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Cosmogenic ^{10}Be dating of the Salpausselkä I Moraine in southwestern Finland

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Abstract

We determined in situ cosmogenic ^{10}Be ages for nine boulders sampled on the Salpausselkä I (Ss I) Moraine. Previous dating of this moraine indicated that it formed during the Younger Dryas Stadial along the southern margin of the Scandinavian Ice Sheet in southern Finland. Our new exposure ages range from 10.9 ± 1.0 to 13.5 ± 1.2 ^{10}Be ka, with an error-weighted mean age of 12.4 ± 0.7 ^{10}Be ka. Our results confirm four previous ^{10}Be ages obtained 40 km northeast of our sample location. The combined data ($n = 13$) indicate that retreat from the Ss I Moraine occurred at 12.5 ± 0.7 ^{10}Be ka, in excellent agreement with an age of 12.1 ka for retreat from the Ss I Moraine based on varve chronologies. These results identify the Ss I Moraine as among the best-dated margins associated with Late Quaternary ice sheets.

1. Introduction

The Ss (Salpausselkä) Moraine complex in southern Finland, a succession of three parallel ridges, Ss I, Ss II, and Ss III (Fig. 1), formed during the last recession of the southern margin of the Scandinavian Ice Sheet (SIS). Of these three ridges, Ss I and Ss II are the best-expressed end moraines in the Finnish landscape (Rainio et al., 1995). The two ridges (Ss I and Ss II) are thought to be contemporaneous with the three Baltic Ice Lake (BIL) levels (Donner, 1969, 1978; Glückert, 1995), termed B I, B II, and B III. The moraine complex primarily comprises glacio fluvial and glacio lacustrine deposits related to ice-margin contact with the various BIL water levels (Björck, 1995; Donner, 1995).

The existing chronology of the Ss Moraines is based largely on varve counting and biostratigraphical evidence supported by radiocarbon ages. Varve chronologies have been continuously revised (Sauramo, 1958; Niemelä, 1971; Cato, 1987; Strömberg, 1990; Björck et al., 1996; Wohlfarth et al., 1997), and errors of up to a thousand years were found in the reference Swedish varve chronology used in the correlation with the floating Finnish varve chronology (Andrén et al., 1999). A recent study by Saarnisto and Saarinen (2001) attempted to define, independently from the Swedish and Finnish varve chronologies, the age of Ss I and Ss II end moraines. Based on varve counts, paleomagnetic measurements and ^{14}C accelerator mass spectrometry (AMS) dating results obtained from series of lake sediment cores from Lake Onega and their correlation with the Finnish varve chronology, Saarnisto and Saarinen (2001) concluded that Ss I and Ss II

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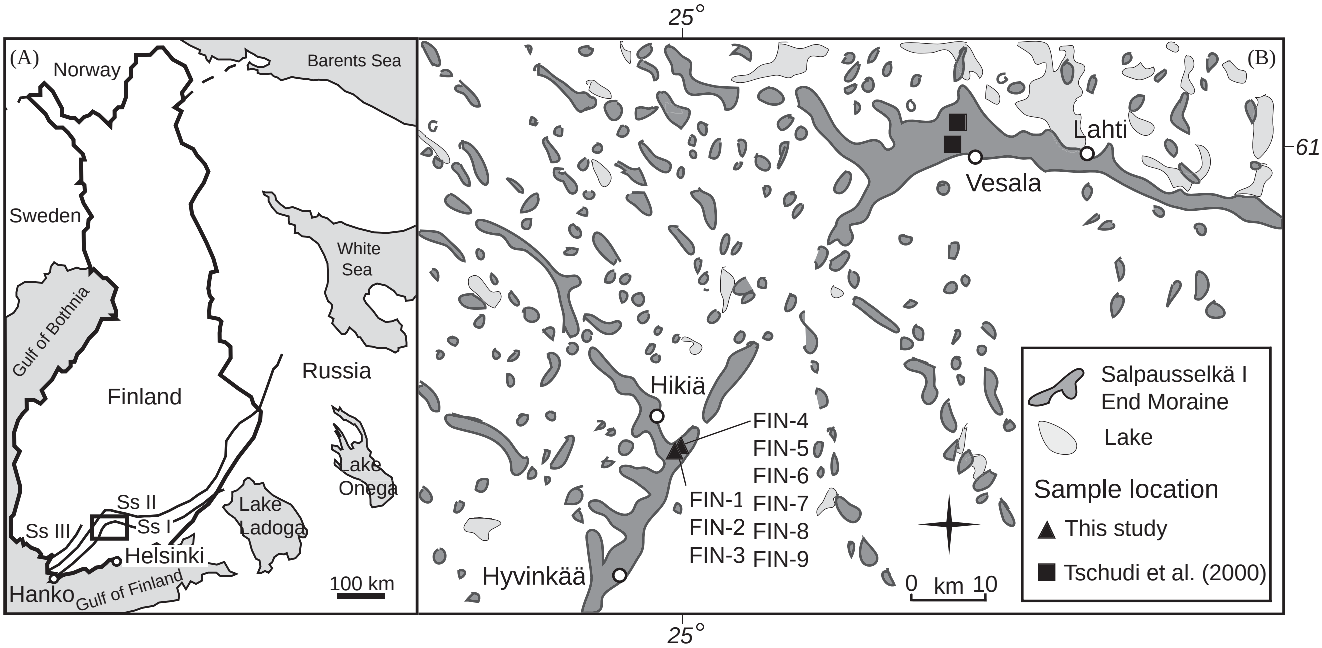

