Cosmogenic ^{10}Be ages on the Pomeranian Moraine, Poland

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We measured the ^{10}Be concentrations in boulders collected from the Pomeranian Moraine in Poland, providing the first direct dating of the southern margin of the Scandinavian Ice Sheet (SIS) in the Polish Lowland. The mean age of 8 ^{10}Be ages of the Pomeranian Moraine in northwestern Poland is 14.3 ± 0.8 ^{10}Be ka, while in northeastern Poland the mean age of 19 ^{10}Be ages of the moraine is 15.0 ± 0.5 ^{10}Be ka. Given the excellent agreement between the two age groups, we calculate a mean age of 14.8 ± 0.4 ^{10}Be ka for final deposition of the Pomeranian Moraine of northern Poland. The age of the Pomeranian Moraine suggests that the southern margin of the SIS was near its maximum extent in Poland at a younger time than previously inferred, and that retreat from the moraine at 14.8 ± 0.4 ^{10}Be ka probably occurred in response to the onset of the Bølling interstade.

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The position of the receding southern margin of the Scandinavian Ice Sheet (SIS) in Poland during the last deglaciation is relatively well defined by several broad, hummocky moraines that cross the northern Polish Lowland (Liedtke 1981; Ehlers 1996) (Fig. 1). However, the timing of ice-margin retreat remains poorly constrained (Andersen 1981; Stankowska & Stankowski 1988; Marks 2002), with existing radiocarbon ages providing only limiting ages on the time of moraine formation. These dating limitations have prevented direct correlations to other ice-margin fluctuations as well as to potential climate forcings, thus obscuring our understanding of the response of the SIS to climate change and its contribution to global sea level change. Surface exposure dating using cosmogenic nuclides produced by secondary high-energy particles in the upper part of the lithosphere (Gosse & Phillips 2001) now provides the opportunity to directly date moraines (Gosse *et al*. 1995; Bowen *et al*. 2002; Licciardi *et al*. 2001, 2004). Here we present 37 ^{10}Be ages that provide the first direct dating of the Pomeranian Moraine, a prominent recessional moraine deposited in northern Poland following the last maximum extent of the SIS (Fig. 1).

Setting

Quaternary deposits in northern Poland largely overlie Miocene sands and Pliocene clays as well as Mesozoic limestones. Several end moraines have been mapped across the northern Polish Lowland (Fig. 1): the Leszno Moraine, the Poznan Moraine (only present in the western part of the Polish Lowland), the Pomeranian Moraine and the Gardno Moraine, which closely follows the Baltic coastline (Galon & Roszkówna 1961; Andersen 1981). This sequence of moraines was deposited by a lobate SIS margin (Mojski 1995) associated with several ice streams that flowed southwards from the Baltic basin (Marks 2002).

Only two sites provide limiting radiocarbon ages on Late Weichselian glacial events in northern Poland. A calibrated radiocarbon age of 26.1 cal. ka BP (22.2 ^{14}C ka BP) (Bard 1998; Hughen *et al*. 2004) on organic deposits provides a maximum limiting age for the first Late Weichselian advance to the Leszno Moraine (Stankowska & Stankowski 1988). Calibrated radiocarbon ages (www.calib.org) on organic deposits from the Odra Bank in the Baltic Sea near the northwestern Polish coast indicate deglaciation of this region between 16.9 ± 0.3 cal. ka BP (14.1 ± 0.2 ^{14}C ka BP) and 15.8 ± 0.5 cal. ka BP (13.1 ± 0.3 ^{14}C ka BP) (Kramarska 1998).

