High-elevation cosmogenic nuclide dating of the last deglaciation in the central Swedish mountains: implications for the timing of tree establishment

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Abstract

We use cosmogenic exposure ages to determine the timing of deglaciation of the Scandinavian ice sheet (SIS) at summit elevation in the central Swedish mountains. Mean exposure ages for boulders on the summit of Mt. Åreskutan (10.6 ±0.6 ka, n = 3, 1420 m a.s.l.) and from the highest-elevation moraine related to SIS deglaciation in Sweden (12.0 ±0.6 ka, n = 3, 1135 m a.s.l.) are consistent with previous lower-elevation radiocarbon age estimates for the timing of deglaciation. Summit areas in this region deglaciated ~12.0-10.6 ka, coinciding approximately with the termination of the Younger Dryas cold interval (11.7 ka). Unusually old radiocarbon ages of tree remains previously studied from the summit-area of Mt. Åreskutan are rejected on the basis of incompatibility with consistent TCN ages for deglaciation, and incompatibility with established paleoecological and paleoglaciological reconstructions. Analysis of the new exposure ages against radiocarbon ages from lower elevation indicates that the SIS decayed rapidly during final deglaciation.

Keywords: cosmogenic exposure dating, radiocarbon dating, moraine, deglaciation, nunatak

Introduction

Tree remains of three species, *Betula pubescens*, *Picea abies*, and *Pinus sylvestris*, have been found at high-elevation alpine sites in central Sweden that are 400-500 m above the modern tree-line. Moreover, these remains are as old as 16.7 ±0.2 cal. ka BP (Kullman 2000, 2001, 2002a), at times when it is commonly perceived that the sites were covered by the Scandinavian ice sheet (SIS; Kleman et al. 1997, Lundqvist 2002). Widespread low-elevation radiocarbon evidence indicates, instead, that deglaciation in the area occurred around 10.3 to 10.0 cal. ka BP (De Geer 1940, Borell and Offerberg 1955, Lambeck et al. 1998, Lundqvist 1969, 2002). The incongruent dates of the tree remains, therefore, potentially have tremendous implications for our understanding of the dynamics of the SIS, the pattern and rate of migration of tree species, the location and role of refugia in re-establishing plants, paleoclimatic conditions, and nunatak microclimate variability. Although the reliability of age constraints is central in obtaining accurate paleoglaciological or paleoecological reconstructions (Birks et al. 2005, 2006, Kullman 2005, 2006) there has been no attempt to directly assess these conflicting radiocarbon data against an independent dating technique. Thus, the objective of our study was to determine independently the timing of deglaciation and to discuss their implications for the potential of tree establishment at high elevation in central Sweden and for the vertical rate of deglaciation. We evaluate the radiocarbon ages of the wood remains against new results from terrestrial cosmogenic nuclide (TCN) exposure dating of glacial erratics at high elevation and discuss their divergence in terms of paleoecological and paleoglaciological implications.

Study area

The study area in the county of Jämtland, central Sweden, includes mountainous areas of moderate relief (~800 m) and adjacent low-relief (~100 m) rolling hill landscape with numerous lakes and peatlands (Fig. 1). Mountains are generally concentrated in the southern half of the study area except

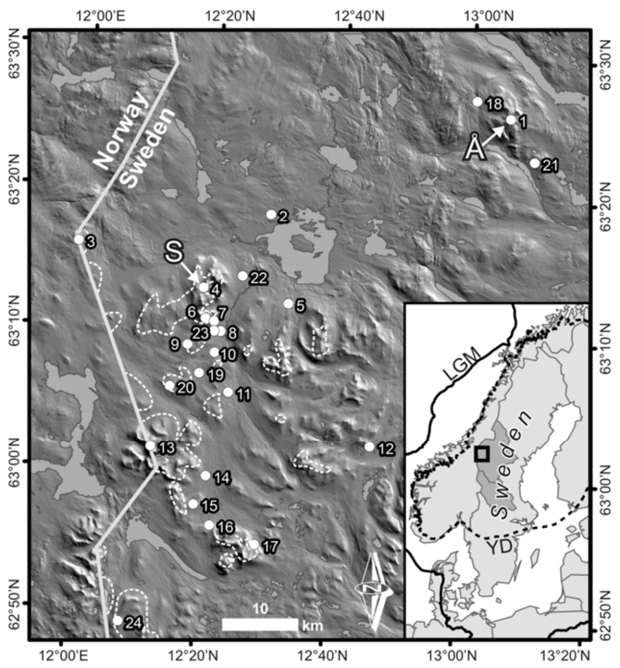

Fig. 1: Regional map of the study area in the county of Jämtland showing location of radiocarbon dates relevant to deglaciation (cf. numbering system in Table 1); radiocarbon dates from the county of Dalarna (Table 1), approximately 80 km south of the study area, are not shown. TCN sample sites for Snasahögarna SIS moraine area at “S” (see Fig. 3) and for Mt. Åreskutan summit erratics at “Å” (arrow). Dashed curves are early ice-free areas in Sweden (Borgström 1989); note Mt. Åreskutan deglaciated later. Ice movement during the late glacial maximum was towards the west (Lundqvist 1969). Inset map shows location of study area just east of the Swedish-Norwegian border in central Sweden, the counties of Jämtland and Dalarna (dark grey), and the LGM and Younger Dryas ice margins (compiled from various sources by Olsen et al. 2001).

for Mt. Åreskutan which occurs largely isolated in the northeast (Å in Fig. 1). The modern tree-line is at about 950-1050 m above sea level (a.s.l.) in this area.

The study area deglaciated 10.3 to 10.0 cal. ka BP (De Geer 1940, Borell and Offerberg 1955, Sveian 1997, Lambeck et al. 1998, Lundqvist 2002). Above the Late Glacial highest coastline and within the study area, studies on moderate elevation lake sediments estimate deglaciation 10.4 ±0.1 cal. ka BP (Bergman et al. 2005). Thus, there is general agreement for the timing of deglaciation between these studies. However, some of the high elevation tree remains are considerably older (Kullman 2002a, 2004b, Kullman and Kjällgren 2006). While traditionally evidence has been interpreted in terms of a thick ice sheet in the study area at that time (e.g., Lundqvist 1969, 2002, Denton and Hughes 1981, Kleman et al., 1997), there remains a possibility that the ice sheet was relatively thin during the Late Glacial (Lambeck et al. 1998) leading to early deglaciation of high elevation areas.

Previous studies have shown the SIS to be more dynamic than previously believed during the Middle and Late Weichselian (Arnold et al. 2002, Olsen et al. 2002, Kjær et al. 2006, Helmens et al. 2007a,b, Ukkonen et al. 2007, Lunkka et al. 2008; Salonen et al. 2008, Alexanderson et al. 2010) including deglaciation of inland portions of neighbouring Norway during the global last glacial maximum (LGM) (Johnsen et al. submitted). The tree mega-fossils (stems, cones and roots) of *Betula pubescens*, *Picea abies*, and *Pinus sylvestris* dated on Mt. Åreskutan are anomalous in age, oldest at 16.7 ±0.2, 13.0 ±0.1, and 13.6 ±0.1 cal. ka BP, respectively (Kullman 2002a, Table 1), and imply that high elevation areas around Mt Åreskutan deglaciated thousands of years before adjacent valleys. Altogether Kullman (2002a, 2005) dated sixteen well-preserved specimens found on the ground surface in the forefield of a receding 'perennial' snow-patch at 1360 m a.s.l. which is only 60 m below the summit and 400-500 m above the modern tree-limits. The surrounding landscape on the summit of Mt Åreskutan is dominated by exposed and glacially sculpted bedrock. Numerous ponds exist that are sometimes bordered by shallow peat or mineral rich soils. Overall the impression is that this mountain-top location is hostile for tree growth even within the modern climate. Within the counties of Jämtland and Dalarna only four other unusually old tree remains have been found (Table 1, Fig. 1, see inset map). Thus, the geographical distribution of unusually old tree remains is especially concentrated to the summit area of Mt. Åreskutan.

Methods

The TCN exposure dating technique can allow determination of the amount of time that a rock surface has been exposed to cosmic radiation (e.g., how long ago an ice sheet deposited an erratic boulder). Cosmic radiation causes the accumulation of ^{10}Be *in situ* within quartz rock and the measurement of the concentration of ^{10}Be against the production rate of ^{10}Be for a given site of known latitude, elevation, topographic shielding,

Table 1: Summary of radiocarbon dates related to deglaciation in the county of Jämtland plus dates of mega-fossil wood from the county of Dalarna. Listed in order of county, sample type, elevation, and age. Continued on next page.