Fig. 1. (A) Map of Finland with the position of the Salpausselkä Moraine complex, (B) Geomorphologic map of the sampling area (adapted from the map "Quaternary deposits of Finland and northwestern Russian Federation and their resources", 1/1 000 000).

were deposited between 12,250 and 11,590 varve years ago, or coeval with the Younger Dryas (YD) cold event. The 660 varve-year bracket for the moraines' deposition agrees with the 600 varve-year bracket as defined by Sauramo (1929) according to his original floating Finnish varve chronology. Sauramo also estimated that Ss I deposition took 217 varve-years and that Ss II deposition took 183 varve-years, with about 200 varve-years for the SIS margin to retreat ca 40 km from the Ss I position to the Ss II.

Tschudi et al. (2000, 2001) applied surface exposure dating (SED) to four boulders sampled from the Ss I Moraine. They obtained error-weighted mean ages of 11.6 ± 0.5 ^{10}Be ka (Tschudi et al., 2000), and 11.9 ± 0.8 ^{26}Al ka (Tschudi et al., 2001), thus supporting a YD age for the moraine. Given the large uncertainties on the ages, however, a post-YD age cannot be ruled out. Here, we present nine new ^{10}Be exposure ages that directly date the well-preserved Ss I Moraine in southwestern Finland. Our data, combined with the four ^{10}Be ages from Tschudi et al. (2000), confirm that the Ss I was deposited during the YD cold event.

2. The Ss I end moraine and the sampling site

We sampled boulders on the western arc of Ss I (Fig. 1), which was deposited in front of the Baltic Sea lobe margin of the SIS (Punkari, 1980). The end moraine extends from Vesala just west of Lahti to Hanko on the southwestern coast of Finland, from which it can be traced several tens of kilometers further to the west on the Baltic seafloor. In this area, the Ss I ridge is composed mainly of glaciofluvial deltas and subaquatic fan deltas that were deposited next to the ice margin into the BIL (Sauramo 1958, Donner, 1969, 1978; Fyfe, 1990). Although the water level history of the Baltic Ice Lake adjacent to the SIS ice margin is relatively well established (Sauramo, 1958; Donner, 1969, 1978), the water level history of BIL has been and still remains controversial (Fyfe, 1990; Saarnisto, 1991; Donner, 1995). Mainly based on elevation data of geomorphologically defined delta levels and paleoshorelines in the area of Ss end moraines, four distinct BIL levels so-called g, B I, B II, and B III have been determined (Donner, 1978). During the time when Ss I was deposited, the highest BIL level stood at B I level while B II and B III levels represent BIL water levels formed when ice front retreated from the Ss I further northwest in the area between Ss I and Ss II and Ss II end moraine belt (Donner, 1995). Due to the isostatic uplift, the elevations of the highest BI level in the western arc of Ss I range from 157 m in Lahti area to 150 m level at Hikiä (Donner, 1978).