All of our samples are associated with the Pomeranian Moraine. Although individual moraine ridges with gentle distal slopes and steep proximal slopes are clearly identifiable in western Poland (Kozarski 1995), most of the Pomeranian Moraine is a kilometer-wide broad corridor of hummocky landscape. This hummocky belt, when not dissected by major rivers

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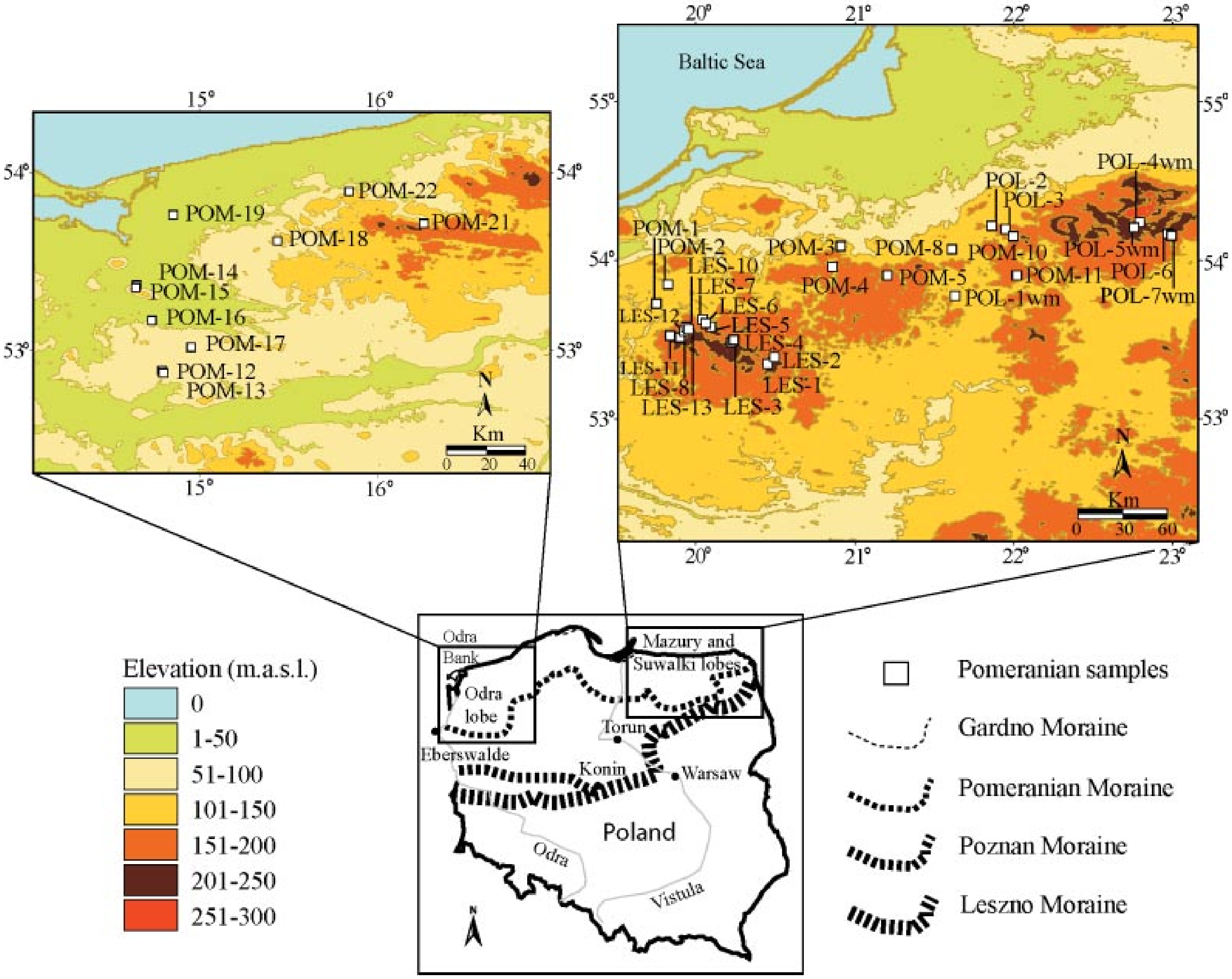

Fig. 1. Digital elevation model of the sampling area (http://lpdaac.usgs.gov). White squares are samples from the Pomeranian Moraine. Moraine outlines are from Boulton *et al*. (2001).

flowing north (Odra and Vistula Rivers), is flanked on its distal slope by extensive outwash plains, a typical landscape at the forefront of an ice-sheet margin.

Sampling strategy

There are few large boulders present on Weichselian moraines in northern Poland. We attribute their scarcity to their removal by humans over the past few centuries, either in association with clearing of fields for agriculture or for use as construction material for buildings, road pavement, and tombstones.

