NEW ^{10}BE COSMOGENIC AGES FROM THE VIMMERBY MORAINE CONFIRM THE TIMING OF SCANDINAVIAN ICE SHEET DEGLACIATION IN SOUTHERN SWEDEN

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ABSTRACT. The overall pattern of deglaciation of the southern part of the Scandinavian Ice Sheet has been considered established, although details of the chronology and ice sheet dynamics are less well known. Even less is known for the south Swedish Upland because the area was deglaciated mostly by stagnation. Within this area lies the conspicuous Vimmerby moraine, for which we have used the terrestrial cosmogenic nuclide (^{10}Be) exposure dating technique to derive the exposure age of six glacially transported boulders. The six ^{10}Be cosmogenic ages are internally consistent, ranging from 14.9 ± 1.5 to 12.4 ± 1.3 ka with a mean of 13.6 ± 0.9 ka. Adjusting for the effects of surface erosion, snow burial and glacio-isostatic rebound causes the mean age to increase only by *c.* 6% to *c.* 14.4 ± 0.9 ka. The ^{10}Be derived age for the Vimmerby moraine is in agreement with previous estimates for the timing of deglaciation based on radiocarbon dating and varve chronology. This result shows promise for further terrestrial cosmogenic nuclide exposure studies in southern Sweden.

Key words: terrestrial cosmogenic nuclide (^{10}Be) exposure dating, deglaciation, Scandinavian Ice Sheet, Vimmerby moraine, Sweden, south Swedish Upland

Introduction

Accurate reconstructions of past ice sheets are needed to better understand their contributions to changes in climate, sea level, and solid Earth geophysics. Ice sheet models play a central role in this effort but are too frequently poorly constrained by field data, especially for the interior areas of former ice sheets. The deglaciation pattern of the Scandinavian Ice Sheet is generally well reconstructed, but the absolute timing and the dynamics of the retreating ice margin are less well known (Lundqvist and Wohlfarth 2001). Several recent studies have shown that the Late Weichselian glacial and deglacial history may be more complicated than generally believed. For example, the western margin of the ice sheet was very dynamic with multiple ice-free periods during the last 40 ka including around the **Last Glacial Maximum (LGM)** (Olsen *et al*. 2001a,b, 2002); large moraine systems from the southeast portion of the ice sheet may be younger than previous estimates (Rinterknecht *et al*. 2006); there were possibly ice-free conditions around the LGM in southern Sweden (Alexanderson and Murray 2007) and southern Norway (Bøe *et al*. 2007); and tree mega-fossils dated from high elevation areas in central Sweden suggest ice-free conditions as early as 17 ka cal. ka BP (Kullman 2002).

In southern Sweden, the deglaciation history is best known in the coastal areas where the Late Weichselian ice margin actively retreated and can be traced by conspicuous moraines (west coast) or by patterns of varved clay deposition (east coast). Above the highest Late Weichselian coastline is the south Swedish Upland, an area with a poor deglacial chronology. The correlation between the west and east coasts, across the south Swedish Upland, is problematic due to a lack of continuous geological and geomorphological evidence and because the chronologies are based on different techniques.