The Ss I moraine ridge in the sample area forms the Hyvinkää plateau, an almost continuous plateau ~40 km long and up to 2 km wide. The samples obtained southeast of Hikiä are located on the Ss I ridge at around 140 m above present sea level. In that area a feeding esker from the northwest brought material to the ice margin beyond which a glaciofluvial delta was formed. The surface of the Ss I ridge at this site is occupied with numerous kettle holes above 150 m. From this level a few meltwater channels reach the 143–145 m-level. With respect to the SED methodology it is important to consider whether the erratic boulders sampled were submerged by the BIL, since submersion would reduce the ^{10}Be production rate. As already described by Ramsay (1922), Sauramo (1958), and Donner (1969, 1978) the highest shore line (i.e. B I level at Hikiä) was placed at 150 m. This elevation is largely based on geomorphologically defined paleoshoreline southwest of the Hikiä ridge although more pronounced paleoshorelines also exist at 143, 140 and 133 m for example. Although the highest shoreline can be seen at 150 m above sea level representing the B I level, we consider that the samples taken from erratic boulders at the 140 m level were deposited in very shallow water as the Hikiä delta was formed and therefore can be used to determine the age of Ss I.

3. Methodology

We sampled nine granitic boulders within 300 m^2 on top of the moraine ridge. Beryllium (Be) was extracted from quartz following a modified version of the procedure given in Kohl and Nishiizumi (1992) and Licciardi (2000). The non-magnetic sample fraction (grain size between 0.25 and 0.71 mm) is first boiled in pyrophosphoric acid to dissolve most of the alumino-silicates. The grain size fraction is then leached repeatedly with solutions of HNO_3 and HF until satisfactory quartz purity is reached. A reference 0.250 mg ^{9}Be spike is added to each sample. We used anion exchange, cation exchange, and selective precipitation techniques to isolate progressively the Be. ^{10}Be/^{9}Be ratios were measured by accelerator mass spectrometry (AMS) at the Tandetron facility, Gif-sur-Yvette, France (Raisbeck et al., 1994), relative to the National Institute of Standards and Technology (NIST) standard (SRM 4325).

Converting ^{10}Be concentrations to exposure ages requires the use of an effective ^{10}Be production rate. We adopt here a value of 5.1 atoms/g/yr (Stone, 2000). This production rate, effective for sea level (1013.25 hPa) and high latitudes ($>60°$), was scaled to the "effective" elevation and geographic latitude of each sample using Stone's factors (2000). Since there is still no consensus regarding these parameters, or their uncertainties, we choose here to report our ages as ^{10}Be ages (Gosse et al., 1995a), somewhat analogous to uncalibrated ^{14}C ages. At some later time, when better information becomes available on the production rate, these ^{10}Be ages can be calibrated to calendar ages.

We do not apply a correction for a potential variability of the paleomagnetic field intensity. The relative ^{10}Be production rate record, derived from the ^{10}Be deposition rate (Frank et al., 1997), shows a significant decrease in the production rate from 30 to 10 ka. However, Masarik et al. (2001) argued that the correction is less than a few percent for samples located above ~35°. All our samples are located at ~61° N, which implies a correction of less than 1% for the production rate.

We thus consider below only sample or site specific uncertainties: topographic shielding, snow cover, sample thickness, erosion, and elevation variation linked to glacio-isostatic rebound and glacio-eustatic changes during the last deglaciation. Shielding by surrounding relief is excluded since the Ss I Moraine defines the highest elevation in the region. Our samples come from the top of boulders that are >1 m tall. We assume that any snow would have blown off rapidly after storms and thus do not correct for snow cover. We used the model of Ivy-Ochs (1996) to correct the production rate for sample thickness. Our corrections are slightly over-estimated compared to numerical simulation results reported by Masarik and Reedy (1995). We corrected the production rate for as much as 3%, whereas the simulation predicts no production rate correction up to the first 12 g/cm^2 (about 4.4 cm).

Most of the samples display either rough surfaces with emergent resistant quartz grains or surfaces that retain polish, indicating little to no erosion. The surface of sample FIN-1 appears more highly weathered and could have experienced greater erosion (i.e. slab erosion), but this is not supported by our sample analysis, as the age is not significantly younger than the other results (Table 1). To estimate the possible effect of erosion on surface exposure ages, we assumed an erosion rate of 1.3 mm/ka estimated by Gosse et al. (1995b) for granite in the western US. Introducing this erosion rate would increase the exposure ages by 1.2–1.5% and increase the error-weighted mean moraine age by 1.3%. We choose to report the exposure ages without including the erosion parameter. Tschudi et al. (2000) adopted a significantly larger erosion rate (5 mm/yr), but for reasons that remain unclear, they obtained correction factors that are both variable and lower (1.2–2.6%) than would be calculated using our methodology.