We sampled 37 boulders from the Pomeranian Moraine: 10 from northwestern Poland, and 27 boulders from northeastern Poland (Fig. 1). Sample altitudes range from 22 m to 302 m above sea level. Boulder heights above the ground ranged from 0.7 m to 3.2 m (average of 1.8 m). Large boulders were chosen on stable surfaces to minimize possible post-depositional movements. We sampled from the flat (dip $<10°$) uppermost portion of all boulders with a manual jackhammer or hammer and chisel. In most cases, we were able to extract a single slab of material a few centimeters thick.

Methodology

We extracted beryllium from quartz following a modified version of the procedure given in Kohl & Nishiizumi (1992) and Licciardi (2000). The chemical preparation was performed at Oregon State University, Washington State University, and at the Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Orsay Campus, France. The grain size fraction between 0.25 and 0.71 mm was leached repeatedly with solutions of HNO_3 and HF (1% each) until satisfactory quartz purity was reached, as determined by ICP-AES. A 0.25 mg ^{9}Be spike was added to each sample. Anion exchange, cation exchange, and selective precipitation techniques were used to isolate and purify the beryllium, which was oxidized as BeO in a quartz crucible. The ^{10}Be/^{9}Be ratios were measured by accelerator mass spectrometry at the Tandetron facility, Gif-sur-Yvette, France (Raisbeck *et al*. 1994).

We used a ^{10}Be production rate of 5.1 atoms g^{-1} yr^{-1} (Stone 2000). This production rate, effective for sea level and high latitude (>60°), was scaled to the altitude and geographic latitude of each sample according to Stone (2000). Because there is no evidence for post-glacial uplift of the Polish Lowland, we make no correction for changes in altitude through time.

No correction for surrounding topographic shielding was necessary. Although many samples come from boulders located in the forest, we did not find a trend in ages from boulders covered by vegetation (young pine trees in our case) compared to ages from boulders that are not covered. Cerling & Craig (1994) calculated the effect of vegetation cover (old growth Douglas fir forest) on the production rate of ^{3}He and concluded that the correction is minor (about 4% reduction of the ^{3}He production rate). We infer that differences in mean biomass and moisture content between tree species would result in an even smaller correction of the production rate in our case and thus do not correct for the vegetation cover effect.

Intermittent snow cover is another parameter that could reduce the production rate. A conservative estimate of 50 cm snow depth for 4 months per year (mean value based on a century-long record) with an absorption length of 160 g cm^{-2} would decrease the production rate by ~1.5%. Because our samples come from the top of large boulders, we assume that any snow was blown off rapidly after storms and had a negligible effect on production. Thus, we do not correct for potential snow cover.

Samples are from granitic or gneissic boulders, which are generally resistant to erosion. We sampled a quartz vein on one boulder (POL-7) that projected 2 to 3 mm above the surrounding boulder surface, suggesting that some erosion has occurred. However, erosion rate and style (grain-scale, slab-scale) likely varies throughout our large sampling area, and it is thus unlikely that the erosion recorded on POL-7 is representative of all our boulder surfaces. Our ages increase by 4% when we use an erosion rate of 3 mm/ka. However, for the reasons mentioned above we chose not to apply any correction to our age calculations for erosion.

Cosmogenic ^{10}Be production decreases with depth and the production rate must be scaled accordingly. We corrected the production rate for sample thickness using an exponential function (Lal 1991), and assuming a density of 2.8 g/cm^{3} for granite and an attenuation length of 150 g/cm^{2} (Brown *et al*. 1992). Given that all of our processed samples are from within 3 cm of the boulder surface, this amounts to a production rate correction of less than 3%.