The Vimmerby moraine (Agrell *et al*. 1976), is

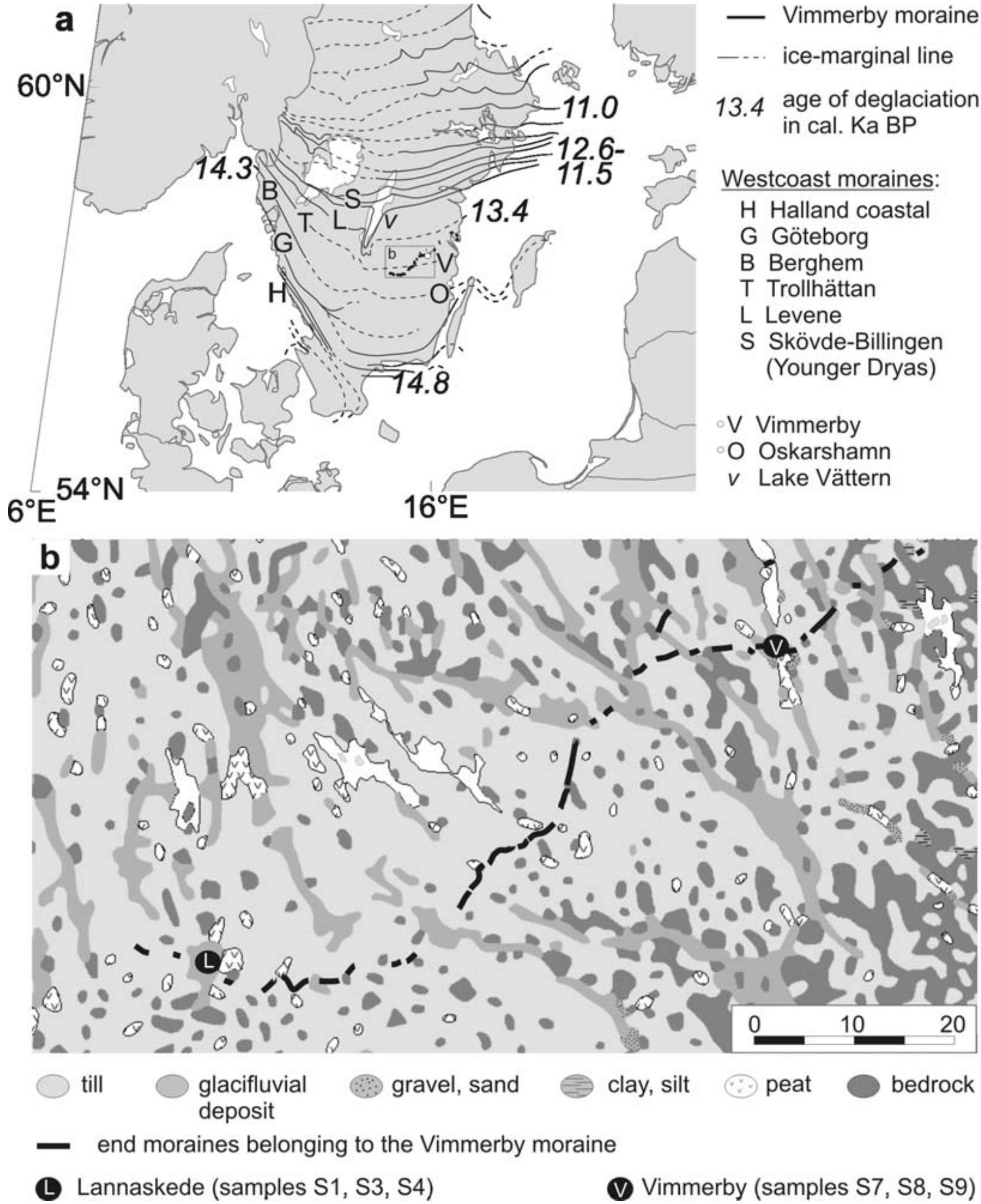

Fig. 1. (A) Location of the Vimmerby moraine on the south Swedish Upland and in relation to the standard deglaciation model of Sweden (Lundqvist 2002). Note that the moraine strikes across assumed ice-marginal lines and thus indicates a slightly different deglaciation pattern. (B) Geological map of the study area, emphasizing the end moraines of the Vimmerby moraine. Samples are from two sites, indicated by black circles. Adapted from the National Quaternary geological database (Geological Survey of Sweden, Permission 30–1730/2006)

a discontinuous ice-marginal zone, at least 100-km-long, lying in the eastern part of the upland (Fig. 1); it is a distinctive feature since ice-marginal features reflecting active ice are very scarce in this part of the upland. New mapping of the moraine shows that it strikes across the tentative ice-marginal lines (isochrones) of the standard deglaciation model, and this indicates that the deglaciation pattern emerging from this new mapping is different from the deglaciation pattern previously assumed (Lundqvist and Wohlfarth 2001; Lundqvist 2002). Thus, dating of this feature would efficiently fill a gap in our knowledge of the deglacial history in the south Swedish Upland and would be useful to compare to other deglaciation chronologies from the region.

