of the Weichselian Glaciation — the last glaciation in the region. The ice deposited at least two layers of till on top of Eemian Interglacial deposits; the interglacial deposits are documented in profiles in Smolniki, Błazkowizna and Szwajcaria (Borówko-Dłużakowa and Halicki, 1957; Ber, 1974, 1998, 2000; Ber *et al*., 1998; Kenig, 1998). Numerous lines of moraines define the extents of different phases of the Weichselian Glaciation. The bottom till is usually correlated with the Świecie Stadial, or with the main stadial of the last glaciation. The top till, which appears at the surface of the Suwałki Lakeland, is correlated with the Pomeranian phase of the last glaciation (Ber, 1967, 1968, 2000; Krzywicki, 1993; Lisicki, 1993, 1998).

Five main sets of moraines (I–V in Fig. 1) were defined in this region on the basis of cartographic, geological and geomorphological studies (Ber, 1967, 1968, 1974, 1982, 1990, 1998; Krzywicki, 1993; Lisicki, 1993, 1998). The southernmost moraines (I) near Augustów define the maximum extent of the main stadial of the Weichselian Glaciation (Ber, 1982, 2000; Krzywicki, 2002), and moraines II through V define the extents of recessional episodes. The appearance of these moraines shows that the ice margin of the Weichselian Glaciation was divided into streams, lobes and smaller tongues (Ber, 1968, 1982; Krzywicki, 1993; Lisicki,

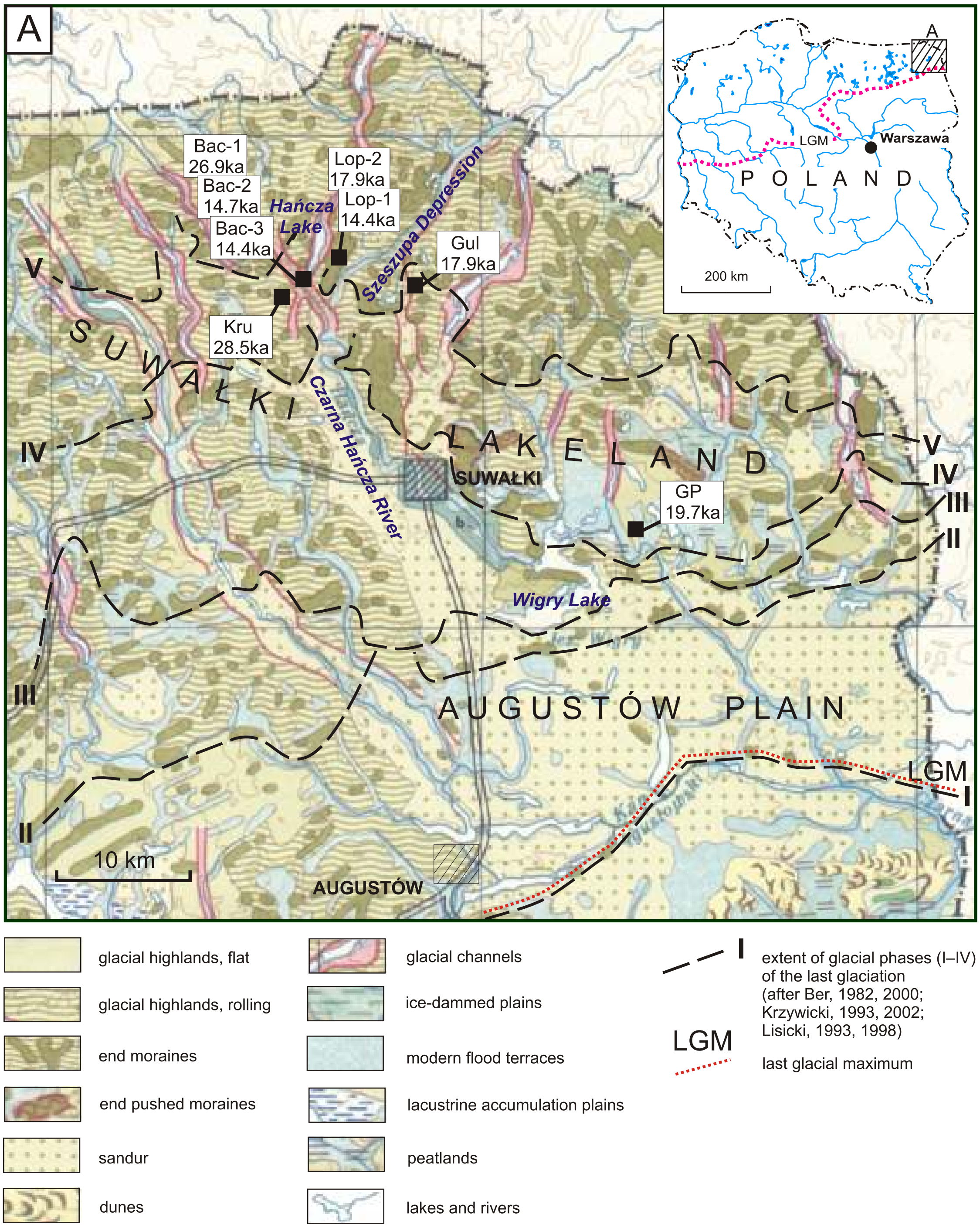

Fig. 1. Geomorphology of northeastern Poland (after Mojski, 1967), with the results of ^{36}Cl dating of erratics (in boxes)

Locations: GP — Gremzdy Polskie; Kru — Kruszki; Gul — Gulbieniszki, Lop — Łopuchowo, Bac — Bachanowo

1993). This fragmenting of the ice margin makes the use of geomorphological criteria in stratigraphic correlations inappropriate. In addition, this region lacks well-documented interstadial deposits that separate the youngest tills, and separation of tills on the basis of their petrographic composition is not always possible because of the similar provenance of the tills (Kenig, 1998). Moreover, dating of glacial deposits, mainly using the thermoluminescence (TL) method, gives equivocal results (Kozarski, 1986, 1995; Wysota 2002).

In the face of such problems, dating of surficial deposits using the cosmogenic ^{36}Cl method is particularly appealing. This method gives the duration of exposure at the surface of a geological material, and thus allows the placement of different lithostratigraphic units on an absolute time scale. Cosmogenic ^{36}Cl dating of erratics from Poland showed a Late Weichselian age of the surficial deposits (Dzierżek *et al.*, 1998). Cosmogenic ^{10}Be indicated that moraines of the maximum glaciation were formed 18.6 ± 2.8 ky ago (Rinterknecht *et al.*,

2003) and those of the Pomeranian phase were deposited 15.0 ± 0.5 ky ago (Rinterknecht *et al*., 2005, 2006) samples from NE Poland only. But, as pointed out by Houmark-Nielsen *et al*. (2006), the ^{10}Be ages seem to post-date the age of moraines, suggesting that some factors (e.g., erosion; see the next paragraph) were overlooked in the analysis and interpretation of the ^{10}Be data.

We realize that cosmogenic inventories in surficial materials depend not only on the exposure duration of these materials, but also on geological complexities, such as prior exposure and erosion, that define the exposure histories of surfaces. These complexities result in a large spread of apparent ages, and must be evaluated for correct interpretation of cosmogenic inventories. We have developed an approach to identify and distinguish the effects of prior exposure and erosion, and then to quantify them in order to calculate appropriate corrections to apparent ages. Corrected ages, called model ages, are used in chronological and palaeogeographic interpretation. These ages constitute the chronological framework necessary for the understanding of ice-sheet behaviour at the end of the last continental glaciation in NE Poland.

METHODS

FIELD AND LABORATORY WORK

Sample locations were selected following detailed geological and geomorphological analysis of the area. Samples were collected from the top few centimetres of large boulders partially burried in the matrix. In addition, samples of the matrix were collected at four locations. Sample preparation and analyses were conducted at the University of Arizona and at Purdue University. We followed the laboratory procedures described in our earlier publications (e.g., Zreda *et al*., 1991; Zreda, 1994). We have analyzed 31 samples of erratics from five localities within the Suwałki Lakeland: Gremzdy Polskie, Kruszki, Gulbieniszki, Bachanowo and Łopuchowo.

PRINCIPLES OF DATING BY COSMOGENIC ^{36}CL

Cosmogenic ^{36}Cl forms in the top few metres of terrestrial rocks by interactions of cosmic-ray neutrons and muons with atoms of K, Ca and Cl (Davis and Scheaffer, 1955; Phillips *et al*., 1986; Zreda *et al*., 1991). Three main nuclear reactions produce ^{36}Cl in rocks: spallation of ^{40}Ca and of ^{39}K, negative muon capture by ^{40}Ca, and neutron activation of ^{35}Cl (Phillips *et al*., 1986; Zreda *et al*., 1991). If the chemical composition of the rock sample is known, and the production rates are known (from calibration studies combined with spatio-temporal scaling studies), the measured inventory of ^{36}Cl can give the time of exposure of the sample at the surface. Accumulation of cosmogenic ^{36}Cl is described as:

$$dN / dt = P - \lambda \times N \qquad [1]$$

where: N — number of atoms of ^{36}Cl, t — exposure duration, P — total production rate from all reactions (changing in time), λ — decay constant for ^{36}Cl ($2.3 \quad 10^{-6} y^{-1}$).