All single exposure ages are reported with a 1σ error corresponding to the analytical uncertainties only. Analytical uncertainties associated with the AMS measurements vary from 7% to 11% in our samples. The uncertainties include a 1σ statistical error in the number of ^{10}Be events counted, a 5% contribution conservatively estimated from observed variations in the standard, and uncertainty in the blank correction (our procedural blank was $6.4 \pm 2.9 \times 10^{4}$ atoms of ^{10}Be ($n = 19$), which is typically 2–3% of the number of ^{10}Be atoms in the samples). The ^{10}Be/^{9}Be ratios were measured relative to the National Institute of Standards and Technology standard (SRM 4325) using the certified ratio of ^{10}Be to ^{9}Be ($26.8 \pm 1.4 \times 10^{-12}$). Since most production rate estimates are based on other standards that are lower by 14% relative to the NIST one (Middleton *et al*. 1993), we corrected the production rate for that difference.

We report our final moraine age as the mean of the sample population because the standard deviation of our sample-age population is dominated by the geological uncertainties, as suggested by the standard deviation of the exposure ages (13%) being larger than the analytical ones (7% to 11%). We interpret the mean age and standard deviation of the mean exposure age (3%) as the final time of deposition of the moraine, and thus as recording the time that the ice margin retreated from the moraine.

Results

Our ^{10}Be ages range from 5.2 to 76.0 ^{10}Be ka (Table 1, Fig. 2). Five samples are anomalously young: LES-2 (6.1 ± 0.7 ^{10}Be ka), LES-3 (6.4 ± 0.6 ^{10}Be ka), LES-7 (5.2 ± 0.6 ^{10}Be ka), POM-12 (6.4 ± 0.6 ^{10}Be ka), and POM-15 (7.4 ± 0.9 ^{10}Be ka). We note that these young results are clustered around an error-weighted mean age (Bevington & Robinson 1992) of 6.2 ± 0.3 ^{10}Be ka. The standard deviation of these five ages (0.8 ^{10}Be ka) is consistent with the analytical uncertainty (0.7 ^{10}Be ka), thus suggesting the possibility that they all have the same age. Although one can speculate on a possible human influence or a climatic event at this time, we currently have no evidence to support either hypothesis.

Samples LES-5 and LES-13 are dated at 36.4 ± 2.2 ^{10}Be ka and 32.2 ± 2.2 ^{10}Be ka, respectively. Because the two boulders have similar exposure ages and because they belong to the same ridge, they may indicate moraine formation during that time. We consider this unlikely, however, because radiocarbon dates from freshwater sediments suggest that the southern part of Sweden was ice-free between 30 and 40 ^{14}C ka BP (Donner 1996). Furthermore, the area had

Table 1. AMS-measured concentrations of ^{10}Be and exposure ages of 37 boulders sampled on the Pomeranian Moraine in Poland.