We have used and present results of one of the first applications of the terrestrial cosmogenic nuclide (^{10}Be) exposure dating technique in southern Sweden with the aim of improving our understanding of the chronological history of the decay of the Scandinavian Ice Sheet, and for comparison to radiocarbon and varve chronology.

Study area and previous research

The south Swedish Upland (57–58°N, 13–16°E) is the highest area in southernmost Sweden and is situated 200–300 m above present sea level (Fig. 1). The crystalline bedrock forms an undulating landscape with isolated inselbergs, valleys and deep-weathered bedrock. The study area in the eastern part of the upland (Fig. 1a) is situated above the Late Weichselian highest shoreline and the surface cover is dominated by till (cover moraine, drumlins, hummocky moraine), glaciofluvial deposits (valley fills, deltas) and peat (Fig. 1b). The common occurrence of hummocky moraine in parts of the south Swedish Upland indicates widespread stagnation (dead ice) instead of active retreat (e.g. Björck and Möller 1987); stagnation discourages the formation of end moraines. The Vimmerby moraine (Agrell *et al*. 1976; Lindén 1984; Malmberg Persson 2001; Persson 2001; Malmberg Persson *et al*. 2007) is thus an exception in the area. It consists of small end moraines and partly till-covered ice-marginal glaciofluvial deposits, and separates an ice-proximal landscape with thicker till cover from one with thin and discontinuous till. Distally, sandurs fill the river valleys down to the highest coastline (115–130 m a.s.l.; Malmberg Persson *et al*. 2007).

The Vimmerby moraine is believed to reflect a still-stand and/or readvance in the general ice-margin retreat during the last deglaciation (e.g. Malmberg Persson 2001). According to the most current accepted deglaciation model for southern Sweden, which uses a combination of calibrated radiocarbon ages, partly radiocarbon-dated clay-varve chronology, and geomorphology (Lundqvist and Wohlfarth 2001), this still-stand and/or readvance happened between 14.0 and 13.3 cal. ka BP, roughly corresponding to Greenland Interstadial 1 (Björck *et al*. 1998). A maximum age for deglaciation in the study area is provided by a well dated site 200 km south, where AMS radiocarbon dating of leaf fragments and twigs gives ages for early vegetation establishment and a minimum age of deglaciation there around 15.1–14.4 cal. ka BP (Davies *et al*. 2004). A minimum deglaciation age for the study area, *c*. 10.0 cal. ka BP (Lindén 1999; calibrated by us using OxCal v4.0.5 and IntCal04 atmospheric curve; Ramsey 2007; Reimer *et al*. 2004), is given by a radiocarbon date of early organic sedimentation in a kettle hole within the moraine.

Methodology

Sampling

The accumulation of *in situ* produced terrestrial cosmogenic ^{10}Be in quartz exposed to cosmic radiation provides a means of determining the amount of time the rock has been at or near the ground surface (Lal 1991; Gosse and Phillips 2001). This technique has proven useful in numerous studies of deglacial histories and landform preservation (e.g. Balco *et al*. 2002; Clark *et al*. 2003; Fabel *et al*. 2002; Licciardi *et al*. 2001; Phillips *et al*. 1997; Rinterknecht *et al*. 2006). Unlike the radiocarbon dating technique that gives the age of events following deglaciation (e.g. migration and establishment of vegetation followed by deposition and preservation of plant remains in a basin), the ^{10}Be-dating technique can give a direct age of deglaciation.

In this study, we collected quartz-rich samples from glacially transported granitic and quartzitic boulders on features belonging to the Vimmerby moraine: an end moraine at Vimmerby and a partly till-covered marginal delta at Lannaskede (Figs 1b, 2; Table 1). To minimize the risk of processes modifying the exposure history of the boulder, such as cosmogenic nuclide inheritance (e.g. Briner *et al*. 2001), boulder exhumation, erosion or moraine deformation (Hallet and Putkonen 1994; Putkonen and Swanson 2003; Zreda *et al*. 1994), we sampled