Assuming continuous exposure and zero concentration of ^{36}Cl at $t = 0$ (the time of first exposure), this equation can be solved for the number of atoms N accumulated in time t:

$$N = \left(P / \lambda\right) \times \left(1 - e^{-\lambda \times t}\right) \qquad [2]$$

where: e — base of natural logarithm.

and for the exposure duration t:

$$t = \left(-1/\lambda\right) \times \ln\left(1 - \lambda \times N / P\right) \qquad [3]$$

CALCULATION OF APPARENT BOULDER AGES

Chlorine-36 ages were calculated using production rates based on the calibration data set of (Phillips *et al*., 1996, 2001), and recalculated using new spatio-temporal scaling functions (Desilets and Zreda, 2003; Desilets *et al*., 2006) and a suite of new corrections for variable environmental conditions (Zreda *et al*., 2005*a*). The new production parameters are (Zreda *et al*., 2005*a*): the production rate of ^{36}Cl due to spallation of ^{39}K, $P_K = 155 \pm 12$ atoms ^{36}Cl (g K)$^{-1}$y^{-1}; the production rate of ^{36}Cl due to spallation of ^{40}Ca, $P_{Ca} = 75.4 \pm 3.7$ atoms ^{36}Cl (g Ca)$^{-1}$y^{-1}; the production rate due to muon capture by ^{40}Ca is 10% of that of spallation of ^{40}Ca (Stone *et al*., 1996, 1998); and the fast neutron intensity, $P_f = 664 \pm 39$ fast neutrons (g rock)$^{-1}$y^{-1}. All production parameters are valid at sea level and at latitudes above 60 degrees. Local production rates for each sample were calculated based on the sample's chemical composition, using the methods described in Phillips *et al*. (2001) and its location (geographic latitude and longitude, and elevation above sea level), using formulas in Desilets and Zreda (2003) and Desilets *et al*. (2006). Corrections for the variable palaeomagnetic intensity were computed using data from Yang *et al*. (2000) for the time interval from 0 to 12 ky, and using data in Guyodo and Valet (1999) for ages older than 12 ky. Corrections for variable position of magnetic poles were calculated using the data in Ohno and Hamano (1992) for ages between 0 and 10 ky. The lack of data beyond 10 ky is not critical because changes of pole positions are integrated out; for the location in this study and for surfaces older than 10 ky, the deviation due to incomplete integration of pole position changes is less than 1%, and the uncertainty on this figure is about 20% of its value, or 0.2% of the calculated age. Snow cover was considered and found to have negligible effects on the accumulation of cosmogenic ^{36}Cl in the samples; therefore, no correction for snow was applied. Likewise, no correction was necessary for topographic obstructions. In contrast, soil water content was found to have a measurable effect on the accumulation of ^{36}Cl in moraine matrix, and was considered in the analysis. Apparent sample (boulder) ages were calculated using equation 3. Uncertainties in the calculated apparent ages, estimated on the basis of analytical errors, are given as one standard deviation (1σ).

EFFECTS OF INHERITANCE AND EROSION ON COSMOGENIC INVENTORIES

Equations 1–3 involve two important assumptions. First, the exposure of the material to cosmic radiation must be continuous, which requires that the surface of the landform not be modified by erosion or other local geological processes. Erosion results in changes of the isotope production rate in a sample below the surface (Zreda *et al*, 1994), which, if unrecognized, results in a cosmogenic age that is usually too young. The second assumption requires that at the time of deposition of the landform the concentration of the isotope be zero. This means that the material from which the landform is constructed was not exposed to cosmic rays before deposition in the landform (i.e., that it does not have an isotope inventory inherited from previous episodes at the surface). Material that has an inherited inventory, and in which this inherited inventory is not identified, will yield an apparent age that is too old. Mathematically, inheritance and erosion appear as separate terms in the appropriately modified differential equation, whose solution is:

$$N = N_0 \times e^{-\lambda \times t} + P/(\lambda + \varepsilon) \times \left(1 - e^{-(\lambda+\varepsilon)\times t}\right) \qquad [4]$$

where: N_0 — number of atoms accumulated previously, existing at time zero (i.e., at the time where the surface was constructed), ε — erosion rate (normalized to have the same units as l and to include both spallation and neutron activation production mechanisms (see: Zreda and Phillips, 1994, for details); other explanations as in equations 1 and 2.

The effects of inheritance and erosion are shown, separately, in Figure 2, and the combined effect of inheritance and erosion is shown in Figure 3.

In the case of inheritance, the material consists of clasts with different histories of exposure to cosmic radiation. If multiple samples are measured, their apparent ages will range from the youngest (containing the smallest amount of inherited isotope; sample 1 in Fig. 2A) to the oldest (containing the largest amount; sample 3 in Fig. 2A), and the youngest apparent age will be closest to the true age of the landform. In the case of erosion, each of the boulders present at the surface today originated at a different depth and, consequently, each of them has had a different history of exposure to cosmic radiation (Zreda *et al.*, 1994). If multiple samples are measured, their apparent ages will range from the youngest (the boulder that spent longest time below the surface, shielded from cosmic radiation; sample 3 in Fig. 2B) to the oldest (the clast that spent most of the time at or just below the surface; sample 1 in Fig. 2B). The oldest of the obtained apparent ages will be usually, though not always, closest to the true age of the landform (Zreda *et al.*, 1994; Zreda and Phillips, 1994). But without the knowledge of the history of exposure to cosmic radiation, distinguishing between these two cases is difficult. Hence, we cannot determine the age of the landform based solely on the measurements of cosmogenic inventories in surficial boulders. But we can do this with additional information from the matrix (see next section).

INTERPRETATION OF ISOTOPE INVENTORIES AND CALCULATION OF LANDFORM AGES

To distinguish the effects of inheritance from those of erosion, we compare the cosmogenic isotope inventory in the ma-

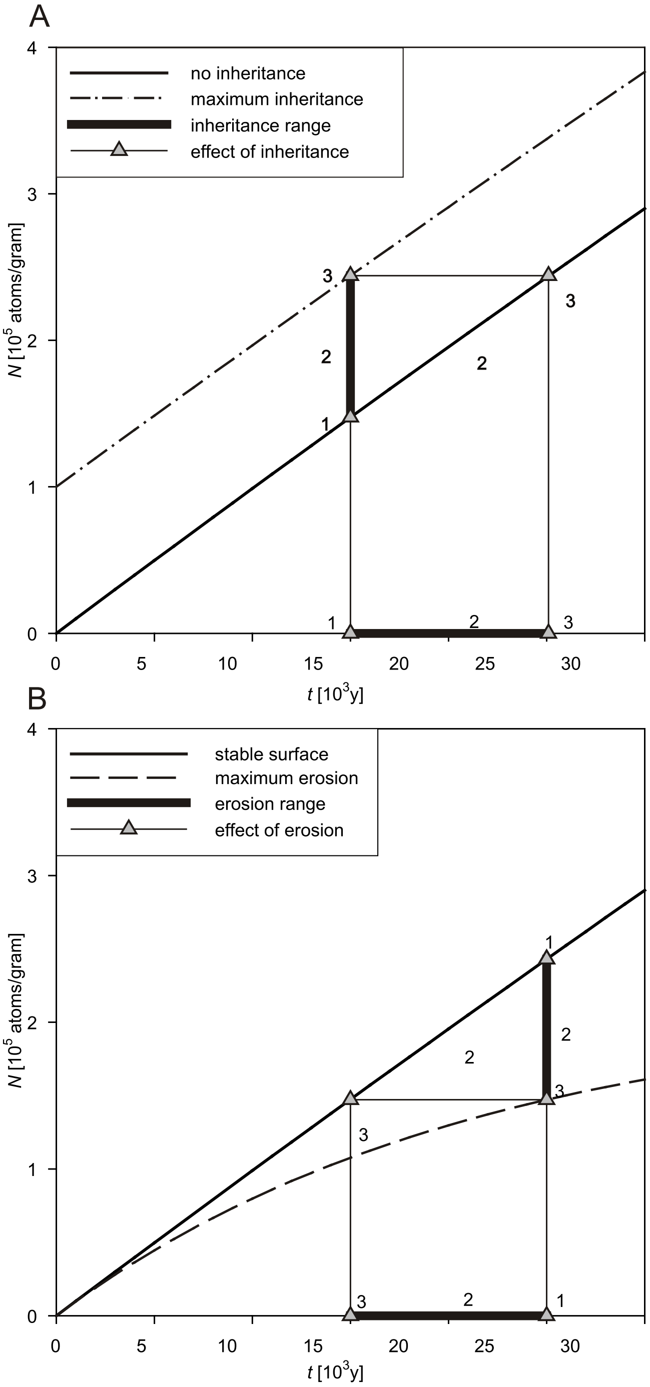

Fig. 2. Effects of inheritance (A) and matrix erosion (B) on cosmogenic age determination

