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Further Details on Holocene Treeline, Glacier/Ice Patch and Climate History in Swedish Lapland

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Abstract:*The present paper reports results from an extensive project aiming at improved understanding of postglacial subalpine/alpine vegetation, treeline, glacier and climate history in the Scandes of northern Sweden. The main methodology is analyses of megafossil tree remnants, i.e. trunks, roots and cones, recently exposed at the fringe of receding glaciers and snow/ice patches. This approach has a spatial resolution and accuracy, which exceeds any other option for tree cover reconstruction in high-altitude mountain landscapes. The main focus was on the forefields of the glacier Tärnaglaciären in southern Swedish Lapland (1470-1245 m a.s.l.). Altogether seven megafossils were found and radio-carbon dated (4 Betula, 2 Pinus and 1 Picea). Betula and Pinus range in age between 9435 and 6665 cal. yr BP. The most remarkable discovery was a cone of Piceaabies, contained in an outwash peat cake, dating 11 200 cal. yr BP. The peat cake also contained common boreal ground cover vascular plant species and bryophytes. All recovered tree specimens originate from exceptionally high elevations, about 600-700 m atop of modern treeline positions.This implies, corrected for land uplift, summer temperatures, at least 3.6 °C higher than present-day standards. The current results,in combination with those from other Swedish glaciers, contribute to a new view on the early postglacial landscape and climate in high-altitude Swedish Scandes*

Keywords: *Treeline, glacier, megafossils, climate change, Holocene, Swedish Scandes, Betulapubescensssp. czerepanovii, Pinussylvestris, Piceaabies*.

1. INTRODUCTION

Recent glacier/ice patch recession in association with post-Little Ice Age climate recovery of the past 100 years or so has exposed a plethora of previously ice-entombedmega fossil tree remains in many parts of the world (Nicolussi & Patzelt 2000; Hormes et al. 2001; Schlűchter & Jörin 2004; Koch et al. 2007, 2014; Grosjean et al. 2007;Benedicht et al. 2008; Wiles et al. 2008;Scapozza et al. 2010;Nicolussi&Schlűchter 2012; Lee 2012). These ancient remnants derive from subglacial preservation sites and are currently exposed at the margin of basins presently occupied by glacier ice and perennial snow. Theyoffer a unique opportunity to improve our understanding about past treeline positions and associated plant cover characteristics and thereby indirectly provide clues to ancient climates. This archive, also containing numerous human and cultural artefacts, has been widely recognized and exploited by archaeologists (e.g. Nesje et al. 2011; Lee &Benedicht 2012;Reckin 2013), but in Scandinavia surprisingly little payed attention to by palaeoecologists.

In the Swedish Scandes, however, important findings of megafossil trees under above-mentioned circumstances, high above current treelines, have been reported and discussed in some studies (Kullman 2004; Öberg & Kullman 2011a; Kullman & Öberg 2013, 2015; Kullman 2017a). These resultshave proven accuracy in time, space and species composition, going far beyond the resolution of pollen analysis and other microfossil approaches (cf. Kullman 2017a) and lining up with inferences originating from DNA-methodologies (Parducci et al. 2012; Parducci & Tollefsrud 2016). Late-glacial andearly-Holocenepresence of boreal tree species are evidenced (megafossils) in this way for restricted sites, situatedmuch higher than current treeline elevations. Hereabouts peat deposits on the open alpine tundra are rare and shallow, with little ability to preserve trees and other macroscopic plant remains from ancient times. Therefore, little has been known about the highest treeline positions and associated plant cover structure during the earliest part of the Holocene. The most promising archives for that purpose are found in glacier cirques and nivation hollows, which were ice free before andbecame ice coveredin accord with the mid-Holoceneneoglacial cooling. In many cases, it is quite obvious that the mega fossil tree remnants have been washed out by subglacialmelt water streams from primary growing sites higher upslope. Some exceptional outlying records of 500-700m higher than present treeline, support an even higher elevational origin as a more general pattern. The possible generality of this supposition needs to be further elucidated in perspective of its implications for Holocene vegetation history and paleoclimate (Öberg & Kullman 2011a,b; Kullman & Öberg 2013, 2015). With this background, the present study reports efforts to sustain and further approach the uppermost limit of megafossil trees within an area previously well researched with respects to megafossil tree remnants (debris wood) occurring at glacier forefields at relatively modest levels above the present-day treelines (Öberg & Kullman 2011a; Kullman & Öberg 2013, 2015).

For logistic reasons it has been judged impractical and dangerous (slippery bedrock, collapsing glacier fronts and moving rock slabs) to investigate these higher potential source areas in search for megafossils. However, during the early autumn of 2017, the present author made a tentative approach, the results of which are reported here.

2. Study Area

The study was carried out within the central Swedish Scandes, in the southern part of the province Lapland (Fig. 1). Focus is here on the forefield of the glacier “Tärnaglaciären”, which is located to the Norra Storfjället massif (65° 51´N; 15° 16´E), with some peaks reaching above 1600 m a.s.l. and valley floors at 700-800 m a.s.l. The glacier is contained within a cirque facing SE (Fig. 2). Currently the glacier area is estimated to c. 0.2 km^2, with an upper and lower margin at 1470 and 1245 m a.s.l., respectively. By the late 19th and early 20th century, the glacier was mapped by Gavelin (1897, 1910), who estimated its area to 0.5 km^2. Thus, the glacier has lost more than 50% of its area during the past 100 years or so, and the lower front has withdrawn by approx. 175 m in elevation. Figure 3depicts the maximum extent of the glacier by the late 19th century, manifested in the form of an incomplete moraine bow in an outwash lake below the glacier, 1070 m a.s.l. (Fig. 3) (cf. Gavelin 1910; Lindgren & Strömgren 2001).Substantial frontal retreat and thinning have taken place since the late 1990s and up to the present day (Fig. 2)

On the slope below the glacier, a large snow/ice patch extends down to theoutwash lake (Fig. 2). The size of this patch varies on an annual basis, depending on prevailing weather conditions. Prior to the present study, most mega fossil recoveries have been made in association with melt water streams close to the lower fringe of this patch.