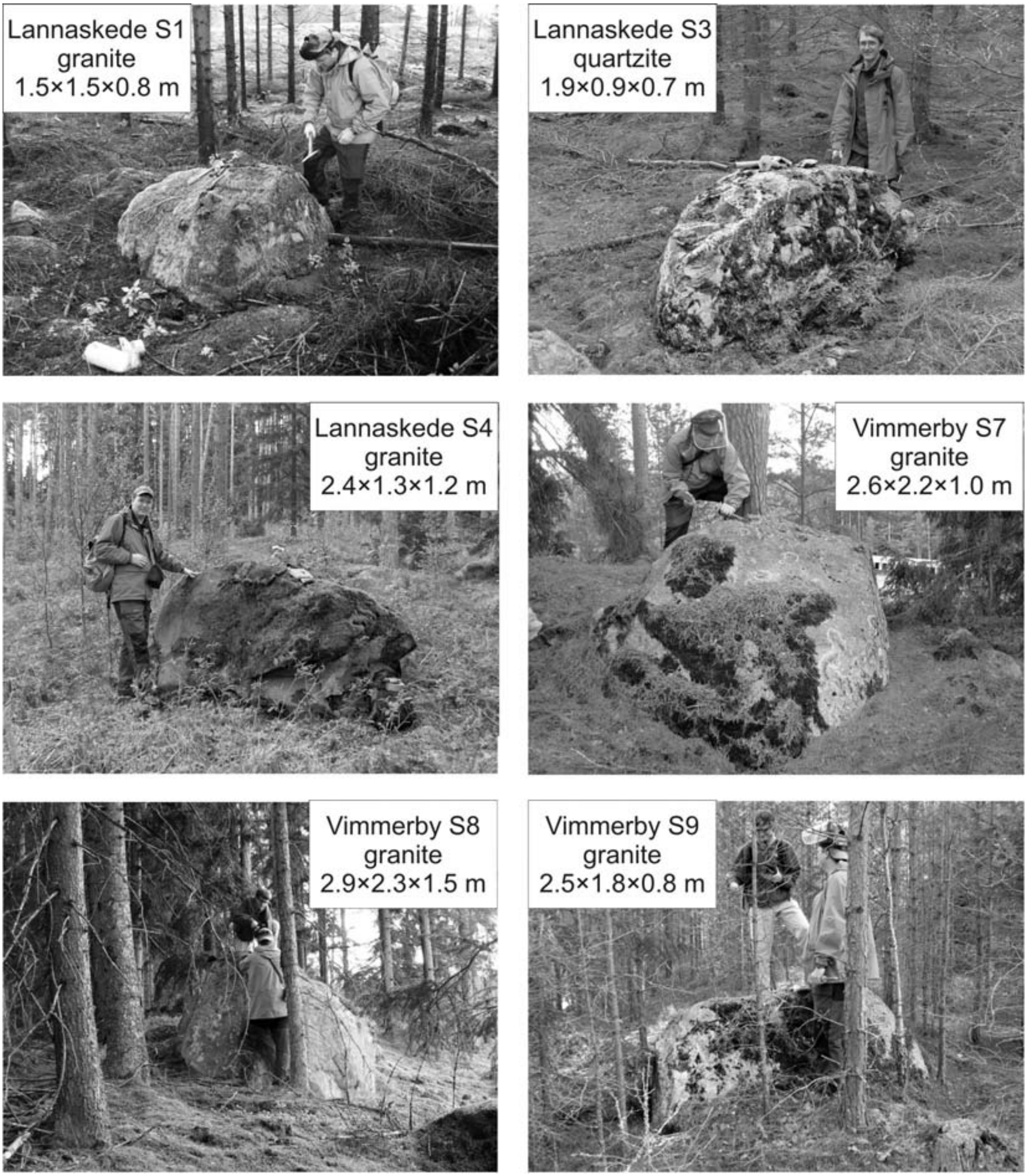

Fig. 2. Sampled boulders at the till-covered ice-marginal delta at Lannaskede and at an end moraine close to Vimmerby. Both sites are part of the Vimmerby moraine

the tops of large (0.9–2.3 m b-axis) rounded to subrounded, weathering-resistant (granitic and quartzitic) boulders. Boulders were resting on top of stable and level surfaces or on the broad crest of the moraine. In total six boulders were processed in the Glasgow University–SUERC cosmogenic nuclide laboratory.