A — effect of inheritance on cosmogenic age determination (A); the assumed (true) age is 15 ky, and the maximum amount of inheritance is equivalent to 10 ky of exposure; all samples are located on the vertical bar located at 15 ky and between the solid line (no inheritance) and dash-dotted line (maximum amount of inheritance); if inheritance is ignored, these samples will yield apparent ages that range from 15 ky to 25 ky (the horizontal thick bar on the time axis); **B** — effects of erosion of matrix and gradual exposure of boulders at the surface on cosmogenic age determination (B); the assumed (true) age is 25 ky, and the erosion rate is such that the youngest apparent age is 15 ky; because boulders have spent different times at different depths, they have different inventories of a cosmogenic nuclide (the vertical thick bar located at 25 ky) and, consequently, different apparent ages, usually younger than the deposition age of the landform (the horizontal thick bar on the time axis); samples denoted by triangles (with numerals) are discussed in text

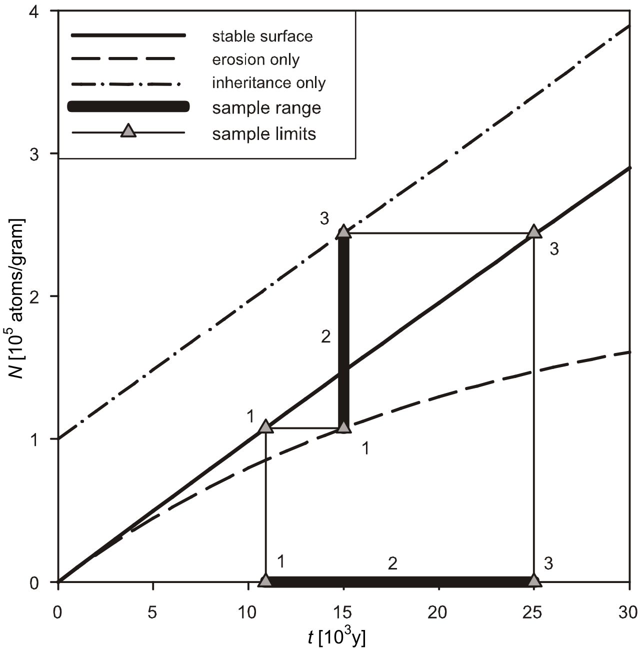

Fig. 3. Combined effect of inheritance and matrix erosion on apparent cosmogenic nuclide ages of boulders

All samples are on the thick vertical bar located at 15 ky; these inventories correspond to apparent ages between 11 ky and 25 ky (thick bar on the time axis); in general, the range of apparent ages depends on the amount of inheritance and on the erosion rate; some combinations of inheritance and erosion have a cancelling effect; this, however, must be considered fortuitous and was not used in quantitative analysis; other explanations as in Figure 2

trix with the inventories of the same isotope in boulders from the same surface. Only one assumption is necessary to analyze the effects of inheritance that boulders and matrix have the same geological exposure history (or, that, on average, the cosmogenic inventory in boulders is the same as that in the matrix). This assumption is valid for geological materials transported and deposited by ice. Such materials are characterized by poor sorting, with all sizes distributed approximately uniformly within the same deposit. Thus, fine clasts and large blocks should have the same prior exposure and, consequently, the same inventory of a cosmogenic isotope. One assumption is made to analyse effects of erosion that erosion gradually exposes boulders that were initially at different depths, and after exposure these boulders remain at the surface.

Under these assumptions, the following analysis of cosmogenic inventories (or apparent ages) in the boulders and matrix is made (see Figs. 2 and 3). Inheritance is manifested by a uniform distribution of apparent ages; all apparent ages are older than the true age of the landform (Fig. 2A), and the matrix has an apparent age similar to the average of the apparent ages of the boulders. In contrast, erosion of matrix and gradual exposure of erratics are manifested by apparent boulder ages that are younger than the true age of the landform (Fig. 2B), and the matrix has an apparent age close to that of the youngest boulder.

Distinguishing between these two cases involves the inverse analysis. If the apparent age of the matrix is similar to the age of the youngest boulders, we have a case of erosion. In contrast, if the apparent age of the matrix is close to the average apparent age of boulders, we have a case of inheritance. Identifying either of these two cases allows for a more reliable, less arbitrary determination of the age of the landform from which the boulders and matrix come. A landform that involves a combination of inheritance and erosion (Fig. 3) can be analyzed by adding to the above inverse analysis the difference between the apparent age of the matrix and of the youngest boulder (to quantify inheritance in the presence of erosion). However, our landforms do not need this complex analysis as they appear to have been affected by either inheritance or erosion, and not by both factors. Landform ages were calculated in two steps. First, we determined whether the spread of ages is caused rather by inheritance or rather by erosion. In the case of inheritance, the youngest boulders (two or more) were chosen as they should have ages closest to the age of the landform; in the case of erosion, the oldest boulders (two or more) were chosen. In the second step, we calculated the age of the landform as a weighted average of the selected boulders, with the weights $w = (t/s)^2$, where t is the sample age, and s is its standard deviation.

RESULTS

The geochemical results are in Table 1, the production parameters and individual ^{36}Cl ages are in Table 2, and the ^{36}Cl ages of surfaces are in Table 3 and Figure 4. All erratics exposed at the surface in the Suwałki Lakeland have ^{36}Cl ages that correlate broadly with the last glacial maximum (LGM). But the individual sample ages display considerable spread, much greater than could be expected on the basis of analytical uncertainties. This led to the realization that the surfaces from which the samples come have experienced complex exposure histories. With additional measurements of ^{36}Cl in matrix samples from four surfaces, the observed distributions of boulder ages can be explained by prior exposure of the boulders to cosmic rays (Bac-2, Bac-3 and Lop-1) or by erosion of the matrix and gradual exposure of the boulders (Bac-1).

SITES, RESULTS AND INTERPRETATION

Site **Gremzdy Polskie (GP)** is located north-east of Wigry Lake, at the back of three latitudinal moraine belts (II, III and IV in Fig. 1); these belts define the extent of the Pomeranian phase and its recessional subphases (Krzywicki, 1993; Lisicki, 1993; Ber, 1990, 1998, 2000). The flat surface of the till, at an altitude of 131–135 m a.s.l., is littered with unusually large erratics (some are more than 2 m in height). Samples from four erratics gave apparent ^{36}Cl ages in the range from 18.6 ky to 23.2 ky, and a mean age of 19.7 ± 1.0 ky (one standard error of weighted mean, 1σ).

Interpretation. All four erratics are from the same geomorphic context, and have similar altitudes and dimensions, leading to a reasonable assumption that their genesis is the same. The older age of sample NP96-14-GP may be due to the presence of ^{36}Cl inherited from previous exposure episode(s). However, because the age difference is small, and sample NP96-14-GP has the largest analytical uncertainty in this group, it is likely that the beginning of exposure of these erratics to cosmic radiation, which is equivalent to the disappear-