Sample ID	Lithology	Boulder height (m)	Sample thickness (cm)	Elevation (m a.s.l.)	Latitude N (DD)[4]	Longitude E (DD)[4]	[^{10}Be] (10^4 atoms g^{-1})	Scaling factor	^{10}Be Age (ka)[1]
Pomeranian Moraine									**14.8 ± 0.4**
POM-15[3]	Granite	1.6	2.0	88	53.3517	14.6436	3.60 ± 0.4	1.10	7.4 ± 0.9
POM-14	Gneiss	1.4	3.0	99	53.3661	14.6508	7.67 ± 0.6	1.12	15.7 ± 1.2
POM-16	Granite	1.3	1.5	96	53.1669	14.7358	6.60 ± 0.5	1.12	13.4 ± 1.0
POM-12[3]	Granite	2.3	1.0	80	52.8856	14.7914	3.12 ± 0.3	1.10	6.4 ± 0.6
POM-13	Granite	0.7	1.0	70	52.8856	14.7914	8.74 ± 0.6	1.09	18.0 ± 1.3
POM-19	Granite	2.7	2.0	22	53.7592	14.8533	6.15 ± 0.5	1.03	13.6 ± 1.1
POM-17	Granite	1.8	1.5	60	53.0175	14.9544	5.10 ± 0.4	1.08	10.8 ± 0.8
POM-18	Gneiss	1.5	1.0	102	53.6133	15.4369	7.42 ± 0.8	1.12	15.0 ± 1.6
POM-22	Granite	1.9	1.5	110	53.8906	15.8381	7.19 ± 0.7	1.13	14.4 ± 1.3
POM-21	Granite	1.3	2.0	133	53.7117	16.2553	6.90 ± 0.5	1.16	13.5 ± 1.0
POM-1	Granite	1.1	1.0	99	53.7236	19.7514	9.25 ± 0.6	1.12	18.6 ± 1.3
POM-2	Granite	1.4	2.0	107	53.8444	19.8236	6.85 ± 0.5	1.13	13.8 ± 1.0
LES-11	Gneiss	1.5	2.0	218	53.5222	19.8375	7.92 ± 0.8	1.11	14.4 ± 1.4
LES-8	Granite	1.1	2.0	255	53.5111	19.9000	10.1 ± 1.1	1.13	17.8 ± 1.9
LES-13[3]	Granite	1.2	2.0	302	53.5528	19.9250	19.1 ± 1.3	1.15	32.2 ± 2.2
LES-10	Granite	1.7	2.0	270	53.5764	19.9417	6.77 ± 0.6	1.14	11.7 ± 1.0
LES-12	Granite	1.6	2.0	275	53.5625	19.9528	8.45 ± 0.7	1.14	14.6 ± 1.2
LES-7[3]	Granite	2.8	2.0	132	53.6250	20.0417	2.65 ± 0.3	1.16	5.2 ± 0.6
LES-6	Gneiss	2.2	2.0	151	53.6006	20.0611	8.06 ± 0.6	1.08	15.7 ± 1.1
LES-5[3]	Granite	2.5	2.0	180	53.5792	20.0944	19.20 ± 1.1	1.09	36.4 ± 2.2
LES-3[3]	Granite	1.6	3.0	212	53.4806	20.2222	3.44 ± 0.3	1.11	6.4 ± 0.6
LES-4	Granite	1.8	2.0	172	53.4944	20.2389	7.38 ± 0.5	1.09	14.0 ± 1.0
LES-1[3]	Granite	2.1	2.0	196	53.3458	20.4500	11.20 ± 0.8	1.10	20.9 ± 1.6
LES-2[3]	Granite	1.3	2.0	179	53.3875	20.4931	3.21 ± 0.3	1.09	6.1 ± 0.7
POM-4	Granite	1.8	1.5	167	53.9569	20.8597	5.95 ± 0.4	1.20	11.3 ± 0.8
POM-3	Gneiss	3.1	2.0	117	54.0861	20.9097	7.91 ± 0.6	1.06	15.9 ± 1.2
POM-5	Granite	1.4	2.0	175	53.9006	21.2028	7.35 ± 0.6	1.21	13.9 ± 1.1
POM-8	Granite	3.1	3.0	138	54.0681	21.6097	7.45 ± 0.7	1.16	14.7 ± 1.3
POL-1wm[2]	Granite	1.4	2.0	117	53.7739	21.6286	7.71 ± 0.5	1.14	15.3 ± 1.2
POL-2	Granite	2.0	2.0	128	54.2147	21.8589	7.81 ± 0.5	1.15	15.3 ± 1.3
POL-3[3]	Granite	2.0	2.0	130	54.1950	21.9464	12.10 ± 0.8	1.15	23.7 ± 2.1
POM-10	Granite	1.6	1.0	173	54.1500	21.9958	6.87 ± 0.5	1.09	12.9 ± 1.0
POM-11	Granite	1.8	1.0	177	53.9006	22.0167	7.74 ± 0.5	1.21	14.5 ± 1.0
POL-5wm[2]	Granite	2.3	2.0	243	54.2039	22.7531	9.44 ± 0.5	1.29	15.6 ± 1.2
POL-4wm[2]	Granite	1.0	2.0	240	54.2358	22.7897	9.04 ± 0.5	1.28	15.5 ± 1.2
POL-6[3]	Granite	1.5	2.0	211	54.1647	22.9683	41.20 ± 2.3	1.25	76.0 ± 5.7
POL-7wm[2]	Quartz vein	3.2	2.0	195	54.1642	22.9700	10.20 ± 0.5	1.23	18.6 ± 1.3

[1] Exposure ages are calculated using the production rate of 5.1 ^{10}Be atoms g^{-1} yr^{-1} and the ^{10}Be half-life of 1.51 Ma. The production rate is scaled for sample location and sample thickness using the rock density of 2.8 g cm^{-3} and the attenuation length of 150 g cm^{-2} (Brown *et al.* 1992). The scaling factor (corresponding to 'effective' average elevation) accounts for the mode of production of ^{10}Be atoms at the boulder surface: 97.8% by spallation and 2.2% by muon capture (Stone 2000). Uncertainty corresponds to analytical uncertainty only for single exposure ages. Uncertainty on the moraine mean age is the standard deviation of the mean exposure age.