Location *(by county and type)*	No. in Fig. 1	Analyzed material	Latitude north	Longitude east	Elevevation (m asl)	^{14}C yr BP (1σ error)	Calibrated age[a] (1σ mid-point)	Sample number	Reference
Jämtland province - mega-fossil wood									
Mt. Lillsylen	13	*Betula pubescens,* wood	63.027	12.201	1495	8030 ±60	8900 ±100	Beta-122313	Kullman 2004a
Mt. Lillsylen	13	*Betula pubescens,* wood	63.027	12.201	1495	8150 ±60	9100 ±100	Beta-172310	Kullman 2004a
Mt. Lillsylen	13	*Betula pubescens,* wood	63.027	12.201	1495	8430 ±70	9500 ±100	Beta-172312	Kullman 2004a
Mt. Lillsylen	13	*Betula pubescens,* wood	63.027	12.201	1495	8710 ±60	9600 ±100	Beta-172311	Kullman 2004a
Mt. Åreskutan	1	*Picea,* cone	63.433	13.100	1360	8640 ±60	9600 ±100	Beta-160729	Kullman 2002a
Mt. Åreskutan	1	*Betula pubescens,* stem	63.433	13.100	1360	8850 ±70	10000 ±200	Beta-152673	Kullman 2002a
Mt. Åreskutan	1	*Pinus,* stem	63.433	13.100	1360	9700 ±90	11000 ±200	Beta-121829	Kullman 2002a
Mt. Åreskutan	1	*Betula pubescens,* root	63.433	13.100	1360	10200 ±90	11900 ±200	Beta-121828	Kullman 2002a
Mt. Åreskutan	1	*Picea,* stem	63.433	13.100	1360	10250 ±90	12000 ±200	Beta-121830	Kullman 2002a
Mt. Åreskutan	1	*Betula pubescens* , stem	63.433	13.100	1360	10380 ±60	12300 ±100	Beta-152671	Kullman 2002a
Mt. Åreskutan	1	*Pinus,* stem	63.433	13.100	1360	10700 ±60	12800 ±100	Beta-133673	Kullman 2002a
Mt. Åreskutan	1	*Picea,* stem	63.433	13.100	1360	11020 ±90	13000 ±100	Beta-121826	Kullman 2002a
Mt. Åreskutan	1	*Pinus,* stem[c]	63.433	13.100	1360	11440 ±100	13300 ±100	Beta-121827[b]	Kullman 2005
Mt. Åreskutan	1	*Pinus,* stem[c]	63.433	13.100	1360	11720 ±90	13600 ±100	Beta-120799[b]	Kullman 2002a
Mt. Åreskutan	1	*Betula pubescens,* stem	63.433	13.100	1360	12870 ±70	15200 ±100	Beta-158301	Kullman 2002a
Mt. Åreskutan	1	*Betula pubescens,* stem	63.433	13.100	1360	14020 ±80	16700 ±200	Beta-133672	Kullman 2002a
Mt. Getryggen	6	*Pinus,* wood	63.181	12.326	1250	9310 ±70	10500 ±100	Beta-184490	Kullman and Kjällgren 2006
Mt. Lillsnasen	4	*Pinus,* stem	63.217	12.317	1180	9840 ±90	11300 ±100	Beta-127895	Kullman and Kjällgren 2000
Mt. Helagfjället	17	*Pinus,* wood	62.917	12.483	1150	11160 ±80	13000 ±100	Beta-127894	Kullman and Kjällgren 2000
Mt. Stor-Ulvåfjället	9	*Pinus,* stem	63.150	12.283	1030	8420 ±80	9400 ±100	Beta-108782	Kullman and Kjällgren 2000
Mt. Getryggen	7	*Betula pubescens,* wood	63.178	12.349	1000	8680 ±100	9700 ±200	St-12980	Kullman 1995
Kloppanåstugan	24	*Pinus,* wood	62.819	12.142	990	8160 ±190	9100 ±300	St-1033	Lundqvist 1969
Hammaren	15	*Pinus,* wood	62.961	12.320	940	8550 ±120	9600 ±100	St-1028	Lundqvist 1969
Hammaren	14	*Pinus,* wood	62.995	12.348	925	8385 ±105	9400 ±100	St-1099	Lundqvist 1969
Vålåstugan	12	*Pinus,* wood	63.039	12.769	880	8030 ±90	8900 ±200	St-1064	Lundqvist 1969
Hammaren	16	*Pinus,* wood	62.937	12.364	870	8150 ±50	9100 ±100	St-6280	Lundqvist 1969
Mt. Enkälen	11	*Pinus,* wood	63.096	12.395	855	9050 ±100	10200 ±200	St-12729	Kullman 1995
Mt. Lillulvåfjället	10	*Pinus,* wood	63.142	12.354	835	8190 ±120	9200 ±200	Beta-57608	Kullman 1995
O Bunnerån	5	*Pinus,* wood	63.203	12.540	810	8295 ±110	9300 ±100	St-1579	Lundqvist 1969
Mt. Getryggen	8	*Alnus,* wood, bark	63.167	12.367	740	8100 ±50	9100 ±100	Beta-106348	Kullman 1998
Mt. Getryggen	8	*Pinus,* wood	63.167	12.367	740	8220 ±70	9200 ±100	Beta-91497	Kullman 1998
Mt. Getryggen	8	*Corylus,* nut	63.167	12.367	740	8270 ±50	9300 ±100	Beta-108756	Kullman 1998
Mt. Getryggen	8	*Betula,* wood	63.167	12.367	740	8270 ±50	9300 ±100	Beta-106347	Kullman 1998
Mt. Getryggen	8	*Corylus,* nut	63.167	12.367	740	8300 ±50	9300 ±100	Beta-108756	Kullman 1998
Mt. Getryggen	8	*Alnus,* cone	63.167	12.367	740	8330 ±50	9400 ±100	Beta-108554	Kullman 1998
Mt. Getryggen	7	*Pinus,* wood	63.178	12.349	720	8460 ±120	9400 ±100	Beta-57645	Kullman 1995
Storkluken	3	*Pinus,* wood	63.265	11.984	700	8600 ±30	9500 ±30	St-819	Lundqvist 1969
Klocka Bog	2	*Pinus,* wood	63.308	12.483	526	8390 ±100	9400 ±100	LuA-5134	Bergman et al. 2004

Table 1: (continued).