Table 1

Geochemical and isotopic composition of samples

Sample ID	Na_2O [wt. %]	MgO [wt. %]	Al_2O_3 [wt. %]	SiO_2 [wt. %]	P_2O_5 [wt. %]	K_2O [wt. %]	CaO [wt. %]	TiO_2 [wt. %]	MnO_2 [wt. %]	Fe_2O_3 [wt. %]	B [ppm]	Sm [ppm]	Gd [ppm]	U [ppm]	Th [ppm]	Cl (± 1σ) [ppm]	$^{36}Cl/Cl$ (± 1σ) × 10^{-15}
NP96-12-GP	2.55	0.02	12.3	74.8	0.01	6.5	0.79	0.23	0.01	1.54	2	1.9	2.1	1.7	4.2	71.8 ± 4.3	216 ± 13
NP96-13-GP	2.73	0.3	13.5	73.4	0.02	5.24	1.07	0.25	0.01	2.09	15.5	3	3	2.1	17	172 ± 2.2	121 ± 6
NP96-14-GP	3.17	0.41	13.6	73.7	0.02	4.89	0.21	0.23	0.02	2.47	47	6	6	1.5	2.4	273.4 ± 5.3	79 ± 7
NP96-15-GP	3.15	0.31	14	74.8	0.01	2.44	3.11	0.15	0.01	1.81	29.5	3	3	0.5	3.2	83.2 ± 2.3	117.7 ± 5.5
NP96-7-SPK	3.22	0.18	13.1	72.3	0.02	5.11	1.15	0.44	0.05	4	24	6	6	2.1	4.7	701.7 ± 11.5	88 ± 12
NP96-8-SPK	3.1	0.07	12.9	73.9	0.01	5.77	0.69	0.29	0.03	2.92	20.5	0	4.5	4.7	8.1	235.4 ± 1.5	146 ± 15
NP97-16-BAC1	2.8	0.2	14.1	75.3	0.01	3.24	2.53	0.098	0.01	1.16	21	0.3	0.3	0.85	1.4	60.1 ± 1.3	140.5 ± 5.6
NP97-17-BAC1	3	0.1	12.5	75.5	0.01	5.8	0.51	0.177	0.02	1.87	3	3.1	2.8	4.05	6.65	464.3 ± 4.3	129 ± 7
NP97-18-BAC1	3	0.45	13	71.4	0.03	5.31	1.2	0.439	0.04	4.26	7	5.45	5.5	3.05	6.35	275.2 ± 4.3	101.2 ± 5.9
NP97-19-BAC1	3.3	0.12	13.65	74.15	0.01	5.54	1.115	0.167	0.02	1.61	10	4.15	5.1	1.1	1.1	201.9 ± 1.3	119 ± 6
NP96-9-SPK	2.72	1.61	15.2	68.4	0.02	1.56	5.16	0.26	0.05	3.43	10.7	2	1.9	0.5	1.1	86.1 ± 1	102 ± 13
NP97-20-BAC2	1.86	0.2	10.9	79	0.08	5.49	0.41	0.042	0.03	1.39	7	2.1	2.3	2.7	4.4	73.8 ± 2.9	148 ± 7
NP97-21-BAC2	3.16	0.27	13.1	76	0.01	4.55	0.99	0.091	0.01	1.13	10	0.7	0.6	2	3.95	27.2 ± 1.2	330 ± 23
NP97-22-BAC2	2.75	0.16	12.7	76.1	0.03	5.12	0.52	0.133	0.01	1.51	12	4.75	4.6	5.8	24	147.8 ± 3	176 ± 9
NP97-23-BAC2	3.32	0.36	15.3	72.3	0.01	2.69	4.06	0.182	0.02	1.9	12	1.55	1.1	0.35	0.8	166.9 ± 2.4	137 ± 6
NP97-24-BAC2	4.99	0.64	12.3	78.2	0.01	1.42	1.38	0.153	0.01	0.95	4	1.8	1.8	0.9	4.85	33.1 ± 0.7	195 ± 9
NP97-25-BAC2	3.47	0.44	14.7	73.1	0.01	2.66	3.21	0.131	0.02	1.73	19	1.15	1	0.65	1.05	75.9 ± 1.8	166 ± 9
NP97-26-BAC3	3.24	0.4	14.2	72.6	0.01	4.59	1.56	0.321	0.01	2.66	6	0.7	0.6	0.35	2.8	121 ± 2.5	122 ± 6
NP97-27-BAC3	2.85	0.26	12.2	72.7	0.02	5.24	1.4	0.481	0.05	4.41	3	6.05	5.3	2.4	5	554.9 ± 9.3	105.6 ± 4.8
NP97-28-BAC3	3.11	0.49	15.5	70.7	0.01	1.54	5.11	0.188	0.02	2.23	7	1.5	1.9	0.15	0.15	81.6 ± 1.3	95 ± 6
NP97-29-BAC	3.29	0.16	15.9	72.1	0.01	2.26	4.73	0.06	0.01	1.08	3	0.7	0.8	0.1	0.45	67.1 ± 2.5	138 ± 6
NP96-10-SPK	0.01	0.01	4.44	93.1	0.01	1.33	0.01	0.03	0.01	0.76	5	1.4	1.3	0.7	3.1	27.1 ± 1.4	226 ± 18
NP97-33-LOP	2.57	0.4	12.1	75.3	0.02	5.37	0.69	0.246	0.02	2.46	9	3	2.2	3.85	18.9	151.6 ± 5.3	165 ± 9
NP97-34-LOP	2.81	0.22	13	76.9	0.01	3.64	2.42	0.091	0.01	1.1	9	0.4	0.4	0.7	2.2	67.3 ± 1.3	172 ± 10
NP97-35-LOP	3.78	0.89	16.2	68.1	0.01	3.12	4.18	0.197	0.04	2.58	5	1.25	1.1	0.4	1.8	49.7 ± 1.8	178 ± 14
NP97-36-LOP	2.59	7.56	17.8	46.4	0.03	0.45	10.1	1.508	0.15	11.8	5	1.65	2.1	0.05	0.45	66.6 ± 2.5	97 ± 9
NP97-37-LOP	2.86	0.54	13.7	73	0.03	5	1.73	0.265	0.01	2.29	4	2.7	1.9	0.3	5.7	135.1 ± 3	103.8 ± 4.6
NP97-38-LOP	4.39	0.61	15	72.1	0.06	4.88	0.59	0.137	0.01	1.29	7	3.45	2.3	1.25	5.25	49.7 ± 1.9	188 ± 9
NP97-39-LOP2	2.67	0.23	13.2	74.4	0.03	5.51	0.94	0.125	0.12	2.4	0	4.55	3.8	4.9	16.7	21.1 ± 0.9	607 ± 20
NP97-40-LOP2	3.06	0.22	13.7	74.6	0.02	5.3	1.35	0.133	0.01	1.21	6	2.8	2	1.8	12.6	78.2 ± 1.2	189 ± 7
NP96-11-SPK	2.78	0.86	14.5	71.3	0.05	4.97	1.5	0.39	0.02	2.95	3	4.1	3.4	1	8.5	42.9 ± 0.6	273 ± 13
NP97-30-BAC1	1.05	0.31	5.14	79.8	0.05	1.62	6.39	0.132	0.01	1.07	7	1.65	1.7	0.9	2.55	59.5 ± 1.8	134 ± 7
NP97-31-BAC2	1.51	0.355	7.005	85.25	0.02	2.275	1.085	0.183	0.01	1.565	9	1.25	1.1	0.55	3.25	52.5 ± 0.9	147 ± 7
NP97-32-BAC3	2.11	0.29	8.35	83.6	0.02	2.82	0.78	0.158	0.01	1.48	9	1.8	1.8	2.3	6.4	53.8 ± 0.8	166 ± 8
NP97-41-LOP	1.17	0.17	5.53	89.1	0.02	1.98	0.59	0.114	0.01	1.05	4	1	1	0.8	2.75	44.2 ± 1.2	149 ± 7

NP — Polish Lowland; 96 — 1996 (year of sampling); GP – Gremzdy Polskie; SPK — Suwalski Park Krajobrazowy; Bac — Bachanowo (1 — highland moraine; 2, 3 — terraces), Lop — Łopuchowo (1, 2 — moraines; horizontal lines separate different landforms

T a b l e 2

Production parameters and apparent ^{36}Cl ages of individual samples

Sample ID	Thickness [cm]	Cosmogenic ^{36}Cl production rates, P [N_{36}g^{-1}y^{-1}]					Inventories of ^{36}Cl [$10^3 N_{36}$ g^{-1}]			Scaling factors			^{36}Cl age [ky]
		P_sp_ca	P_sp_k	P_mu	P_n	P_total	N_{36}_m (±1σ) (measured)	N_{36}_r (radiogenic)	N_{36}_c (±1σ) (cosmogenic)	S_sp	S_th	S_mu	
NP96-12-GP	3	0.47	9.74	0.03	3.15	13.4	266 ± 23	15.0	251 ± 23	1.16	1.16	1.08	19.2 ± 1.7
NP96-13-GP	3	0.64	7.89	0.04	6.68	15.3	358 ± 18	77.6	280 ± 24	1.16	1.16	1.09	18.8 ± 1.6
NP96-14-GP	2	0.13	7.50	0.01	7.71	15.3	371 ± 34	23.9	347 ± 34	1.18	1.17	1.09	23.2 ± 2.3
NP96-15-GP	3	1.83	3.63	0.13	3.13	8.72	166 ± 9	7.5	159 ± 9	1.16	1.16	1.09	18.6 ± 1.1
NP96-7-SPK	3	0.76	8.50	0.05	24.7	34.0	1051 ± 144	111	940 ± 146	1.29	1.30	1.15	28.5 ± 4.4
NP96-8-SPK	3	0.45	9.57	0.03	9.16	19.2	584 ± 60	86.5	498 ± 63	1.29	1.29	1.15	26.7 ± 3.4
NP97-16-BAC1	2	1.62	5.24	0.11	2.67	9.64	144 ± 7	5.5	138 ± 7	1.25	1.25	1.13	14.6 ± 0.7
NP97-17-BAC1	3	0.34	9.64	0.02	21.7	31.7	1020 ± 56	190	830 ± 68	1.29	1.29	1.15	27.0 ± 2.2
NP97-18-BAC1	2	0.79	8.81	0.05	10.6	20.2	476 ± 29	76.8	399 ± 33	1.28	1.28	1.14	20.2 ± 1.6
NP97-19-BAC1	2	0.73	9.19	0.05	8.17	18.1	409 ± 21	17.7	391 ± 21	1.28	1.28	1.15	22.1 ± 1.2
NP96-9-SPK	3	3.29	2.51	0.22	4.12	10.1	151 ± 19	5.7	146 ± 19	1.24	1.24	1.13	14.6 ± 1.9
NP97-20-BAC2	2	0.26	8.77	0.02	3.28	12.3	186 ± 11	19.3	167 ± 12	1.23	1.23	1.12	13.8 ± 1.0
NP97-21-BAC2	3	0.63	7.29	0.04	1.34	9.30	153 ± 13	7.0	146 ± 13	1.24	1.24	1.13	16.0 ± 1.4
NP97-22-BAC2	2	0.34	8.48	0.02	6.08	14.9	445 ± 25	120	325 ± 34	1.27	1.27	1.14	22.4 ± 2.4
NP97-23-BAC2	2	2.65	4.43	0.17	7.82	15.1	387 ± 18	8.0	379 ± 18	1.28	1.28	1.15	25.9 ± 1.2
NP97-24-BAC2	2	0.89	2.31	0.06	1.77	5.03	109 ± 6	9.1	100 ± 6	1.27	1.26	1.14	20.4 ± 1.2
NP97-25-BAC2	2	2.09	4.37	0.14	3.38	9.99	215 ± 13	5.6	209 ± 13	1.27	1.27	1.14	21.5 ± 1.3
NP97-26-BAC3	2	0.99	7.37	0.07	5.46	13.9	251 ± 13	11.9	239 ± 14	1.24	1.24	1.13	17.6 ± 1.0
NP97-27-BAC3	3	0.91	8.55	0.06	22.6	32.1	997 ± 48	120	877 ± 54	1.27	1.27	1.14	28.2 ± 1.7
NP97-28-BAC3	3	3.20	2.43	0.22	4.14	9.98	133 ± 9	1.4	131 ± 9	1.22	1.22	1.12	13.4 ± 0.9
NP97-29-BAC	2	2.98	3.59	0.20	3.55	10.3	158 ± 9	1.7	156 ± 9	1.23	1.23	1.12	15.4 ± 0.9
NP96-10-SPK	3	0.01	2.24	0.00	1.83	4.07	104 ± 10	3.2	101 ± 10	1.31	1.31	1.16	25.5 ± 2.5
NP97-33-LOP	3	0.46	9.00	0.03	7.01	16.5	428 ± 28	94.4	333 ± 34	1.30	1.30	1.16	20.7 ± 2.1
NP97-34-LOP	2	1.59	6.01	0.10	3.39	11.1	196 ± 12	7.8	188 ± 12	1.28	1.28	1.15	17.3 ± 1.1
NP97-35-LOP	2	2.73	5.14	0.18	2.40	10.5	151 ± 13	4.4	147 ± 13	1.27	1.27	1.14	14.3 ± 1.3
NP97-36-LOP	1	6.61	0.74	0.44	2.38	10.2	111 ± 11	0.9	110 ± 11	1.25	1.25	1.13	11.0 ± 1.1
NP97-37-LOP	2	1.13	8.21	0.07	6.14	15.6	239 ± 12	21.3	218 ± 13	1.27	1.27	1.14	14.2 ± 0.8
NP97-38-LOP	2	0.39	8.04	0.03	2.23	10.7	160 ± 10	12.2	148 ± 10	1.27	1.27	1.14	14.0 ± 1.0
NP97-39-LOP2	3	0.62	9.16	0.04	1.00	10.8	218 ± 12	14.6	203 ± 12	1.29	1.29	1.15	19.2 ± 1.1
NP97-40-LOP2	2	0.89	8.78	0.06	3.61	13.3	252 ± 10	34.3	217 ± 12	1.28	1.28	1.15	16.6 ± 0.9
NP96-11-SPK	3	0.94	7.87	0.06	1.91	10.8	200 ± 10	11.2	189 ± 10	1.23	1.23	1.12	17.9 ± 1.0
NP97-30-BAC1	25	3.41	2.18	0.25	3.20	9.04	124 ± 7	3.7	120 ± 8	1.24	1.24	1.13	not determined
NP97-31-BAC2	25	0.57	3.00	0.04	2.76	6.36	116 ± 6	3.2	113 ± 6	1.26	1.25	1.13	not determined
NP97-32-BAC3	25	0.40	3.67	0.03	2.71	6.81	134 ± 7	9.5	124 ± 7	1.25	1.25	1.13	not determined
NP97-41-LOP	25	0.31	2.66	0.02	2.52	5.52	98.6 ± 5.4	2.9	95.7 ± 5.4	1.29	1.29	1.15	not determined