[2] Error-weighted mean of AMS measurement replicates.

[3] Samples that were not used to calculate the moraine age. The boulders could have been subject to multiple exposure, burial periods, post-depositional exhumation or surface erosion (see text for discussion).

[4] Decimal degree.

been overridden when the ice advanced to its last maximum extent. We thus suggest that LES-5 and LES-13 reflect inherited ^{10}Be associated with prior exposure. We similarly attribute the old ages of samples POL-6 (76.0 ± 5.7 ^{10}Be ka) and POL-3 (23.7 ± 2.1 ^{10}Be ka) to inherited ^{10}Be.

In the same data set, samples POM-1 and POM-13 (18.6 ± 1.3 ^{10}Be ka and 18.0 ± 1.3 ^{10}Be ka, respectively) have ages that may suggest deposition in association with the Leszno Moraine, but their geographic and geomorphologic positions suggest they are associated with the Pomeranian Moraine. Sample POM-1 is located too far north and is too low in elevation with respect to the position of the Leszno Moraine. Sample POM-13, on the other hand, is located at the southern end of the south–north sampling transect in western Poland, and is thus a good candidate for the Leszno Moraine. However, the sample is located north of the Warsaw–Toruń–Eberswalde spillway (Fig. 1) that drained meltwater from the southern SIS margin during the Pomeranian phase (Marks 1999), suggesting that it was deposited on the Pomeranian Moraine. We thus included samples POM-1 and POM-13 in the Pomeranian Moraine age calculation.