Measurements and calculations

All samples were processed for ^{10}Be from quartz following procedures based on methods modified from Kohl and Nishiizumi (1992) and Child *et al.* (2000). Approximately 20 g of pure quartz was separated from each sample, purified, spiked with *c.* 0.25 mg ^{9}Be carrier, dissolved, separated by ion

Table 1. Summary of terrestrial cosmogenic nuclide (^{10}Be) exposure data.

Sample	Lab ID	Altitude (m a.s.l.)	Lat. (°N)	Long. (°E)	Shielding factor	Thickness* correction	[^{10}Be]† (10^4 atom/g)	Exposure age[e] (kyr)‡
S1	b1722	208	57.3947	14.9039	1.0000	0.975	7.61 ± 0.43	12.4 ± 1.3 (0.7)
S3	b1723	211	57.3866	14.8983	0.9809	0.975	8.98 ± 0.47	14.9 ± 1.5 (0.8)
S4	b2474	217	57.3808	14.8787	0.9731	0.967	8.00 ± 0.41	13.4 ± 1.3 (0.7)
S7	b1727	145	57.6695	15.8057	1.0000	0.975	7.62 ± 0.40	13.3 ± 1.3 (0.7)
S8	b1434	136	57.6700	15.8064	0.9761	0.975	7.99 ± 0.42	14.4 ± 1.4 (0.7)
S9	b1808	140	57.6688	15.8031	1.0000	0.967	7.51 ± 0.58	13.2 ± 1.5 (1.0)

[a] Calculated using a rock density of 2.7 g/cm^3 and an effective attenuation length for production by neutron spallation of 160 g/cm^2.
[b] Measured at SUERC-AMS relative to NIST SRM with a nominal value of ^{10}Be/^{9}Be = 3.06 x 10^{-11} (Middleton *et al*. 1993). Uncertainties propagated at ±1σ level including all known sources of analytical error.
[c] Exposure ages calculated using the CRONUS-Earth ^{10}Be-^{26}Al exposure age calculator version 2 (http://hess.ess.washington.edu) assuming no prior exposure and no erosion during exposure. The quoted values are for the 'Lm' scaling scheme which includes palaeomagnetic corrections (Balco *et al*. 2008). Uncertainties are ±1σ (68% confidence) including ^{10}Be measurement uncertainties and a ^{10}Be production rate uncertainty of 9%, to allow comparison with ages obtained with other methods. Values in parentheses are uncertainties based on measurement errors alone, for sample-to-sample comparisons.

chromatography, selectively precipitated as hydroxides, and oxidized. AMS measurements were carried out at the SUERC AMS Facility. Measured ^{10}Be/^{9}Be ratios were corrected by full chemistry procedural blanks with ^{10}Be/^{9}Be of <3 × 10^{-15}. Independent measurements of AMS samples were combined as weighted means with the larger of the total statistical error or mean standard error. We calculated the analytical uncertainty by assuming that the uncertainties in AMS measurement and Be carrier are normal and independent, adding them in quadrate in the usual fashion (e.g. Bevington and Robinson, 1992). The resulting analytical uncertainties range from 5 to 8% (Table 1). All ^{10}Be concentrations were converted to exposure ages by using a production rate linked to a calibration data set using a ^{10}Be half-life of 1.5 Ma.

Measured ^{10}Be concentrations were converted to surface exposure ages using the CRONUS-Earth ^{10}Be–^{26}Al exposure age calculator version 2 (http://hess.ess.washington.edu), assuming no prior exposure and no erosion during exposure. The results for the different ^{10}Be production rate scaling schemes used by the online calculator yielded ages that vary by less than 2%. The quoted surface exposure ages (Table 1) are for the 'Lm' scaling scheme which includes palaeomagnetic corrections (Balco *et al*. 2008).