P_sp_ca — production rate of ^{36}Cl due to spallation of calcium; P_sp_k — production rate of ^{36}Cl due to spallation of potassium; P_mu — production rate of ^{36}Cl due to slow muon capture by calcium; P_n — production rate of fast neutrons; the production rates are in atoms ^{36}Cl per gram of rock per year; S_sp — scaling factor for spallation; S_th — scaling factor for neutron activation; S_mu — scaling factor for slow muon capture; N_{36}_m — measured number of atoms of ^{36}Cl; N_{36}_r — number of atoms of nucleogenic ^{36}Cl; N_{36}_c — number of atoms of cosmogenic ^{36}Cl; other explanations as in Table 1 ance of ice cover, is approximated by the weighted mean of all samples, 19.7 ± 1.0 ky. Alternatively, after eliminating the oldest age on the basis of possible inheritance, the weighted mean would be 18.8 ± 0.9 ky. And an age calculated for two erratics that have no evidence of erosion, samples NP96-12-GP and NP96-15-GP would be 18.8 ± 1.0 ky. The weighted mean age is always the same, within 1σ, regardless of interpretation.

Site **Kruszki (Kru)** has only one dated erratic, located at the surface of a plateau (232 m a.s.l.), some 4 km to the south-west of the southern end of Hańcza Lake. The site is in the forefront of moraines that define the youngest subphase of the Pomeranian phase in the Suwałki Lakeland (Lisicki, 1993). The boulder is 0.8 m high and is well rooted in the matrix. It has a cosmogenic age of 28.5 ± 4.4 ky; the large uncertainty is due to analytical uncertainty in the measurement of ^{36}Cl.

Interpretation. Geological and palaeogeographic analysis indicates that this age is too old. Within uncertainty, the exposure age of this surface makes its formation contemporary with the maximum advance of the last glaciation. On the geological map (Ber, 1967) surface deposits in this area have ages assigned to within the glaciation only (the Weichselian), but not to within a stadial or phase. This observation will be useful in the analysis of the palaeogeographic significance of the oldest ages obtained for the nearby sites at Bachanowo.

Site **Bachanowo (Bac)** consists of three flat surfaces in the area of Czarna Hańcza River, to the south of Hańcza Lake. The highest level (Bac-1), at an altitude of 232 m a.s.l., was formed during the first stage of erosion of the bouldery highland till by glaciofluvial waters. Two lower levels are erosional terraces at altitudes of 222 m a.s.l. (Bac-2) and 212 m a.s.l. (Bac-3). All three surfaces contain numerous medium-sized erratics (up to 1 m tall), most of them rooted in the matrix. The largest concentration of erratics is on the highest surface. Slightly smaller boulders occur at the terrace of the modern river. Five samples were collected from the oldest surface (Bac-1). The calculated apparent ages display a large scatter: two samples have ages of approximately 27 ky, two others are in the interval 20–22 ky, and one has an age of 14.6 ky. A sample of matrix collected from the same surface gave an apparent age of 15.5 ky. Seven samples were collected from surface Bac-2. The oldest boulder has an age of about 26 ky, three samples are in the interval 20–22 ky, and three others fall in the interval 13.8–16.8 ky. The matrix from Bac-2 gave an apparent age of approximately 21 ky. The low-

Table 3

^{36}Cl ages of surfaces from the Suwałki Lakeland, NE Poland

Sample ID	Boulder height [m]	Latitude (°N)	Longitude (°E)	Altitude [m a.s.l.]	^{36}Cl age [ky]	
					Boulder	Surface
Gremzdy Polskie, highland (GP)						
NP96-12-GP	0.7	54.074	23.190	130.5	**19.2 ± 1.7**	19.7 ± 1.0
NP96-13-GP	0.7	54.077	23.173	136	**18.8 ± 1.6**	
NP96-14-GP	1.3	54.078	23.174	136	**23.2 ± 2.3**	
NP96-15-GP	0.6	54.078	23.174	136	**18.6 ± 1.1**	
Kruszki, highland (Kru)						
NP96-7-SPK	0.8	54.235	22.784	232	**28.5 ± 4.4**	28.5 ± 4.4
Bachanowo, highland (Bac-1)						
NP96-8-SPK	0.4	54.235	22.792	232	**26.7 ± 3.4**	26.9 ± 2.0
NP97-16-BAC1	1.0	54.238	22.792	232	14.6 ± 0.7	
NP97-17-BAC1	1.0	54.238	22.792	232	**27.0 ± 2.2**	
NP97-18-BAC1	0.5	54.238	22.792	232	20.2 ± 1.6	
NP97-19-BAC1	0.7	54.238	22.792	232	22.1 ± 1.2	
Bachanowo, terrace (Bac-2)						
NP96-9-SPK	0.6	54.236	22.792	222	**14.6 ± 1.9**	14.7 ± 0.9
NP97-20-BAC2	0.8	54.238	22.792	222	**13.8 ± 1.0**	
NP97-21-BAC2	0.4	54.238	22.792	222	**16.0 ± 1.4**	
NP97-22-BAC2	0.5	54.238	22.792	222	22.4 ± 2.4	
NP97-23-BAC2	1.0	54.238	22.792	222	25.9 ± 1.2	
NP97-24-BAC2	0.3	54.238	22.792	222	20.4 ± 1.2	
NP97-25-BAC2	0.5	54.238	22.792	222	21.5 ± 1.3	
Bachanowo, terrace (Bac-3)						
NP97-26-BAC3	0.5	54.238	22.792	212	17.6 ± 1.0	14.4 ± 1.0
NP97-27-BAC3	0.4	54.238	22.792	212	28.2 ± 1.7	
NP97-28-BAC3	0.7	54.238	22.792	212	**13.4 ± 0.9**	
NP97-29-BAC3	0.6	54.238	22.792	212	**15.4 ± 0.9**	
Łopuchowo, moraine (Lop-1)						
NP96-10-SPK	0.4	54.258	22.832	250	25.5 ± 2.5	14.4 ± 1.0
NP97-33-LOP1	0.6	54.258	22.832	250	20.7 ± 2.1	
NP97-34-LOP1	1.0	54.258	22.832	250	**17.3 ± 1.1**	
NP97-35-LOP1	0.5	54.258	22.832	250	**14.3 ± 1.3**	
NP97-36-LOP1	0.5	54.258	22.832	250	**11.0 ± 1.1**	
NP97-37-LOP1	0.5	54.258	22.832	250	**14.2 ± 0.8**	
NP97-38-LOP1	0.5	54.258	22.832	250	**14.0 ± 1.0**	
Łopuchowo, moraine (Lop-2)						
NP97-39-LOP2	1.0	54.258	22.832	250	**19.2 ± 1.1**	17.9 ± 1.3
NP97-40-LOP2	0.7	54.258	22.832	250	**16.6 ± 0.9**	
Gulbieniszki, outwash (Gul)						
NP96-11-SPK	1.5	54.265	22.928	200	**17.9 ± 1.0**	17.9 ± 1.0
Bachanowo and Łopuchowo, matrix, 20% soil H_2O						
NP97-30-BAC1	n/a	54.238	22.792	232	**15.5 ± 1.0**	
NP97-31-BAC2	n/a	54.238	22.792	222	**21.5 ± 1.1**	
NP97-32-BAC3	n/a	54.238	22.792	212	**20.8 ± 1.2**	
NP97-41-LOP	n/a	54.258	22.832	250	**18.6 ± 1.0**	

Table 3 cont.