Location (*by county and type*)	No. in Fig. 1	Analyzed material	Latitude north	Longitude east	Elevevation (m asl)	^{14}C yr BP (1σ error)	Calibrated age[a] (1σ mid-point)	Sample number	Reference
Jämtland province - lake sediment									
Lake Stentjärn	20	*Salix,* bud scales	63.100	12.242	987	9165 ±120	10400 ±100	LuA-5477	Bergman et al. 2005
Lake Stentjärn	20	*Empetrum* , seeds and leaf parts	63.100	12.242	987	9250 ±50	10400 ±100	Poz-2750	Bergman et al. 2005
Lake Spåime	19	*Salix,* fruits, scales, leaves and twigs	63.117	12.317	887	9315 ±160	10500 ±200	Ua-16388	Hammarlund et al. 2004
Lake Ullsjön	18	*Dryas octopetala,* seeds and leaf parts	63.452	13.010	734	9225 ±75	10400 ±100	LuS-6447	this study
Jämtland province - peat									
Storulvån	23	bulk peat	63.167	12.350	750	8835 ±115	9900 ±200	Ua-14621	Segerström and von Stedingk 2003
Storulvån	23	bulk peat	63.167	12.350	750	8930 ±145	10000 ±200	Ua-14920	Segerström and von Stedingk 2003
Mt. Getryggen	8	*Quercus,* leaf	63.167	12.367	740	8030 ±50	8900 ±100	Beta-108752	Kullman 1998
Mt. Getryggen	8	*Alnus,* leaf	63.167	12.367	740	8060 ±50	8900 ±100	Beta-108753	Kullman 1998
Mt. Getryggen	8	*Ulmus,* leaf	63.167	12.367	740	8510 ±60	9500 ±60	Beta-108758	Kullman 1998
Årebjörnen	21	moss and *Ericaceae* leaves	63.383	13.167	700	8750 ±65	9800 ±100	Ua-21758	Ek 2004
Storsnasen I	22	bulk peat	63.233	12.417	680	8530 ±95	9500 ±100	Ua-13310	Segerström and von Stedingk 2003
Storsnasen II	22	bulk peat	63.233	12.417	680	8855 ±105	10000 ±200	Ua-13315	Segerström and von Stedingk 2003
Klocka Bog	2	Moss stems and leaves	63.308	12.483	526	8055 ±95	8900 ±200	LuA-5135	Bergman et al. 2004
Dalarna province - mega-fossil wood									
Mt. Storvätteshågna		*Pinus,* wood	62.117	12.450	1180	8500 ±60	9500 ±60	Beta-172317	Kullman 2004b
Mt. Storvätteshågna		*Pinus,* wood	62.117	12.450	1180	9070 ±70	10300 ±100	Beta-172305	Kullman 2004b
Mt. Storvätteshågna		*Pinus,* wood	62.117	12.450	1180	9230 ±50	10400 ±100	Beta-178795	Kullman 2004b
Mt. Nipfjället		*Pinus,* wood	61.983	12.850	1160	8050 ±70	8900 ±100	Beta-169410	Kullman 2004b
Mt. Städjan		*Pinus,* wood	61.917	12.883	1100	10500 ±60	12500 ±100	Beta-158305	Kullman 2004b
Mt. Städjan		*Pinus,* wood	61.917	12.883	1100	10500 ±60	12500 ±100	Beta-158305	Kullman 2004b
Mt. Storvätteshågna		*Pinus,* wood	62.117	12.450	1070	8380 ±50	9400 ±100	Beta-158314	Kullman 2004b
Mt. Städjan		*Pinus,* wood	61.917	12.883	1055	7890 ±60	8800 ±200	Beta-178797	Kullman 2004b
Mt. Storvätteshågna		*Pinus,* wood	62.117	12.450	1035	8050 ±70	8900 ±100	Beta-169411	Kullman 2004b
Mt. Städjan		*Pinus,* wood	61.917	12.883	1035	8190 ±60	9100 ±100	Beta-178794	Kullman 2004b
Mt. Storvätteshågna		*Pinus,* wood	62.117	12.450	940	8040 ±60	8900 ±100	Beta-172316	Kullman 2004b
Mt. Storvätteshågna		*Pinus,* wood	62.117	12.450	940	8040 ±60	8900 ±100	Beta-172316	Kullman 2004b
Mt. Barfredhågna		*Larix,* twig and cone	62.067	12.417	915	8160 ±70	9100 ±100	Beta-178796	Kullman 2004b
Mt. Storvätteshågna		*Betula,* wood	62.117	12.450	915	8360 ±60	9400 ±100	Beta-178799	Kullman 2004b
Mt. Storvätteshågna		*Quercus,* nutshell	62.117	12.450	910	8560 ±40	9500 ±40	Beta-158310	Kullman 2004b
Mt. Storvätteshågna		*Corylus,* acorn	62.117	12.450	910	8670 ±40	9600 ±100	Beta-158309	Kullman 2004b
Mt. Barfredhågna		*Picea,* large cone	62.067	12.417	850	8490 ±70	9500 ±70	Beta-108767	Kullman 2001

[a] Calibrated age is the midpoint of the 1σ calibrated age range with the uncertainty as half this range. Calibrated using OxCal 4.0 and the IntCal 04 calibration curve (Reimer et al. 2004).

[b] Samples Beta-120799 and Beta-121827 from Mt. Åreskutan are from the same piece of wood with the first from the younger part of the trunk while the second was from its center.

and sample thickness, provides determination of the exposure age (Lal 1991, Gosse and Phillips 2001). This technique has proven useful in numerous studies of deglacial histories and landform preservation (e.g., Phillips et al. 1997, Licciardi et al. 2001, Balco et al. 2002, Fabel et al. 2002, in review, Stroeven et al., 2002, Clark et al. 2003, Rinterknecht et al. 2006). Unlike the radiocarbon dating technique that dates events following deglaciation, TCN exposure dating can yield the direct age of deglaciation.

The data presented in this paper are part of a large TCN dating campaign for central Sweden. In this paper we present data from erratic boulders from the mountains Åreskutan and Snasahögarna (Å and S in Fig. 1). These data are most relevant to addressing the high elevation radiocarbon ages and for assessing the vertical rate of deglaciation in central Sweden. We collected quartz rich samples from glacially transported boulders from the summit of Mt. Åreskutan (at 1415-1420 m a.s.l.) and from a newly discovered moraine on Mt. Snasahögarna (1125-1149 m a.s.l.), which, incidentally, is the highest elevation moraine related to the SIS discovered so far in Sweden (Heyman 2004, Heyman and Hättestrand 2006). The Snasahögarna SIS moraine stretches to an elevation of 1190 m a.s.l. To minimize the risk of having ages biased by processes such as cosmogenic nuclide inheritance (e.g., Briner et al. 2001), boulder exhumation, surface erosion or moraine degradation (Hallet and Putkonen 1994, Zreda et al. 1994, Putkonen and Swanson 2003), we sampled the tops of large (>1.0 m b-axis), weathering-resistant (granitic and quartzitic) boulders, and in sets of three. Boulder surfaces and adjacent ground were carefully inspected for indications of the amount of differential erosion of erosion. The height of quartz nodules and veins above adjacent softer rock within each boulder were used to estimate the amount of surface erosion. In total six boulder samples 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

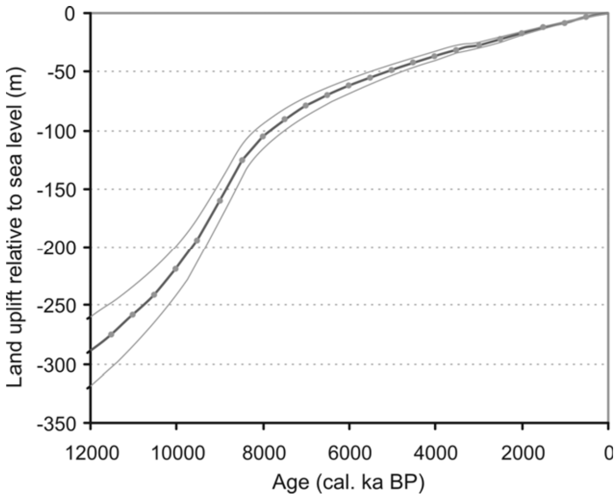

Fig. 2: Land uplift curve of study area adjusted for relative sea level changes. Ten percent confidence interval shown. See text for explanation.

c. 0.25 mg ^{9}Be carrier, dissolved, separated by ion chromatography, selectively precipitated as hydroxides, and oxidized. Accelerated Mass Spectrometry (AMS) measurements were completed at the SUERC AMS Facility. Measured $^{10}Be/^{9}Be$ ratios were corrected by full chemistry procedural blanks with $^{10}Be/^{9}Be$ of $<3 \times 10^{-15}$. 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 quadrature in the usual fashion (e.g., Bevington and Robinson 1992). The resulting analytical uncertainties range from 3 to 6% (Table 2). 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.

Using the CRONUS-Earth exposure age calculator version 2.2 (http://hess.ess.washington.edu), measured ^{10}Be concentrations were converted to surface exposure ages, assuming no prior exposure and no erosion since deposition. The results for the different ^{10}Be production rate scaling schemes used by the online calculator yielded ages that vary by about 5% for each sample. The surface exposure ages were calculated using the ‘Lm’ scaling scheme which includes paleomagnetic corrections (Balco et al. 2008; Table 2).