Because of the elevation dependence of the ^{10}Be production rate, we must account for the elevation variation through time as a consequence of glacio-isostatic uplift. Southern Finland has been undergoing post-deglacial isostatic rebound, with modern lithosphere responses ranging from 10 mm/yr at the northern tip of the Bothnia Peninsula to 1–2 mm/yr in the Gulf of Finland (Milne et al., 2001). We used the local sea level record of isostatic uplift (Donner, 1968) and far-field records of sea level rise (Bard et al., 1990, 1996; Fleming et al., 1998) (Fig. 2 inset (B)) to derive the integrated change in production rate experienced by our samples as

Table 1
Sample characteristics, ^{10}Be concentrations and calculated surface exposures ages

Sample ID	Lithology	Boulder height (m)	Thickness (cm)	Altitude (m)	Latitude N (DD)	Longitude E (DD)	[^{10}Be] (10^4 atoms/g)[a]	Scaling factor[b]	^{10}Be age (^{10}Be ka)[c]
This study									
FIN-1	Granite	1.00	3.0	140	60.7308	24.9597	6.22±0.45	1.12	13.0±1.1
FIN-2	Granite	1.40	1.7	140	60.7308	24.9597	5.73±0.46	1.12	11.8±1.1
FIN-3	Granite	2.00	2.0	140	60.7308	24.9597	5.26±0.39	1.12	10.9±1.0
FIN-4	Granite	1.00	2.0	140	60.7308	24.9619	5.80±0.43	1.12	12.0±1.1
FIN-5	Granite	1.20	3.4	140	60.7308	24.9619	6.31±0.44	1.12	13.2±1.1
FIN-6	Granite	1.35	2.6	140	60.7308	24.9619	5.68±0.41	1.12	11.8±1.0
FIN-7	Granite	1.50	2.5	140	60.7308	24.9619	6.49±0.46	1.12	13.5±1.2
FIN-8	Granite	1.40	2.0	140	60.7308	24.9619	6.54±0.45	1.12	13.5±1.2
FIN-9	Granite	2.70	2.0	140	60.7308	24.9619	6.33±0.45	1.12	13.1±1.1
Tschudi et al. (2000)							[d]		[e]
Sal 1	Granite	3.00	4.0	160	61.0000	25.3900	7.50±0.50	1.16	13.3±1.1
Sal 3	Granite	0.50	3.0	160	61.0000	25.3900	7.07±0.48	1.16	12.4±1.0
Sal 4b	Quartz vein	1.50	2.0	160	61.0200	25.4000	6.95±0.49	1.16	12.1±1.0
Sal 5	Granite	3.50	2.0	160	61.0200	25.4000	7.26±0.54	1.16	12.6±1.1

[a]Measured using the NIST standard ratio of ^{10}Be to ^{9}Be and corrected for the mean blank value of 6.4±3.5 10^4 atoms ^{10}Be. All ^{10}Be concentrations are reported $\pm 1\sigma$ error corresponding to the analytical uncertainties as described in the text.

[b]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). We used a density of 2.8 g/cm^3 and an attenuation length of cosmic rays of 150 g/cm^2 to calculate the correction factor for sample thickness.

[c]Surface exposure ages are calculated using a production rate of 5.1 atoms/g/yr at sea level (1013.25 hPa) and latitude >60° scaled for Scandinavian uplift and reduced by 14% to account for different standard used in these measurements compared to that used to make production rate measurements (see text for details).

[d]Measured at the ETH/PSI tandem facility at ETH-Zürich using the standard S555 (^{10}Be/^{9}Be S555 = 95.5×10^{-12}), which is a secondary standard to the materials used to determine the half-life of ^{10}Be (Hofmann et al., 1987), but is offset with the NIST standard by ~11%.

[e]Surface exposure ages are calculated using our method.

a result of post-glacial uplift. We corrected for as much as 202 m of uplift in the sampling area as the former BIL level was adjacent to the SIS margin during the formation of the Ss I Moraine. This gives the estimated altitude correction factors ranging from 0.93 to 1.16 (Fig. 2 inset (C)). We include a 5% systematic uncertainty in this correction factor.