Bachanowo and Łopuchowo, matrix, 30% soil H_2O						
NP97-30-BAC1	n/a	54.238	22.792	232	16.1 ± 1.0	
NP97-31-BAC2	n/a	54.238	22.792	222	22.4 ± 1.2	
NP97-32-BAC3	n/a	54.238	22.792	212	21.6 ± 1.2	
NP97-41-LOP	n/a	54.258	22.832	250	20.1 ± 1.1	

uncertainties in ^{36}Cl ages: boulder ages are reported with 1σ standard deviation calculated by propagation of analytical uncertainties; feature ages are reported with 1 σ weighted standard error of the weighted mean; only samples whose age is shown in bold letters (filled circles in Fig. 4) were included in the calculation of the mean; n/a — not applicable

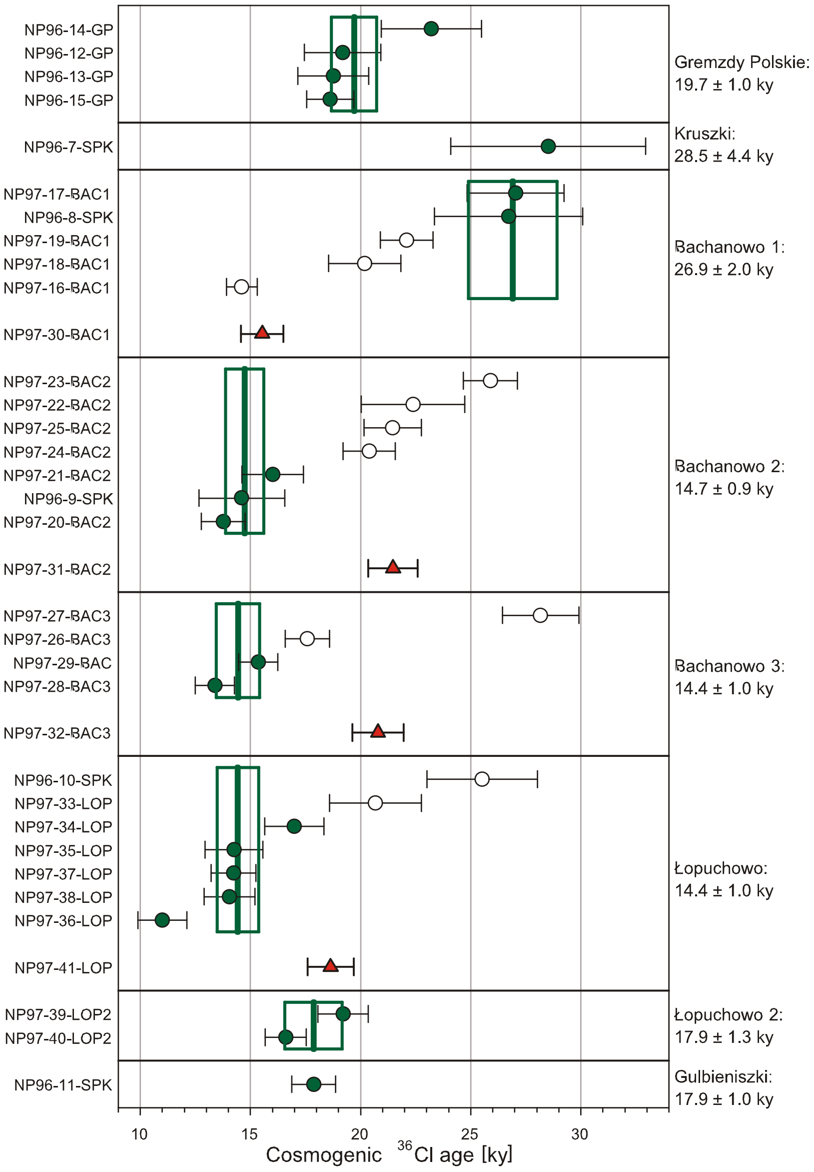

Fig. 4. Cosmogenic ^{36}Cl ages of boulders (circles) and matrix (triangles)

Filled circles indicate the samples that have been used in the calculation of weighted mean ages (also shown in bold in Table 3)

est surface (Bac-3) was dated using four samples. The oldest sample has an age of 28 ky, and the other three samples are in the interval 13.4–17.6 ky. The matrix from surface Bac-3 has an exposure age of approximately 21 ky.

Interpretation. Chlorine-36 inventories in 16 boulder samples from the glacial highland and from erosional terraces of Czarna Hańcza show highly variable apparent ages that range between 13 ky and 28 ky. This wide range of ages is not surprising, particularly in light of the apparent ages of the matrix samples from the same surfaces. Boulders present within the glacial till were gradually exposed at the surface by erosion of the highland surface, which resulted in the large spread of their apparent ages (*cf.* Zreda *et al.*, 1994, 2005*b*). That this spread is due to erosion and not inheritance is demonstrated by the young apparent age of the matrix and by its agreement with the age of the youngest boulder from surface Bac-1. In this case, the oldest ages are closest to the true age of the landform. Thus, two oldest boulder ages, whose ages are nearly identical, give an average age of the landform of 26.9 ± 2.0 ky. In the case of the two lower surfaces — typical erosional terraces — the situation is reversed. Boulders that have older apparent ages could have been transported to the place of deposition from areas that have higher altitudes and that were exposed earlier by erosion and slope processes. The oldest dates on both terraces (26 ky on Bac-2 and 28 ky on Bac-3) are the same as dates from the nearby highlands at Kruszki (28 ky) and from the highest surface at Bachanowo (Bac-1, 27 ky). The matrix from both terraces is older than the youngest boulders, which, according to our interpretive model, indicates a significant amount of ^{36}Cl inherited from previous exposure episodes. Thus, the youngest boulder ages, three from Bac-2 and two from Bac-3, are closest to the true depositional ages of the terraces: terrace Bac-2 has an average age of 14.7 ± 0.9 ky, and terrace Bac-3 is 14.4 ± 1.0 ky old. These mean ages are identical, within 1σ errors, which suggests that only a short time separated the two episodes of erosion.

Site **Łopuchowo (Lop)** includes two of several moraine belts located to the east of Hańcza Lake, in the Szeszupa Depression (Fig. 1), at altitudes reaching 250 m a.s.l. Geological and geomorphological analysis suggests that these moraines were deposited during the youngest recessional (Szeszupa) subphase of the Pomeranian phase (Krzywicki, 1993; Lisicki, 1993). Two samples from a moraine on the outside of the Szeszupa Depression (Lop-2) gave ages of 19.2 ky and 16.6 ky. Seven samples from erratics in a moraine near the centre of the depression (Lop-1) yielded ages ranging from 25.5 ky to 11.0 ky, and the matrix from the same surface gave an age of 18.6 ky.

Interpretation. Such a wide range of apparent ^{36}Cl ages of erratics, combined with the matrix age that is much older than the youngest erratic, shows that the moraine was constructed from a material containing a significant amount of inherited ^{36}Cl. Thus, the five youngest boulder ages are used to calculate the deposition age of moraine Lop-1, 14.4 ± 1.0 ky. For surface Lop-2 we take the mean of the two samples, 17.9 ± 1.3 ky, as the formation age of the moraine. The age of moraine Lop-1, 14.4 ky, probably shows the time of intensive melting of ice and indicates the younger time limit of moraine formation near Łopuchowo. This age is similar to the age of formation of terraces Bac-2 and Bac-3 in the nearby glacial channel of the Czarna Hańcza River, 14.7 ± 0.9 ky and 14.4 ± 1.0 ky, which indicates that these processes were contemporaneous.

Site **Gulbieniszki (Gul)** comprises only one large (1.5 m tall) boulder found inside the "Jeleniewo outwash channel" in the foreland of the last (V) recessional (Szeszupa) subphase of the Pomeranian phase (Ber, 1968; Krzywicki, 1993). This area reaches an altitude of 200 m a.s.l. And the sample gave an apparent ^{36}Cl age of 17.9 ± 1.0 ky.