Physical factors influencing ^{10}Be ages

Various physical factors can affect the accuracy of the exposure age calculations such as: (1) moraine degradation (Putkonen and Swanson, 2003); (2) variation in the initial conditions of the population of boulders delivered to the site, for example, cosmogenic nuclide inheritance (e.g. Briner *et al*. 2001); (3) the weathering and erosion of the rock surface during exposure that removes *in situ* produced terrestrial cosmogenic nuclides from the sampled surface; (4) the partial shielding of the rock surface from cosmic rays by seasonal snow cover; (5) the partial shielding of the rock surface from cosmic rays by vegetation or by burial under water; or (6) the changing elevation of the rock surface due to glacio-isostatic movement (Gosse and Phillips 2001). Apart from inheritance, all these factors cause ^{10}Be ages to appear too young and without adjusting for them ^{10}Be ages will be minimum ages. On the other hand, if inheritance is dominating, ^{10}Be ages will give maximum ages.

Glacio-isostatic rebound changes the elevation of the sample site during exposure, which in the case of uplift will cause air pressure to decrease over time. This means that the cosmic ray flux will vary through time. Usually this can be corrected for by using a nearby relative sea-level curve and integrating the changes in ^{10}Be production related to relative sea-level changes over time. However, the nearest sea-level curves are from the east coast of Sweden where before 9.5 ka cal. ka BP water levels were influenced by the isolated Baltic Ice Lake and Ancylus Lake. As air pressure changes were likely more influenced by changes in sea level than local lake levels, the portion of the water level curve prior to 9.5 ka cal. ka BP does not accurately reflect the changes in air pressure. Fortunately, detailed modelling of shoreline displacements in south-central

Sweden and the evolution of the Baltic Sea since the LGM has been completed (Lambeck *et al.* 1998). As part of this work water-level curves were produced showing both the inclusion and exclusion of ice and land damming. In other words, the water-level curve that excludes the effect of damming is effectively the sea-level curve that should represent changes in air pressure. Therefore we used the nearest modelled water level curve from Oskarshamn, *c.* 55 km south of Vimmerby. The highest coastline using the Oskarshamn water-level curve is 130 m and is similar to the highest coastline for the Vimmerby moraine at 115–130 m (Malmberg Persson *et al.* 2007). Since the highest coastline elevations are similar between these two sites we did not apply a scaling factor.

Results and discussion

Glacially transported boulder ^{10}Be ages

The six apparent exposure ages range from 14.9 ± 1.5 to 12.4 ± 1.3 ka with a mean of 13.6 ± 0.9 ka (with uncertainty at 1σ standard deviation of the ages; Table 1).

Boulder exhumation and cosmogenic nuclide inheritance do not appear to be significant issues since our ages were consistent for boulders from stable and level surfaces and from the broad crest of the moraine. There were also no indications in the field of significant erosion or weathering of the boulder surfaces. If we assume a reasonable boulder-surface constant erosion rate of 1 mm/ka, the mean apparent exposure age increases by *c.* 1% (Table 1). A medium density (0.3 g/cm^3) snow cover of 0.3 m thickness on top of the boulders for four months a year would similarly increase the mean exposure age by only 1% (Wastenson 1995; Gosse and Phillips 2001). The effect of shielding by the burial from water is not considered as both sites are above the Late Weichselian highest coastline and above any local lakes. Also, the shielding effect from vegetation is less than 1% and so is not considered (Plug *et al.* 2007).

The integrated production rate from isostatic rebound accounts for a *c.* 4% increase in the exposure age within the study area. Another factor that affects air pressure, in addition to elevation changes, is the presence of the nearby ice sheet (Staiger *et al.* 2007); however, since the southern margin of the Scandinavian ice sheet retreated rapidly this effect is unlikely to have persisted for long enough to affect the calculated exposure ages. Altogether, these effects give an adjusted mean exposure age for the six boulder samples of *c.* 14.4 ± 0.9 ka (an increase of *c.* 6% from the unadjusted exposure age).

Comparisons with other data from the area

The mean apparent cosmogenic exposure age of the six boulders of 13.6 ± 0.9 ka is within the previously estimated deglaciation age range for the area of 14.0–13.3 cal. ka BP (Lundqvist and Wohlfarth 2001 and references therein) and within uncertainties to the ^{10}Be age adjusted for the effects of erosion, snow and glacio-isostatic rebound of 14.4 ± 0.9 ka. Thus, given the similarity between the results of the different approaches used (radiocarbon dating, varve chronology, and now ^{10}Be dating), we are confident that the deglacial age for the Vimmerby moraine is *c.* 14 ka and possibly slightly older if we consider the adjusted mean ^{10}Be age. This result also demonstrates that the ^{10}Be dating approach works well in this area for boulders from moraines and till surfaces, and may be a useful technique for other areas in southern Sweden. It is not yet understood why optically stimulated luminescence ages of glaciofluvial sediments associated with the Vimmerby moraine are many thousands of years older (Alexanderson and Murray 2007, submitted).