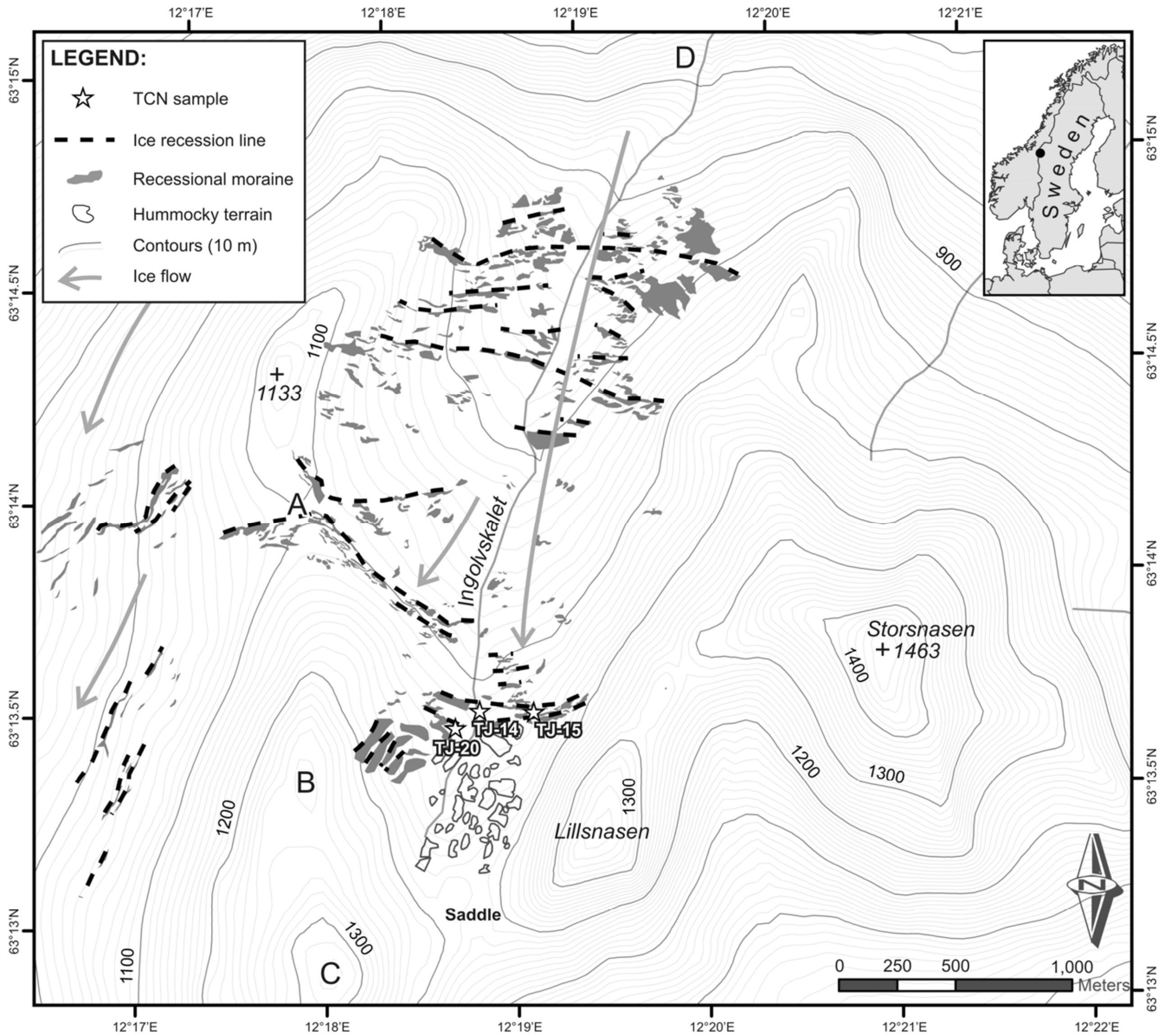

Fig. 3: Map of recessional ice sheet moraines and TCN sample locations in the Snasahögarna area (cf. Fig. 1, location 22). Inferred ice flow direction is also shown. Letters refer to same locations in Fig. 4.

^{10}Be age adjustments

The accuracy of the exposure age calculations can be affected by various physical factors: (1) moraine degradation (Putkonen and Swanson 2003), (2) cosmogenic nuclide inheritance (e.g., Briner et al. 2001), (3) the weathering and erosion of the rock surface during exposure, (4) the partial shielding of the rock surface from cosmic rays by topography, seasonal snow cover, and vegetation, or (5) 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.

During the exposure history of a site, the air pressure will change due to the combined affect of glacio-isostatic rebound and eustatic change; these factors cause changes in the local air pressure over time that in turn alters the cosmogenic nuclide production rate and apparent exposure age. Thus, we estimated the land uplift corrected for sea level changes and used this information to adjust the apparent TCN exposure age for each site (cf. Stone 2000, Johnsen et al. 2009). The employed land uplift curve was generated for the study area by interpolating between shoreline displacement curves located to the west and east (using Dahl and Nesje 1996, and shoreline displacement curves of

Fig. 4: Photograph looking south up into the west side of the Ingolvskalet valley - see Fig. 3. Snow-free moraine crests are indicated by black arrows. White letters correspond to lettered locations in Fig. 3.

Lidén 1938, Mörner 1980, Kjemperud 1981, and Sveian and Olsen 1984) for ages less than 9 cal. ka BP, and referring to regional glacio-isostatic modelling results of Lambeck et al. (1998) for ages from 9 to 12 ka (Fig. 2).

Results

Winter fieldwork helped reveal a system of moraines that were produced during decay of the SIS within a broad u-shaped valley, named Ingolvskalet, that cuts into the west shoulder of Mt. Snasahögarna (Fig. 1, location 22, and Fig. 3). Using aerial photographs coupled with field observations, and GIS, detailed mapping of these moraines was completed (Fig. 3, 4, and 5). The geographical pattern of the moraines, including the location of the highest moraines at only 1 km from a saddle, indicate that they were produced from the decay of the SIS rather than from a retreating local alpine glacier (Fig. 1); as concluded by Lundqvist (1969, 1973) and for similar moraines east of the Mt. Snasahögarna (Borgström 1979). Three boulders from the crest of the highest moraine gave consistent ages (10.1 ±0.6 ka, n = 3; Table 2, Fig. 3). The three ages overlap within 1σ when considering the measurement errors alone.

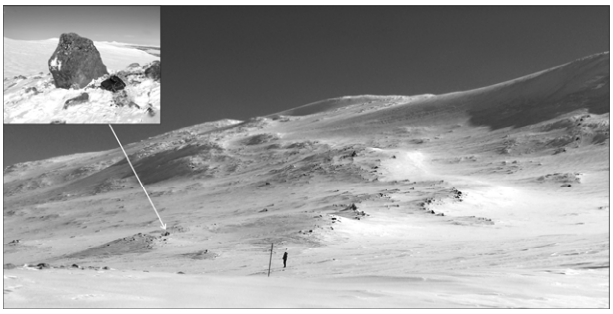

Fig. 5: Photograph of moraine extending up the eastern, snow-covered slope of upper-Ingolvskalet valley. This is the highest elevation moraine related to the Scandinavian Ice Sheet yet identified in Sweden (1190 m a.s.l.). Note person for scale. Inset photograph shows sample TJ-15 and arrow indicates location in photograph.

Erratic boulders from the summit of Mt. Åreskutan also produced exposure ages that are consistent with each other (9.0 ±0.5 ka, n = 3; Table 2, Fig. 1, location 1, Fig. 6). The three ages overlap within 1σ when considering the measurement errors alone. Close inspection of the boulder surfaces and adjacent ground surface indicated little signs of erosion. Boulders were either sitting on bare bedrock or shallow (<20 cm) minerogenic soils likely of weathered till origin. Close examination of the lithologies and angularity of clasts on the ground surface against each sampled boulder revealed that spallation was not an important process. Measurement of the height of quartz veins and nodules against softer parent rock divided by the TCN exposure age indicates a reasonable weathering rate of about 1 mm ka^{-1}. Such an erosion rate would