Interpretation. The age of the Gulbieniszki erratic is the same as that of the nearby moraine Lop-2. The deposition of this boulder belongs to the glacial till found at shallow depths underneath sandy deposits of a sandur in the valley. The results suggest that this till should be correlated with one of the recessional phases of the Weichselian Glaciation. The sandur must have formed later, during continued recession of ice.

DISCUSSION

PALAEOGEOMORPHOLOGICAL INTERPRETATION

The erratics dated by ^{36}Cl came from different geomorphic settings: glacial plateau, end moraines, erosional terraces, and glacial channel. The ^{36}Cl ages determine the time of first exposure of the erratics to cosmic radiation, which is contemporaneous with the disappearance of the ice sheet. These dating results, together with maps (Fig. 1) of deglaciation obtained from morpho- and lithostratigraphic analysis (Ber, 1967, 1982, 2000; Krzywicki, 1993; Lisicki, 1993), allow for the determination of the age of recessional phases. The ^{36}Cl results confirm the Weichselian age of the landscape in the Suwałki Lakeland (Fig. 5). At the time when the LGM end moraines were formed on the Augustów Plain, the highlands near Kruszki and Bachanowo were free of ice, as demonstrated by the old ages, 26–28 ky, of erratics at these two sites. One possible explanation of ice-free conditions uses the idea of nunataks (Ber, 2000), remnants of older highlands preserved from the time of the maximum Weichselian Glaciation, and not covered by ice during later glacial advances. Given the lobate character of glacial advances, existence of nunataks seems likely (Houmark-Nielsen, 1987; Marks, 2002). The nunataks underwent fast erosion by waters from melting ice sheets. The evidence of this early erosional phase is surface Bac-1, whose age is approximated by its oldest erratics to 27 ky. The end of erosion could not be determined with the cosmogenic method. The ^{36}Cl results from two erosional terraces, Bac-2 and Bac-3, show intensified erosion 14–15 ky ago, during the last recessional glacial phase (Vb) and during the final melting of regional ice. The lowest terrace, not dated with ^{36}Cl, was formed probably at the time of final melting of ice in the Szeszupa Depression, or in the Holocene. The minimum limiting age of the disappearance of ice from this area can be deduced using the pollen record obtained from the deposits of Lake Szurpiły, where organic sedimentation started 11.6 ky ago, during Younger Dryas times (Bińka, 1993). Plants recorded in the lower part of the record indicate tundra with dominant *Juniperus* and *Chenopodiacea*, whereas birch and pine occur less frequently.

The erratics at Gremzdy Polskie are at the back of the recessional moraine belts (IV, Fig. 1), and their deposition must be associated with the ice lobe that formed these moraines. Because the age of these erratics is approximately 19.7 ky, the moraines must have been formed a little earlier. Previous interpretations assigned these moraines to the recessional Hańcza subphase of the Pomeranian phase (Lisicki, 1993; Krzywicki, 1993, 2002). However, our results suggest that these moraines are correlative with the maximum Pomeranian phase. The Pomeranian phase is dated at 16.5 ky on an uncalibrated ^{14}C scale (Kozarski, 1995), or approximately 19.6 ky in calibrated ^{14}C years (Fig. 5; calibrated using *Calib. 5.0 program*; Stuiver *et al*., 2005). It follows that the two more extensive moraine belts near Wigry lake (II and III) must have been formed during earlier glacial episodes. Thus, it is possible to correlate moraine belt III with the Chodzież subphase, and belt II with the Poznań phase, as suggested by Ber (1982). The Poznań phase is recorded clearly in the morphology of Western Poland, although it has no clear lithostratigraphic signature (Kozarski, 1995). The idea that the ice sheet of the Poznań phase, and not the Leszno phase, was most extensive in northeastern Poland is well known (Woldstedt, 1931; Galon and Roszko 1961; Mojski, 1968). Wysota (2002) suggests that it left not only end moraines, but also its own layer of till. In the light of our ^{36}Cl results these proposed ideas will have to be re-evaluated.

Chronological interpretation of the youngest moraine belt (V) in the Suwałki Lakeland is based on the two sites at Łopuchowo, for which we calculated two different ages: 14.4 ky (Lop-1) and 17.9 ky (Lop-2). This disparity probably reflects different depositional conditions during long-lasting stagnation of ice margins, or two different stages of activity of the retreating ice. The mean ^{36}Cl age of site Lop-2, 17.9 ky, dates the stage of active ice that formed moraine belt Va in the Suwałki Lakeland. This age correlates with calibrated ^{14}C ages of the Gardno phase of the last glaciation (Kozarski, 1986, 1995; Rotnicki and Borówka, 1995). The youngest ^{36}Cl ages in Łopuchowo show that the subsequent stage of ice melting (Vb) happened 14.4 ky ago.

A comparison of the ages of erratics in Gulbieniszki (Gul) and in Gremzdy Polskie (GP), located tens of kilometres apart, shows that a large area of the Suwałki Lakeland to the east of the town of Suwałki was deglaciated 18–20 ky ago. These observations, together with different distances between moraines of different ages and the complex shapes of these moraines, preclude a model of simple frontal deglaciation of this area (*cf.* Galon and Roszko, 1961; Ber, 1968, 1982, 2000; Kozarski,

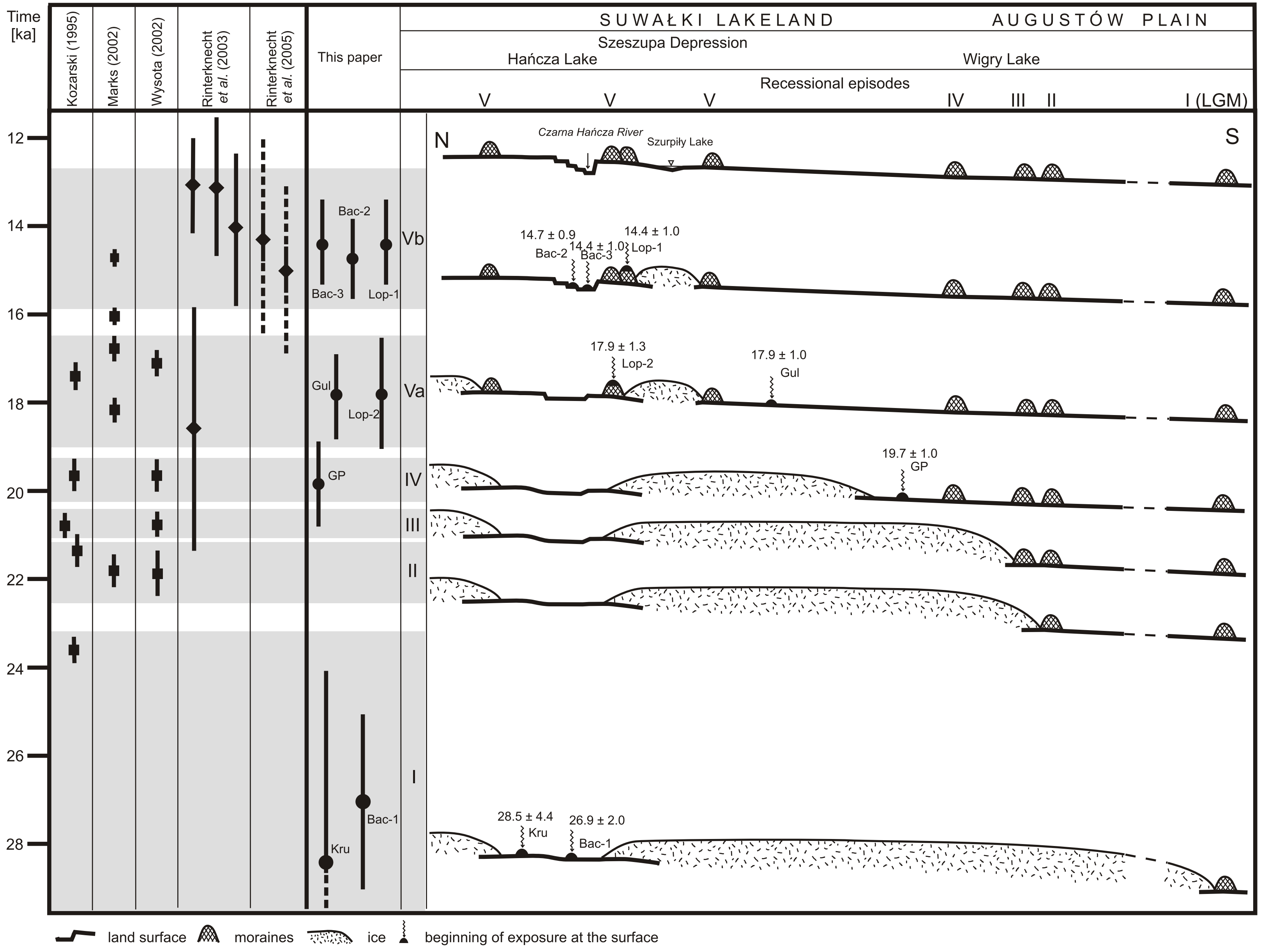

Fig. 5. Deglaciation of northeastern Poland at the end of the Pleistocene; cosmogenic ^{36}Cl ages are shown in the context of the chronostratigraphy of the Weichselian Glaciation

squares — ^{14}C ages (Kozarski, 1995; Marks, 2002; Wysota, 2002), converted to calendar years using the *Calib5.0 program* (Stuiver *et al.*, 2005); rhombs — ^{10}Be ages (Rinterknecht *et al.*, 2005; 2003); circles — ^{36}Cl ages (this work); I–V — recessional episodes; other explanations as in Figure 1