Analytical uncertainties associated with the AMS measurements vary from 6.9% to 8.0% in our samples. These 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. The ^{10}Be/^{9}Be ratios were measured relative to the NIST certified ratio of ^{10}Be to ^{9}Be ($26.8 \pm 1.4 \times 10^{-12}$). Most production rate estimates are based on other standards, which are lower by 14% relative to the NIST one (Middleton et al., 1993). We corrected the production rates for that difference.

4. Results

We expect the nine boulder surface histories to be similar due to sample proximity, and surface exposure ages should accordingly be similar. Taking into account only the measurement uncertainties, the ^{10}Be ages range from 10.9±0.8 to 13.5±1.0 ka (Fig. 2) with a weighted-mean standard deviation of 7.4%, which is what is expected on the basis of our analytical uncertainties (6.9–8.0%). This suggests that the random uncertainties are dominated by the analytical uncertainties rather than the geological ones. In the absence of obvious geological uncertainties, except those possible ones linked to erosion, we calculate an error-weighted mean age of the nine exposure ages of 12.4±0.7 ^{10}Be ka, including the estimated 5% systematic uncertainty introduced by the site specific uplift correction.

5. Discussion and conclusion

Tschudi et al. (2000) calculated a mean moraine age of 11.6±0.5 ^{10}Be ka from four samples, accounting for a 5 mm/kyr erosion factor. Within errors, this surface exposure age agrees with our moraine age (12.4±0.7 ^{10}Be ka). However, because of differing laboratory protocols adopted to derive exposure ages (i.e. ^{10}Be standard, choice of the production rate, the scaling method, assumed erosion rate), and to incorporate