Confident correlation of the Vimmerby moraine to moraines in the west half of southern Sweden remains problematic because (1) there is not a large difference in the ages of moraines as the overall rate of deglaciation was relatively fast compared to the resolution of the dating methods, and (2) at Lake Vättern located in central southern Sweden, ice-marginal positions for different time periods were in similar positions (Lundqvist and Wohlfarth 2001). Thus, the Vimmerby moraine may correlate with the Trollhättan moraine, or with the Berghem or Levene moraines (Fig. 1a; Lundqvist and Wohlfarth 2001). Tracing the ice margin east of the Vimmerby moraine is more complicated because (1) ice positions within the Baltic Sea basin are not well known, and (2) the rate of deglaciation in the southeast portion of the ice sheet (northern Poland and the Baltic states) was also relatively fast compared to the resolution of the dating methods (Rinterknecht *et al.* 2006).

Conclusion

^{10}Be ages for the Vimmerby ice-marginal zone of 13.6 ± 0.8 (14.4 ± 0.9 adjusted) ka are in agreement with previous estimates for the timing of deglaciation based on radiocarbon dating and varve chronology. Thus, the southern margin of the Scandinavian Ice Sheet was at the Vimmerby moraine *c.* 14 ka ago. It is not clear which of the moraines west of the study area correlate with the Vimmerby moraine, and even less clear for moraines from the southeast portion of the ice sheet (northern Poland and the Baltic states). Nevertheless, the internal consistency of the six ^{10}Be ages and their compatibility with previous radiocarbon ages and varve chronology indicate that the terrestrial cosmogenic nuclide (^{10}Be) dating technique works well for erratic boulders within this area. This result shows promise for further terrestrial cosmogenic nuclide exposure studies in southern Sweden. Future research efforts should focus on more detailed mapping of the various moraine systems in southern Sweden, and employ an integrated dating approach (e.g. radiocarbon dating of the first establishment of vegetation, ^{10}Be dating of erratic boulders, and optically stimulated luminescence dating of glaciofluvial and other sediments).

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Late Quaternary ice sheet history and dynamics in central and southern Scandinavia

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Part of the key to predicting the future behaviour of the Earth is linked to our understanding of how ice sheets have operated in the past. Recent work suggests an emerging new paradigm for the Scandinavian ice sheet (SIS); one of a dynamically fluctuating ice sheet. This doctoral research project explicitly examines the history and dynamics of the SIS at four sites within Sweden and Norway, and provides results covering different time periods of glacial history. Two relatively new dating techniques are used to constrain the ice sheet history.

Dating of sub-till sediments in central Sweden and central Norway indicate ice-free conditions during times when it was previously inferred the sites were occupied by the SIS. Consistent exposure ages of boulders from the Vimmerby moraine in southern Sweden indicate that the southern margin of the SIS was at the Vimmerby moraine ~14 kyr ago. In central Sweden, consistent exposure ages for boulders at high elevation agree with previous estimates for the timing of deglaciation around 10 ka ago, and indicate rapid thinning of the SIS during deglaciation.

Altogether this research conducted in different areas, covering different time periods, and using comparative geochronological methods demonstrates that the SIS was highly dynamic and sensitive to environmental change.

I was born and raised on Vancouver Island on the west coast of Canada surrounded by beautiful mountains and coastline, where I developed a deep curiosity and passion for understanding the workings of nature. I completed a Bachelor of Science degree with distinction in Geography 1998 at the University of Victoria, Canada. Then I completed a Masters of Science degree in Geography 2004 at Simon Fraser University, Canada, for which I was awarded the Canadian Association of Geographers Starkey-Robinson Award 2005. I began a PhD in 2004 in Stockholm, Sweden investigating the dynamics of the Scandinavian ice sheet, and eating brown cheese with waffles under the midnight sun.

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