1995). We speculate that whereas in some areas and at some times frontal deglaciation was the dominant mechanism of ice disappearance, the area to the east of Suwałki experienced areal deglaciation. Determination of deglaciation rates is difficult, as each ice lobe could have formed and disappeared at its own rate, different and independent of other lobes. Deglaciation rates for Western Poland were calculated to be in the range from 44 m/y (Kozarski, 1986), through 50 m/y (Rotnicki and Borówka, 1995), to 77 m/y (Wysota, 2002). Interestingly, Boulton *et al.* (2001) approximated the rate of disappearance of ice sheet from northern Europe to be in the range from tens to hundreds metres per year, with generally faster rates in eastern Europe. Our analysis of the ^{36}Cl ages shows that in northeastern Poland, the average rate of retreat of the ice margin, deduced from the position of end moraines, must have been much lower than those proposed by previous estimates. The difference in the ages of recessional moraines IV and V is only about 2 ky, and the distance between them is from several kilometres to 25 km. In Western Poland, distances between analogous moraine belts of the Weichselian Glaciation are on the order of several tens kilometres to hundreds kilometres (Galon and Roszko, 1961; Kozarski, 1995). In the Suwałki Lakeland, moraine belts are closer to each other (Fig. 1). The maximum extent of the Weichselian Glaciation is shifted about 2°N of the position of the contemporary moraines in Western Poland. Three factors are responsible for this difference: (1) the geological structure (the depth to the basement, the activity and directions of the main tectonic features, and their response to ice loading and unloading); (2) differences in climate (continentality increasing eastward); and (3) the location of the main ice lobes (Houmark-Nielsen, 1987; Lagerlund, 1987; Wysota, 2002).

INFERRED CHRONOLOGY OF EVENTS

A comparison of the ^{36}Cl ages of the erratics from the Suwałki Lakeland with the existing chronological data on the last glaciation permits the following reconstruction of geological events in the region. During the advance of the Weichselian ice sheet, whose maximum extent is delineated by moraines I of the Augustów Plain, some areas of the highland, such as that at Kruszki, were free of ice, probably since at least 28.5 ky ago. During subsequent glacial phases, these areas underwent erosion; the earliest stages of erosion were recorded in erratics dated to about 27 ky ago.

Indirectly, we can conclude that the southernmost moraine belt near Wigry Lake (II) was formed during the Poznań phase, in agreement with the interpretation of Ber (1982). But moraine belt III, previously interpreted as part of the maximum Pomeranian phase (Ber, 1982, 2000), can be correlated with the Chodzież subphase, on the basis of the ^{36}Cl ages of erratics from Gremzdy Polskie. Moraine belt IV, which delineates the extent of the Hańcza subphase, was formed before 19.7 ky ago (site GP), probably during the maximum extent of the Pomeranian phase. The disappearance of ice cover was not uniform, and the ice recession generated large amounts of meltwater, and caused intensified erosion of ice-free areas outside the ice margin.

The recessional moraines Va, for example outer moraines at Łopuchowo, were formed about 18 ky ago, during the Gardno phase. Our ^{36}Cl ages suggest that during stagnation of ice sheet on the line of Gardno moraines on the southern coast of the Baltic Sea, an ice lobe existed also in the Suwałki Lakeland. But the spatial correlation between these regions is unclear and requires further studies.

The Bachanowo terraces, Bac-2 and Bac-3 (Fig. 5), were formed about 14.6 ky ago. Simultaneous melting of ice in the nearby Szeszupa Depression resulted in the formation of younger moraine belts (Vb) near Łopuchowo about 14.4 ky ago.

The youngest stage of deglaciation, and the time of intensive melting of ice, in the Szeszupa Depression took place after 14.4 ky ago. By that time, the formerly massive ice was probably fragmented into large bodies of dead ice. The final deglaciation must have occurred shortly afterwards, probably during Bølling time. During the Younger Dryas, the sedimentary basin of Szurpiły Lake developed in the Szeszupa Depression (Bińka, 1993).

Our proposed chronology of the recession of the Weichselian ice sheets from the Suwałki Lakeland was developed by combining cosmogenic ^{36}Cl dating of erratics with geological and geomorphological analysis. However, the interpretations presented above are not necessarily unique, as both the chronological and palaeogeographic data have certain associated uncertainties. Parallel work in the European Lowlands, carried out with the use of cosmogenic ^{10}Be (Rinterknecht *et al.*, 2003, 2005, 2006), lead to conclusions that differ from ours. This discrepancy shows that our models of deglaciation need additional work, primarily to generate more reliable ages. But despite these potential problems, based on our limited number of ^{36}Cl dates, we can propose one general conclusion: that moraine belts whose formation was previously considered simultaneous do not have to be contemporary. Sections of these moraine belts, hundreds of kilometres long, could have been formed at different times (*cf.* Houmark-Nielsen, 1987; Boulton *et al.*, 2001; Marks, 2002; Wysota, 2002). The Suwałki Lakeland is a good example of this possibility. Ice lobes of a single glacial phase, coming from different directions and moving at different rates, resulted in the formation of a complex system of end moraines, often pushed, and difficult to correlate on the basis of their morphology (Ber, 2000, 2004; Krzywicki, 2002). Additionally, younger ice sheets did not cover all areas of older highlands, which is demonstrated by older ^{36}Cl ages of erratics from these nunataks. All these complications make cosmogenic dating uncertain, and interpretations based on these data open to question. But new advances in cosmogenic dating methodology will result in more accurate and precise ages, and thus also in more objective correlations of glacial deposits and events.

CONCLUSIONS

Chlorine-36 in erratics from the Suwałki Lakeland, northeastern Poland, have provided insights into the factors that influence cosmogenic accumulation and inventories in materials from continental glacial deposits, and have generated new information on the regional deglaciation at the end of the last glacial cycle.

1. The application of cosmogenic ^{36}Cl to dating continental glacial deposits yields satisfactory results. But the results must be

analyzed in the broader geological context, taking into account inheritance of ^{36}Cl from previous exposure episodes, and the effects of erosion and gradual exposure of erratics at the surface. Both processes have deterministic and stochastic components, which makes analysis difficult and perhaps non-unique.

2. Cosmogenic ^{36}Cl ages of erratics from a single moraine often display a large variance, probably caused by geological processes modifying the moraine material before, during and after moraine formation. Analytical uncertainties alone cannot explain the observed sample-to-sample variability.

3. Erratics that contain cosmogenic isotopes inherited from previous exposure episode(s) are easily identified in a group of a few samples. Additional measurements of the same cosmogenic isotope in the matrix are useful in distinguishing effects of inheritance from effects of erosion, and in correcting for these effects.

4. Some of the ^{36}Cl ages reported are in apparent conflict with previous geological studies and with the ^{10}Be ages of Rinterknecht *et al.* (2005, 2006). It is therefore necessary to verify these ages, both ^{36}Cl and ^{10}Be, for example by dating the same samples with both isotopes, or by measuring additional samples from areas with simpler stratigraphy. Multiple isotopes measured on the same samples would indicate whether there are consistent differences between isotopes, for example caused by incompatible production rates. Expanding the scope of sampling to other areas would result in a larger data set on which to base palaeogeographic conclusions.

5. All dated landforms have ages correlative with the main stadial (LGM) or one of the recessional phases of the Weichselian Glaciation.

6. The oldest erratics from the highlands near Kruszki and in Bachanowo (Bac-1) date the transgression of the ice sheet to its maximum extent. These dates confirm the idea of nunataks present during younger glacial phases of the Weichselian Glaciation (Ber, 1982, 2000).

7. Moraine belts (IV) near Wigry Lake were formed about 19.7 ky ago, during the Pomeranian phase of the last glaciation. Indirectly, moraine belts II and III to the south of Lake Wigry can be assigned to the Poznań phase and to the Chodzież subphase.

8. Moraine belt Va was formed about 18 ky ago and can be correlated with the maximum extent of the Gardno phase; the final stage of melting of ice (Vb) near Łopuchowo happened about 14.4 ky ago.

9. Degradation of exposed highlands was stepwise. The first stage is dated to about 27 ky (Bac-1), and two younger ones to about 14.6 ky ago (Bac-2 and Bac-3).

10. The final melting of ice in the Szeszupa Depression ended after 14.4 ky ago. During the Younger Dryas, lacustrine sedimentation in Lake Szurpiły had already begun.

11. Horizontal deglaciation rates in NE Poland are difficult to estimate because deglaciation was not always frontal, but often areal. Where records of moraines position and age exist, for example moraines IV and V, the frontal deglaciation rates are calculated to be on the order of 10 m/y, much lower than previously thought.

12. It is likely that the main moraine belts that define the extents of particular glacial phases of the Weichselian Glaciation are not isochronous; different sections of moraine belts were formed at different times. This conclusion supports the idea that during ice-sheet advances individual lobes moved independently, and during recessions different parts of the ice sheet were melting at different rates. We conjecture that dating of one section of the Scandinavian Ice Sheet margin may not carry chronological information about any other section; what is often referred to as the southern margin of the Scandinavian Ice Sheet probably was not isochronous.

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