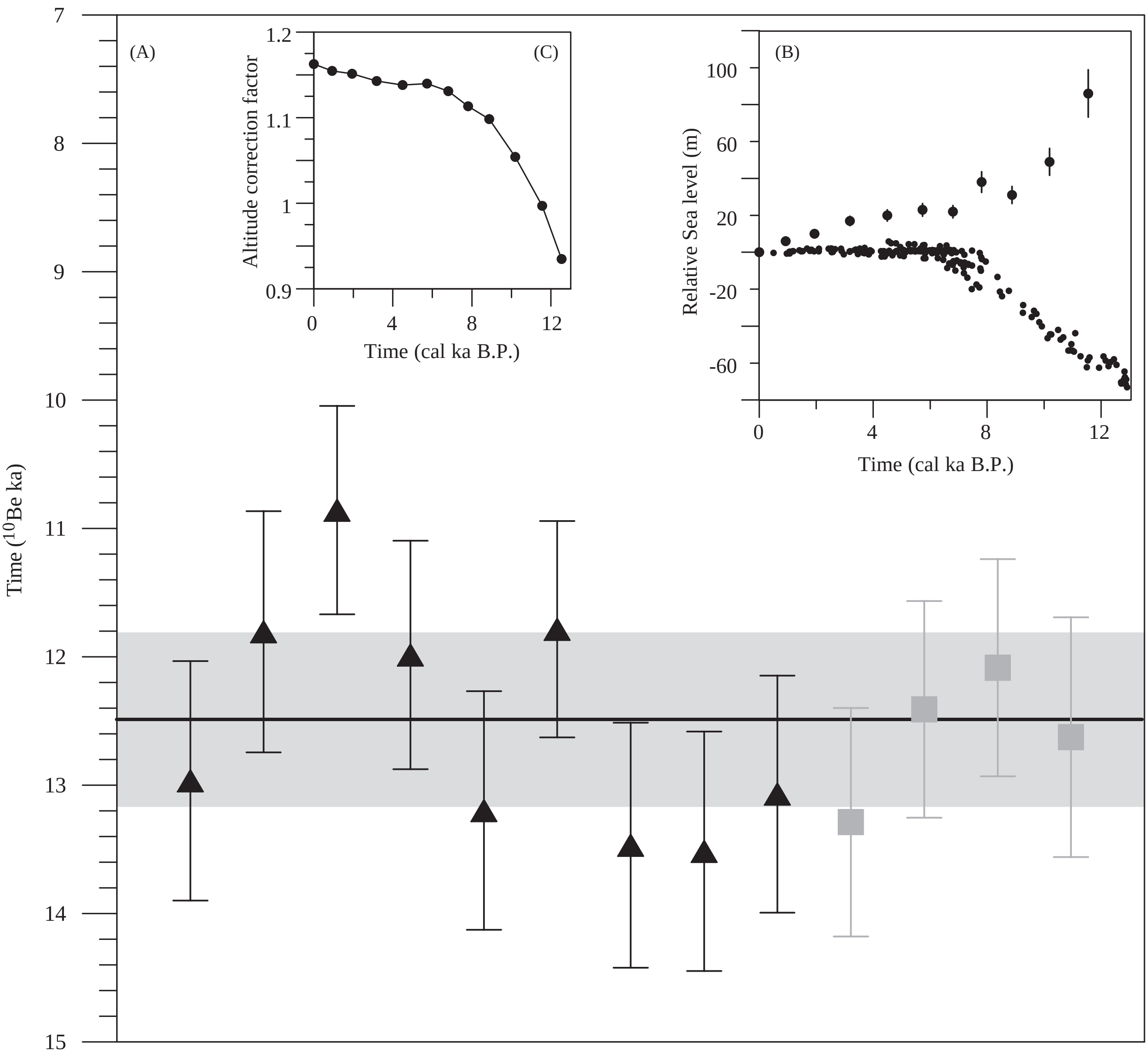

Fig. 2. (A) Exposure ages for boulders from the Ss I moraine in southwestern Finland. Black triangles are exposure ages for the boulders from the Hyvinkää plateau (this study), gray squares are exposure age for boulders from the Vesala plateau (Tschudi et al., 2000). Error bars are 1σ as define in the text. The black horizontal line is the error-weighted mean of the exposure ages with the shaded band delimiting 1σ uncertainty, including that of the uplift estimate. Samples are displayed with increasing eastern longitude, (B) Relative sea level history for southwestern Finland. The upper curve relates to the uplift relative to the modern sea level (Donner, 1968). The lower curve is the sea rise relative to the modern sea level (Bard et al., 1990, 1996; Fleming et al., 1998), (C) Estimation of the altitude correction factor calculated from the records in (B) and using the correction factors based on air pressure as described by Stone (2000).

uncertainties (for example, Tschudi et al. do not distinguish between random and systematic uncertainties) direct comparisons of results from different laboratories requires some standardization of data (Tuniz et al., 1998). Accordingly, we have recalculated the four exposure ages determined by Tschudi et al. (2000) following the same calculations as described in the above methodology section (assuming no erosion and taking the boulders uplift history into account) to derive an error-weighted mean age of 12.6 ± 0.9 ^{10}Be ka. As the four boulders were also sampled on the Vesala plateau 40 km from our sample site, and thus essentially on the same exact moraine surface, we add the Tschudi et al. (2000) results to our data to calculate an error-weighted mean moraine age of 12.5 ± 0.7 ^{10}Be ka ($n = 13$).

The varve chronology established by Saarnisto and Saarinen (2001) places the beginning of Ss I formation at 12.3 varve ka. According to Sauramo's (1929) varve counting, moraine formation occurred over 217 years, indicating that the ice lobe would have retreated from its marginal position around 12.1 varve ka. This is in good agreement with our result of 12.5 ± 0.7 ^{10}Be ka for the age of abandonment of the Ss I moraine. Indeed, the excellent agreement between the varve age and our raw ^{10}Be age could be taken as an indication of the validity of both ages, and thus support the assumptions used in making our exposure age calculation, including the production rate estimate. However, one cannot also exclude the possibility of compensating errors.

Counting annual ice layers places the onset of the YD Stadial at 12.9 ± 0.2 ka in the GISP 2 ice core (Alley et al., 1993), and 12.7 ± 0.1 ka in the GRIP ice core (Johnsen et al., 1992). Rainio (1995) suggested that the SIS retreated at least 80 km north of what is now Ss I before it readvanced. Assuming that the readvance of the SIS occurred in response to YD cooling, these relations suggest that the southern margin of the SIS advanced ~80 km in less than 700 years, indicating a rate of advance of ~110 m/yr (Ehlers, 1990).

Both our new ^{10}Be ages and the varve chronology suggest that the southern SIS margin subsequently began to retreat to the Ss II Moraine during the YD, which ended at 11.5 ± 0.2 ka (Alley et al., 1993). If a climatic response, this may indicate a switch to negative mass balance through a moisture control. Alternatively, this retreat may indicate a dynamic response associated with drawdown of ice through the Gulf of Bothnia.

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