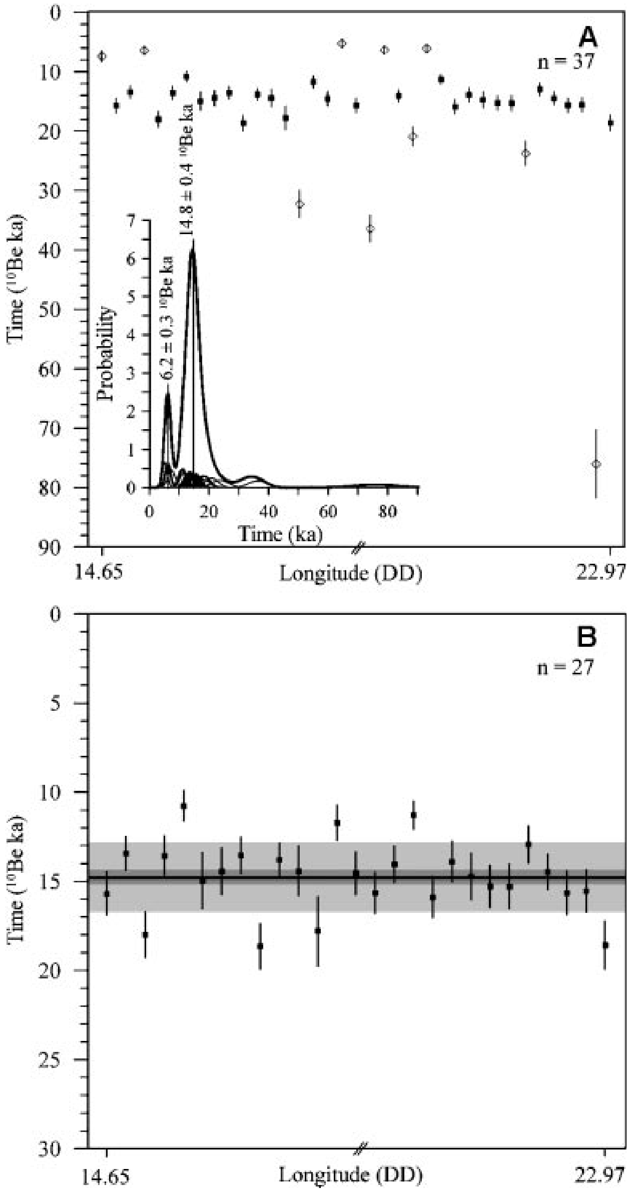

Fig. 2. A. Exposure ages for 37 boulders on the Pomeranian Moraine. Open diamonds are data not used in the mean moraine age calculation. Inset graph shows the probability curves for 37 exposure ages. Probability values are normalized so that each probability distribution is equal to 1. The sum of the probabilities is shown as a thick black curve. The vertical lines are the ages of the clusters as calculated in the text. B. The Pomeranian Moraine age (black line) does not include the exposure ages of samples POL-3, POL-6, POM-12, POM-15, LES-1, LES-2, LES-3, LES-5, LES-7, and LES-13 (highlighted as open diamonds in (A)). Samples are ordered with respect to their longitude on the moraine. Error bars on single exposure ages in (A) and (B) are 1σ analytical uncertainties only, as described in the text. Shaded bands in (B) represent: in dark grey the standard deviation of the mean exposure age; in light grey the standard deviation of the exposure ages.

Because sample LES-1 (20.9 ± 1.6 ^{10}Be ka) is 2.4 standard deviations from its group average, we performed a statistical test (Chauvenet's criterion; Taylor 1997) to decide whether or not to reject the sample from the remaining Pomeranian Moraine samples. The result of this test suggests that sample LES-1 should be rejected from the moraine age calculation. Sample LES-1 may reflect deposition associated with the Leszno Moraine but we again reject this hypothesis because its geographical location and altitude indicate deposition in association with the Pomeranian Moraine. We thus attribute its age to prior exposure and inherited ^{10}Be.

Three samples (POM-4: 11.3 ± 0.8 ^{10}Be ka, POM-17: 10.8 ± 0.8 ^{10}Be ka, and LES-10: 11.7 ± 1.0 ^{10}Be ka) have exposure ages contemporaneous with the Younger Dryas cold event. Although the position of these boulders is clearly too far to the south to have been deposited along the SIS margin during the Younger Dryas (Rinterknecht *et al.* 2004), the exposure ages could not be objectively excluded from our sample population based on the Chauvenet statistical test. We have thus included these exposure ages with the remaining samples to determine the age of the Pomeranian Moraine.

The mean age of eight samples from the Pomeranian Moraine in northwestern Poland is 14.3 ± 0.8 ^{10}Be ka, whereas the mean age of 19 samples from the moraine in northeastern Poland is 15.0 ± 0.5 ^{10}Be ka. Assuming the two age populations have a normal distribution, we performed two statistical tests to determine if there were any statistical differences between the two groups. An F-test indicates that the population variances are equal ($F_{7,18}$ (0.95) = 1.06). A *t*-test indicates that the means of the two populations are equal ($t_{25.975} = 0.78$, significant at 95% confidence). Because there are no statistical differences, we combined the two populations to calculate a single age of 14.8 ± 0.4 ^{10}Be ka ($n = 27$) for retreat of the southern SIS margin from the Pomeranian Moraine in northern Poland.

Conclusions

A calibrated radiocarbon date of 16.9 cal. ka BP on organics from the Odra Bank (Kramarska 1998) (Fig. 1) indicates that the SIS margin was north of the Polish Baltic coast at that time. The youngest calibrated radiocarbon age from the Odra Bank is 15.8 cal. ka BP. Our data suggest that the ice margin receded from the Pomeranian Moraine at 14.8 ± 1.0 ka (the error includes a 6% uncertainty in the production rate; Stone 2000). Accordingly, we interpret these ages to indicate that the ice margin had readvanced to the Pomeranian Moraine after 15.8 cal. ka BP, and retreated from the moraine at 14.8 ± 1.0 ka. Our new age for the Pomeranian Moraine also indicates that the southern SIS margin was near its maximum extent at a younger time than previously inferred (Andersen 1981; Marks 2002), and that retreat likely represents a response to the abrupt warming of the North Atlantic region associated with onset of the Bølling interstade ~14.6 cal. ka BP.

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