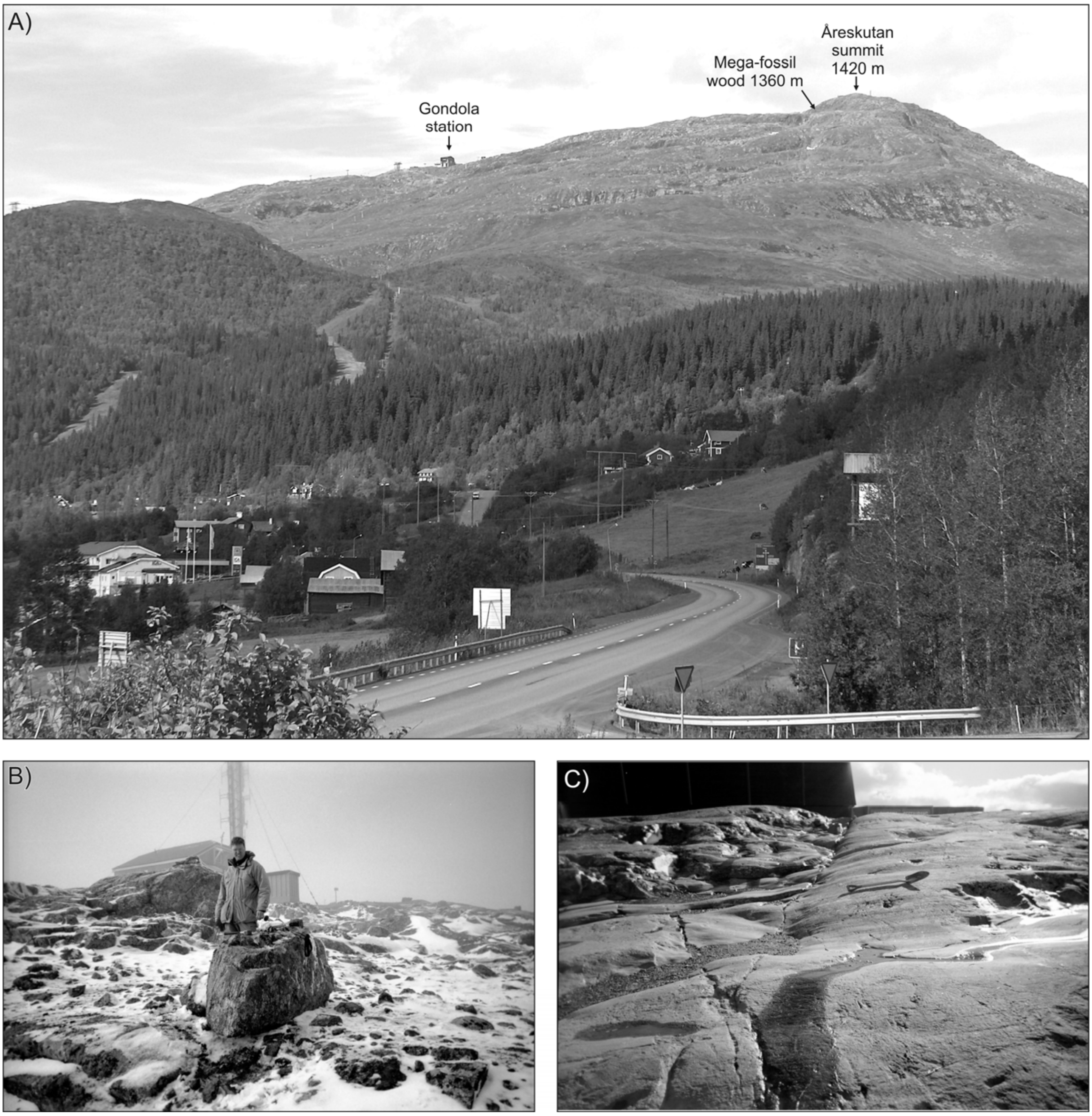

Fig. 6: Photographs of Mt. Åreskutan; located at point 1 in Fig. 1. (A) Overview photograph taken from valley at 400 m a.s.l. to northwest indicating the location of the mega-fossil tree remains at 60 m below the summit and 400-500 m above modern tree-line (Kullman 2002a), and the location of the three TCN samples at the summit. (B) TCN sample TJ-1 from boulder partially resting on bedrock east of communications tower. (C) Example of glacially-moulded bedrock next to gondola station that was also found up to the summit; indicating warm-based ice sheet conditions.

produce less than a 1% age increase and so is ignored in our calculations. For interest, a large 3 mm ka^{-1} erosion rate would increase ages less than only 2.5% (~275-305 years). Similar observations to Mt. Åreskutan were made at and adjacent to each boulder on the Snasahögarna moraine, indicating that an erosion rate of 1 mm ka^{-1} is also reasonable here.

Further adjustments to the apparent TCN exposure ages must be made when considering the effect of land uplift and snow shielding during the exposure history of the boulders. By considering the land uplift history of the sites (Fig. 2), the TCN ages increase by 4.7% and 6.4% for Mt. Åreskutan and the Snasahögarna moraine, respectively. The difference in these adjustments is caused by their differences in apparent age and elevation. Recalcu-

Table 2: Terrestrial cosmogenic nuclide (^{10}Be) exposure data for central Sweden boulders (county of Jämtland) from the summit of Mt. Åreskutan and the Snasahögarna SIS moraine.

Lab ID	Elevation (m asl)	Lat (°N)	Long (°E)	Sample lithology	Shielding factor	Thickness[a] correction	[^{10}Be][b] (10^4 atom/g)	Exposure age[c] (kyr)	Adjusted age[d] (kyr)
Mt. Åreskutan summit erratics									
TJ-1	1415	63.431	13.095	granite	0.999	0.960	16.30 ±0.74	9.2 ±0.9 (0.4)	10.8 ±1.0
TJ-2	1414	63.431	13.094	quartz band	1.000	0.976	16.15 ±1.05	8.9 ±1.0 (0.6)	10.5 ±1.1
TJ-3	1420	63.431	13.094	quartzite	1.000	0.960	15.96 ±0.77	8.9 ±0.9 (0.4)	10.5 ±1.0
Mt. Snasahögarna SIS moraine									
TJ-14	1125	63.225	12.309	quartz band	0.999	0.976	14.41 ±0.50	10.1 ±0.9 (0.3)	12.1 ±1.1
TJ-15	1149	63.225	12.314	quartz band	1.000	0.976	14.80 ±0.50	10.2 ±0.9 (0.3)	12.2 ±1.1
TJ-20	1130	63.225	12.307	quartz band	0.998	0.976	14.26 ±0.43	10.0 ±0.9 (0.3)	11.9 ±1.1

[a] Calculated using a rock density of 2.65 g/cm^3, an effective attenuation length for production by neutron spallation of 160 g/cm^2, and erosion rate of 1 mm/kyr.

[b] Measured at SUERC-AMS relative to NIST SRM with a nominal value of $^{10}Be/^{9}Be = 3.06 \times 10^{-11}$ (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 2.2 (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.

[d] Adjusting for the effects of snow cover (~12% for both sites) and crustal rebound (6.4% for Snasahögarna, and 4.7% for Mt. Åreskutan). See text for explanation.

lating the TCN ages using conservative 10% bounds on the land uplift curve (Fig. 2) results in adjustments that vary by only 0.6%. Thus the accuracy of the land uplift curve insignificantly affects the calculated age.

Based on precipitation data from the region (Sweden Meteorological and Hydrological Institute), field observation, and local knowledge, we estimate the snow thickness over the tops of boulders to be 3 m and persist for four months each year. This snow thickness and of medium density of 0.2 g cm^{-3} (cf. Lundberg et al. 2006) causes a 12% increase in the TCN ages (Gosse and Phillips 2001). Note that doubling this thickness to 6 m per four months a year less than doubles the increase in the TCN ages to 22%. Thus, when adjusting for the combined affects of land uplift and snow burial, the apparent mean TCN exposure age for Mt. Åreskutan increases by 17.6% to 10.6 ±0.6 ka, and for the Snasahögarna moraine increases by 19.4% to 12.0 ±0.6 ka.

Discussion

TCN ages

The three consistent TCN exposure ages of erratic boulders from the summit of Mt. Åreskutan indicate that the mountain top deglaciated about 10.6 ±0.6 ka when erosion rates, glacio-isostatic rebound, and snow shielding effects are taken into consideration (Table 2). Exhumation processes that could cause ages to appear younger than their true age are disregarded because the erratic boulders were resting on bedrock or shallow soils. If nuclide inheritance was an important process then the ages would appear older than their true depositional age; which would be unreasonable to expect as at least the valley bottoms deglaciated around the same time or slightly later (Sveian 1997, Lundqvist 2002). Thus, the TCN exposure ages from the summit of Mt. Åreskutan are considered reliable.

We collected a lake core from Lake Ullsjön (5 km northwest of Mt. Åreskutan, at 734 m a.s.l.; Table 1, Fig 1, location 18). Within the first organics deposited above glacial clay we found and dated *Dryas octopetala* seeds and leaf parts to 10.4 ±0.1 cal. ka BP. This species is commonly associated with the tundra paleoenvironment following deglaciation in Scandinavia (e.g., Bergman et al. 2005). Thus, this date is considered a reliable estimate of the timing of local deglaciation and is in good agreement with other palaeoecological evidence in the area (e.g., Bergman et al. 2005) and TCN adjusted exposure ages.

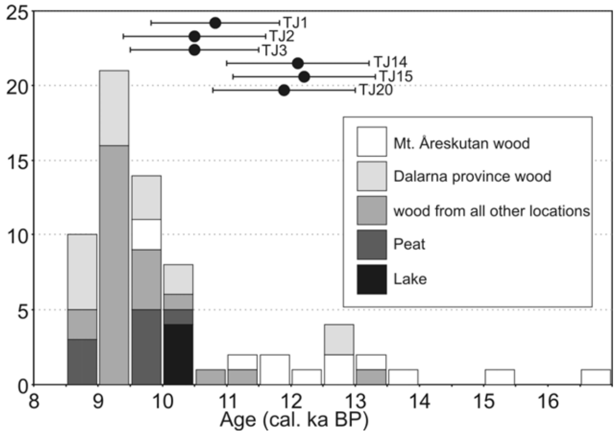

Fig. 7: Count versus age (cal. ka BP) of calibrated radiocarbon dates related to deglaciation in the counties of Jämtland and Dalarna (See Table 1). The graph shows the contribution of each type of date to the total per given 500 year interval. Date types are: mega-fossil wood from Dalarna, mega-fossil wood from Mt. Åreskutan, all other mega-fossil wood from Jämtland, lake sediment, and peat. Also shown are TCN datings from Mt. Åreskutan and Snasahögarna SIS moraine; error bars are 1σ.

The TCN adjusted exposure ages from the Snasahögarna moraine are older than those from Mt. Åreskutan (adjusted mean age of 12.0 ±0.6 ka, n = 3; Table 2). This age difference probably reflects a geographical pattern of deglaciation whereby the SIS margin was at the Snasahögarna moraine at 1150 m a.s.l., while Mt. Åreskutan, 280 m higher but also 35 km east (up-ice) from Mt. Snasahögarna, still remained ice-covered. This is consistent with detailed ice margin reconstructions for deglaciation of the area (cf. Borgström 1989, maps A and D). In addition, differences in average snow thickness over the Holocene may have been important between the sites in which case we may have underestimated it at Mt. Åreskutan or overestimated it at Snasahögarna. For example, we would have to more than double the snow thickness from our current estimate at Mt. Åreskutan to adjust the ages to be close to the ages at Snasahögarna. Because all boulders from the Snasahögarna moraine were from the crest, this minimized the chance that exhumation may have been an important process that could cause TCN ages to appear too young. Nevertheless, the TCN ages from the Snasahögarna moraine and Mt. Åreskutan are quite similar as they overlap within one sigma of each other (Table 2).

Radiocarbon ages and comparison to TCN ages

Figure 7 and Table 1 show a summary of radiocarbon dates related to deglaciation in county of Jämtland plus dates of mega-fossil wood from the southern neighbouring county of Dalarna. The majority of the dates fall within the 8.5 to 10.5 cal. ka BP range, while most of the older dates are from Mt. Åreskutan (Fig. 7). Ideally, we might expect the TCN and radiocarbon samples to date the start of ecological succession, whereby the TCN ages represent immediate deglaciation and a barren landscape, and where pioneering species (from lake cores) would perhaps be 200 years younger (Bergman et al. 2005), followed by tree and peat species. Agreeing with this succession, dates from lake cores of pioneering flora representing a tundra paleoenvironment are consistent at 10.4 to 10.5 cal. ka BP (n = 4) which overlap within uncertainty with the TCN ages from Mt. Åreskutan (see Table 2), although central values are slightly younger. Peat dates are in turn slightly younger than the dates from lake sediment. Thus, the pattern of the histogram of radiocarbon dates from the region reflects the stages of ecological succession with the exception of some old dates from tree remains, principally from Mt. Åreskutan.

A summary of ages that relate to deglaciation and from a range of elevations from the study area can provide a general picture of the vertical rate of deglaciation (i.e., a vertical deglaciation curve). Using radiocarbon ages alone would indicate that high elevation areas deglaciated considerably earlier than lower elevation areas as indicated by deglaciation curve 1 in Figure 8. Note that the portion of the curve older than 11 ka is the minimum-age deglaciation curve since it is based only on tree remains. When plotting the TCN ages from high elevation against the radiocarbon ages, there is a clear conflict for those ages from Mt. Åreskutan (Fig. 8). How is it that the three ages for glacial erratics on the mountain summit (adjusted mean age of 10.6 ±0.6 ka) are so much younger than radiocarbon ages nearby on the same mountain? The following three hypotheses attempt to accommodate both the old radiocarbon ages from high elevation and the TCN ages, however, all three hypotheses are ultimately rejected.

Hypothesis 1: *Erosion and/or snow burial led to much younger apparent ages than the true deposi-*

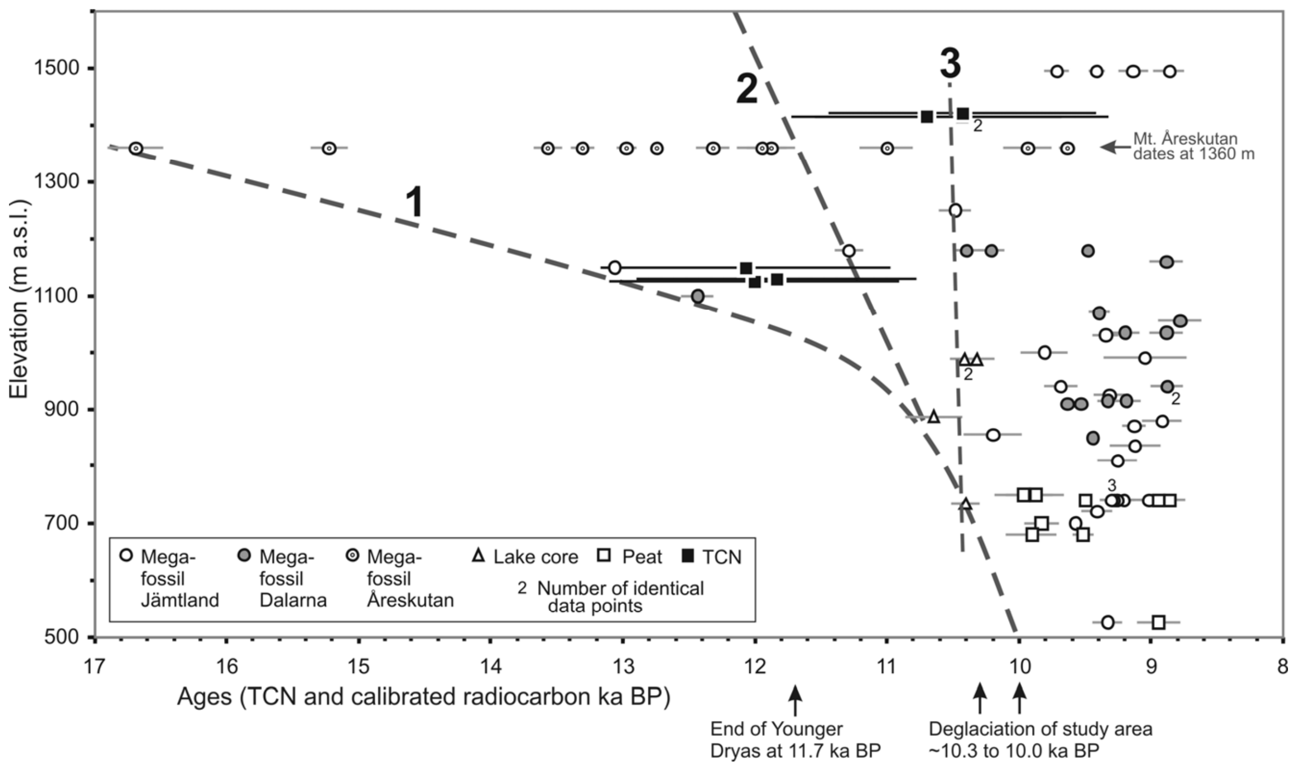

Fig. 8: Vertical deglaciation curves (elevation versus age) for the study area using radiocarbon dates related to deglaciation of megafossil wood from the counties of Jämtland (including Mt. Åreskutan) and Dalarna, dates from lake sediment and peat, and TCN adjusted exposure ages. Error bars are 1σ. Curve 1 is based on the acceptance of high-elevation radiocarbon ages, principally from Mt. Åreskutan. Curve 2 is based on TCN ages and rejection of old radiocarbon ages from high elevation (~0.5 m $year^{-1}$). However, as the value for ice sheet thinning of 0.5 m $year^{-1}$ is derived from data over a large area, it is averaging estimates over space and time; and local vertical rates of deglaciation can therefore be higher. Curve 3 is the approximate local deglaciation curve for the Mt. Åreskutan area, using central datapoints on TCN adjusted exposure ages and radiocarbon dates (data points 6, 18, 19, and 20; Fig. 1, Table 1), providing a local vertical rate of deglaciation of ~5 m $year^{-1}$. Also shown are the end of the Younger Dryas cold interval at 11.7 ka BP, and the deglaciation of the east and west edges of the study area at ~10.3 and 10.0 cal. ka BP, respectively. Note that the small numbers indicate the number of identical or near-identical data points.

tional age of the erratics. If this hypothesis is true, the exposure age of the erratics should be at least as old as the oldest tree megafossils on Mt. Åreskutan, ~17 cal. ka BP. When considering erosion only, an unrealistic erosion rate of 50 mm ka^{-1} would be needed make 17 ka erratic boulders on Mt. Åreskutan have an apparent exposure age of 10.6 ka. This extremely high rate of erosion would mean 85 cm of rock loss from the top surface of each sampled boulder. Furthermore, if the boulders experienced a high amount of erosion it is highly unlikely that this amount would be similar for all three boulders to get similar ages. As described above, careful inspection of boulder surfaces and adjacent material indicated that erosion rates were low (Fig. 6). Similarly, as snow has a low density and poorly shields cosmic rays, unrealistic snow thicknesses, in excess of 10 m for a third of a year (Gosse and Phillips 2001), would be required to cause 17 ka boulders to be perceived as 10.6 ka. Therefore hypothesis 1 is rejected.

Hypothesis 2: *There was a small glacier or dead-ice remnant on the mountain summit shielding the glacier erratics while trees were growing nearby.* Ice flow indicators (striae, and moulded and plucked bedrock) at and surrounding the summit of Mt. Åreskutan indicate only westward paleo-ice flow despite variations in topography (ground slope and aspect). The summit area is also covered in glacial erratics. If the summit area was host to an alpine glacier, there would be ice flow indicators that would reflect a thin glacier with flow that was topographically-influenced. In addition, it is unlikely that there would be many erratics under a former alpine glacier due to glacier flow to the margins of the glacier. Thus, abundance of erratics in the summit area and ice flow indicators reveal that glacier flow was largely uninfluenced by the underlying topography (i.e., produced by an ice sheet) and that there was not an alpine glacier on the summit area of Mt. Åreskutan. Moreover, to grow an alpine glacier on the summit of the mountain would require a cooler climate than today which would mean that the tree-line would be even lower than today; the tree megafossils were found 400-500 m above modern tree-line and only 60 m below the summit (Fig. 6). One could invoke a dead-ice remnant on the mountain covering the sites of the boulders, but not the site where trees were living, for a duration of approximately seven thousands years after deglaciation at 17 ka. Because dead-ice is dynamically inert, it wouldn't have left any traces of ice flow such as striae, moulding or bedrock plucking, or move erratic boulders around. However, it would require a rather cold climate to allow for a slow melt-back over thousands of years. Whereas this may have been the case for during the Younger Dryas, a slow melt-back climate before the Younger Dryas would potentially have been hostile to tree growth. As well, the similarly-aged Snasahögarna moraine supports the TCN ages from Mt. Åreskutan (Fig. 8). Thus, glacier erratics from the summit of Mt. Åreskutan were not shielded by an alpine glacier or dead-ice remnant to give apparent young ages. Therefore, hypothesis 2 is rejected.

Hypothesis 3: *Trees were growing at this site and then were overrun but not excavated by the SIS; then erratics were deposited on the mountain summit during the final deglaciation.* Glacially moulded, plucked and striated bedrock found from the summit of the mountain to its base indicate that the ice sheet was warm-based in this area at some point during glacial history. Thus the ice sheet that moulded, plucked and striated bedrock would certainly also have excavated soils, peat and wood from its base. The almost uninterrupted range of radiocarbon ages of tree remains from Mt. Åreskutan from 9.6 to 16.7 cal. ka BP indicates that there would not be an opportunity for the ice sheet to readvance over the mountain summit and deposit erratic boulders (Table 1) at 10.6 ±0.6 ka, even if it did so without erosion of the substrate. Therefore, hypothesis 3 is rejected.

The rejection of these three hypotheses implies that it is unlikely that a sequence of events or processes could lead to both the radiocarbon ages and TCN ages from the summit area of Mt. Åreskutan being compatible with each other. Based on TCN measurements and other deglaciation evidence cited above, it appears objectively much more reasonable to favour the TCN apparent exposure ages as representing deglaciation of the summit area of Mt. Åreskutan over the old radiocarbon ages because: (1) the TCN ages are consistent with each other and with well-established ages for deglaciation from middle and lower elevation sites in the study area, (2) the TCN ages for the Snasahögarna moraine are consistent and overlap within 1σ with TCN ages from Mt. Åreskutan (Table 2), and (3) the radiocarbon ages are incompatible with other paleoecological and paleoglaciological evidence for Scandinavia (Birks et al. 2005, 2006; see below).

Paleoglaciological and paleoecological considerations

While, as argued above, the strongest evidence to oppose the old radiocarbon dates from Mt. Åreskutan are incompatible TCN exposure ages, a number of other arguments have been presented in the literature that address paleoecological aspects of high-elevation Late Glacial trees (Kullman 2002a, 2005, 2006, Birks et al. 2005, 2006). In the further analysis, it is assumed that Mt. Åreskutan represented a nunatak environment if trees were to have grown there since 17 ka. This is because many lines of evidence show that the SIS at 17 ka extended beyond the west coast of Norway (cf. Kleman et al. 1997, Sveian 1997, Lundqvist 2002, Svendsen et al. 2004) and to southern Sweden (Lundqvist and Wohlfarth 2001, Sandgren and Snowball 2001; Fig. 1, see inset map).

A nunatak environment would seem to be inhospitable to tree growth, as the summer temperature would most likely be below the thermal requirement of even the hardiest species, *Betula pubescens,* which currently requires ~9 °C mean July temperature in the west Norwegian mountains (Odland 1996). It appears even more strenuous to argue in favour of germination or growth conditions during the Younger Dryas (~12.8 to 11.7 ka, Muscheler et al. 2008) at 1360 m a.s.l. in the Swedish mountains, in light of documented rapid and sustained fall in temperatures during this cold interval (Coope et al. 1998, Isarin and Bohncke 1999, Brooks and Birks 2000), yet four of the radiocarbon dates from Mt. Åreskutan fall within this interval (Table 1). In addition, soil was skeletal or non-existent on the glacially scraped Mt. Åreskutan landscape. This would certainly not satisfy the ecological requirements of *Picea abies* which requires acid soils with adequate nutrients (Nikolov and Helmisaari 1992). Although, Kullman (2002a) has reported the discovery of *Picea abies* saplings at Mt. Åreskutan (1385 m a.s.l.; ~415 m above modern *Picea abies* tree-line) where the standard-level mean temperature for June to August is ~5°C, which is a lower thermal level for sustained tree growth and reproduction than generally understood (Kullman 2002b). Whatever the actual thermal requirements for tree growth, at sometime after deglaciation *Betula pubescens*, *Picea abies*, and *Pinus sylvestris* grew at 1360 m a.s.l. near the summit area of Mt. Åreskutan.

If *Betula*, *Picea* and *Pinus* occupied nunataks or other near-ice-margin areas, it is surprising that they did not spread out from there after deglaciation of lower-elevation terrain (cf. Segerström and von Stedingk 2003, Birks et al. 2005, Hammarlund et al. 2004). As revealed through lake sediments, the first flora in the area at lower elevation at 10.5 cal. ka BP was a pioneer, mountain-type, assemblage. *Picea* spread in the area thousands of years later, in fact only 3500 years ago (Lundqvist 1969, Giesecke and Bennett 2004, Bergman et al. 2005), probably from the west rather than from high elevation areas in central Sweden (Persson 1975; see Giesecke and Bennett 2004).

Kullman (2002a) proposed that boreal trees survived the glaciation along the southwest coast of Norway and migrated eastward early in the Late Glacial to early deglaciated parts of the central Swedish mountains. However, numerous macrofossil studies show that during the Late Glacial tree-*Betula* was absent, or occurred so localized that it has remained undetected, in southwest Norway (Birks et al. 2005 and references therein). Similarly, there is no macrofossil or fossil stomata evidence for the presence of *Picea* and *Pinus* to indicate that they survived the glaciation in southwest Norway or that they were present in the Late Glacial (Giesecke and Bennett 2004, Birks et al. 2005). Hence, the refuge area for the trees thought to have grown on Mt Åreskutan appears to have been unpopulated with them for the time period of the Late Glacial. We refer the reader to Kullman (2002a, 2005, 2006) and Birks et al. (2005, 2006) for further detailed discussion on paleoecological aspects of Late Glacial high elevation trees in central Scandinavia.

Causes of radiocarbon age bias

Based on new TCN apparent exposure age results and paleoecological arguments, the old radiocarbon ages from high elevation sites in central Sweden, and particularly from Mt. Åreskutan, would seem to be unreliable. Re-investigations of the dated tree samples were not possible (Kullman, pers. com. 2006) and we therefore examine four potential explanations as to the causes of the radiocarbon age bias. Firstly, continuous decay processes probably occurred on exposed wood remains as protective perennial snow banks would not always have existed, especially during the Holocene climatic optimum. Such decay processes would predictably lead to erroneously young ages (e.g., Baker et al. 1987). However, the sixteen dated specimens were reported to be well-preserved and included bark for some specimens despite sitting on the ground surface for thousands of years (Kullman 2002a). The inner and outer portions of a stem from Mt. Åreskutan (lab numbers Beta-121827 and Beta-120799, Kullman 2002a, 2005; Table 1) gave a similar age (11,440 ±100 and 11,720 ±90 ^{14}C ka BP, respectively) indicating that if contamination did not affect the inner portion of the trunk as much as the outer portion, then it may not be an important process for this sample.

Secondly, another possible cause of older radiocarbon ages is lightning (Libby and Lukens 1973, Harkness and Burleigh 1974, Bowman 1990, Paiva 2009). Lightning is more common at high elevation and generates neutrons which may alter the properties of the wood. In this respect, it is noteworthy that the old radiocarbon ages (Fig. 8) occur at high elevation where there is a higher frequency of lightning.

Thirdly, contamination processes may lead to radiocarbon ages being too old. It is more likely that contamination of ancient samples by younger carbon would have a much greater affect than contamination of younger specimens by older carbon (Bowman 1990). In this case, the dated wood would be ancient. Ancient trees may therefore derive from stratigraphic units in the up-ice region that date beyond the limit of radiocarbon dating (>50 ^{14}C ka BP; Lundqvist 1967) and that contain pollen and wood fragments of the same tree species as those found on Mt. Åreskutan. However, the well-preserved physical condition of the Mt. Åreskutan samples (Kullman 2002a) potentially precludes this possibility.

Fourthly, contamination processes may lead to radiocarbon ages being too young. Although less effective (Bowman 1990), there also is a possibility for old/dead carbonate in the catchments where tree remains have been found. Lundqvist (1969, figure 17) shows the occurrence of limestone outcropping 4-6 km east (up-ice) and southeast of Mt. Åreskutan (Lundegårdh et al. 1984). We speculate that the ice sheet could have incorporated limestone erosional products in till on Mt Åreskutan and that the old/dead carbonate could be utilised by the plants, or absorbed after their death through groundwater (Bowman 1990), leading to some erroneously older radiocarbon dates from Mt Åreskutan.

We concur with Birks et al. (2005) that the radiocarbon dated high elevation wood samples should be assessed carefully for possible sources of contamination and have their tree-rings analysed against the Scandinavian Holocene tree-ring sequence. In particular we suggest for these samples that cellulose be chemically extracted from both the inner and outer portions of all stems, and dated.

Implications of new deglaciation ages

With the rejection of radiocarbon dates from high elevation locations in central Sweden and using new high-elevation TCN apparent exposure age data, the timing of deglaciation at high elevation and the vertical rate of deglaciation must be re-examined. These values can only be estimated because of the uncertainties associated with the TCN ages along with the difference in mean age between the Mt. Åreskutan and Snasahögarna moraine sites. Nevertheless, high-elevation areas deglaciated sometime after ~12.0-10.6 ka, coinciding approximately with the termination of the Younger Dryas cold interval (11.7 ka, Muscheler et al. 2008; Fig. 8, curve 2). During the termination of the Younger Dryas, the margin of the SIS was ~85 km and ~60 km west of Mt. Åreskutan and Mt. Snasahögarna, respectively (Reite 1994, Sveian 1997). The mean vertical rate of deglaciation for the study area was ~0.5 m $year^{-1}$. However, as this value is derived from data over a large area, it is averaging estimates over space and time; and thus local vertical rates of deglaciation can be higher. The approximate vertical rate of deglaciation for the Mt. Åreskutan area, using central values for TCN adjusted exposure ages and radiocarbon dates (data points 6, 18, 19, and 20; Fig. 1, and Fig. 8, curve 3), may have been as high as ~5 m $year^{-1}$. There is no evidence apart from the old radiocarbon dates for a local vertical rate of deglaciation as low as 0.007 m $year^{-1}$ (Fig. 8, curve 1). This means that high elevation areas within central Sweden remained ice covered and could not be colonised by trees as early as 17 ka. Interestingly, TCN exposure age dating work ~195 km south of our study area at Elgåhogna close to the Swedish-Norwegian border indicates that during the LGM the ice sheet surface was above 1460 m a.s.l., and that rapid deglaciation commenced about 12 ka (Goehring et al. 2008). This corresponds well with estimates for deglaciation from our study area.

Conclusion

Three terrestrial cosmogenic nuclide (TCN) exposure ages from the summit of Mt. Åreskutan (1360 m a.s.l.) in central Sweden are consistent with each other (adjusted mean age of 10.6 ±0.6 ka) and are similar to lower-elevation dates for deglaciation from the region. However, the TCN ages are incompatible with reported old radiocarbon dates from wood of three tree species from the summit area (as old as 16.7 ±0.2 cal. ka BP). We cannot find a plausible hypothesis that accommodates both the radiocarbon and TCN ages from this site.

Three TCN samples were collected from the highest elevation SIS moraine in Sweden. Located 35 km down-ice from Mt Åreskutan, the Snasahögarna SIS moraine samples yielded consistent TCN ages (sampled at 1125-1149 m a.s.l.; adjusted mean age of 12.0 ±0.6 ka). The difference in TCN ages between Mt. Åreskutan and the Snasahögarna SIS moraine probably reflects a geographical difference in the timing of deglaciation between sites and possibly a difference in the actual historical snow depths.

We reject the reported old radiocarbon ages on the basis of (1) incompatibility with consistent TCN ages and (2) incompatibility with paleoecological and paleoglaciological evidence for deglaciation (Birks et al. 2005). Nevertheless, the mere *presence* of tree remains of three different species at this high elevation, and well-above (400-500 m) the modern-tree line, still allows for some speculation with regards to their climatic interpretation. The problem lies in reliably dating these tree remains. Assuming these are younger tree remains, consistent with TCN age results, we suggest that contamination from calcareous bedrock or neutron production from lightning may have caused the age bias. We also strongly recommend that specimens for radiocarbon dating be thoroughly tested to ascertain possible sources of contamination and that complementary dating techniques be employed before proposing radical changes to the established paleoglaciological and paleoecological history.

Mt. Åreskutan within central Sweden did not deglaciate as early as ~17 ka. High-elevation areas in this region deglaciated ~12.0-10.6 ka, coinciding approximately with the termination of the Younger Dryas cold interval (11.7 ka). The vertical rate of deglaciation may have been as high as ~5 m $year^{-1}$ but was more typically 0.5 m $year^{-1}$. We propose that sometime after deglaciation *Betula pubescens*, *Picea abies*, and *Pinus sylvestris* grew at 1360 m a.s.l. near the summit area of Mt. Åreskutan.

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

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Doctoral Thesis in Quaternary Geology at Stockholm University, Sweden 2010

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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