The bedrock is of Cambro-Silurian origin, mostly mica schists. Quaternary deposits embrace glacifluvial accumulations, till and peat. A weakly sub oceanic climate characterizes the area. The nearest meteorological station is Hemavan, 475 m a.s.l., situated in the Uman River Valley, c. 10 km southwest of the study site. The mean temperature forJune-August and the year are 10.1 and -0.4°C, respectively. Annual precipitation is 680 mm.

Currently, mountain birch (*Betulapubescens ssp. czerepanovii*) constitutes the upper treeline in this area, 790 m a.s. l. (Fig. 4). The nearest treeline of Norway spruce (*Piceaabies*) and Scots pine (*Pinussylvestris*) are at 710 and 690 m a.s.l., respectively. During the past 100 years, the treelines of those species have advanced by a maximum of more than 200 m (Kullman & Öberg 2009), which appears to have taken them to a position uniquely high for the past 7000 years or so (Kullman 2017b). Overviews of the structure and dynamics of the treeline eco tone in the Scandes are provided by Kullman (2010) and Wielgolaski et al. (2017).

Fig1.*Map showing the location of the study area (●) in northern Sweden*.

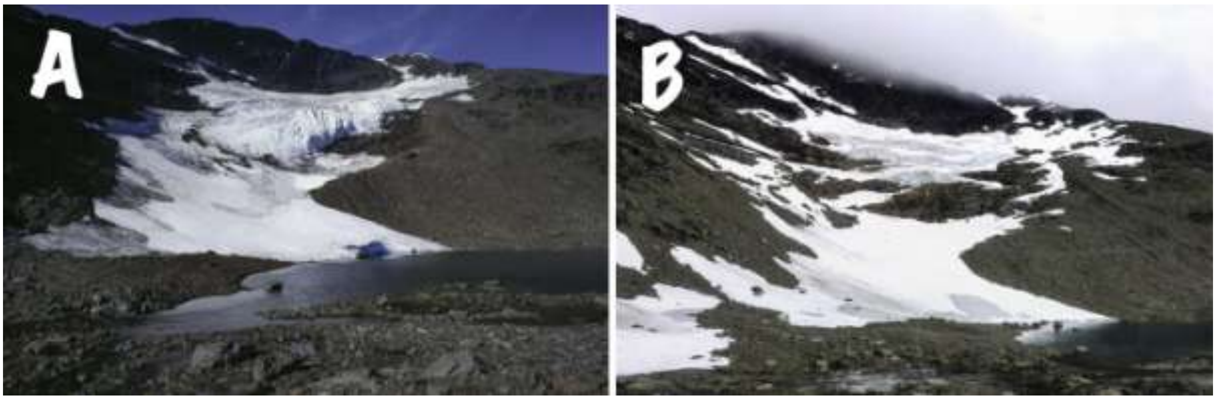

Fig 2.*The glacier Tärnaglaciären, the snow/ice patch and outwash lake below (1070 m a.s.l.).* ***A.*** *Prospect from southeast, 1999-09-06 (Photo: F. Lindgren & M. Strömgren).* ***B****. Virtually the same view 2017-09-01. The glacier has perceivably thinned since 1999"Photo: 2017-09-01".*

Fig3.*Theoutwash lake below the glacier, 1070 m a.s.l. By the late 19th century, the lower glacier front was located at the morainic ridges, protruding above the water surface (Gavelin 1910)Photo: 2017-09-01.*

Fig4.*The current treeline of Betulapubescens ssp. czerepanovii, 790 m a.s.l., right to the east and downslope of Tärnaglaciären (arrow). The solitary birch copse is located at the bank of the main meltwater stream from the glacier"Photo: 2017-09-01".*

3. METHODS

During the autumn of 2017 the fore fields adjacent to the lower and lateral margins of the glacier Tärnaglaciären were thoroughly scrutinized for the presence of out washed mega fossils and other identifiable plant remains. Recovered specimens were wrapped in aluminium foil and stored frozen until delivery to the dating laboratory. Species identification was unambiguous in all cases, based on bark fragments, cone and leaf characteristics. All recovered woody remnants were sampled and altitudes were determined by a GPS navigator (Garmin 60CS), calibrated against distinct points on the topographical map. Reported altitudes are rounded off to the nearest 5 m. The nomenclature of vascular plants follows Öberg et al. (2017).

Radiocarbon dating of recovered specimens has been performed by Beta Analytic Inc., Miami, USA. All original radiocarbon dates and time-scales in running text and figures are converted to calendar years before present (cal. yr BP), with “present” = AD 1950, based on IntCal13 (Reimer et al. 2013) and for the sake of simplicity, they are cited as “intercept values”.Outwash peat cakes and their contained macrofossils (e.g. cones, leaves and bryophytes) were dated indirectly on the basis of 2 cm thick bulk peat slices.

4. RESULTS

This study adds seven new dates of megafossil tree remnants (4 *Betula*, 2 *Pinus*, *1 Picea*) to a previous sample of 21 specimens from the same glacier (12 *Betula*, 9 *Pinus*) (Kullman & Öberg 2015). Individual dates are given in Table 1 and the samples are depicted in Figures 5-7. They range in elevation between 1410 and 1275 m a.s.l., which is about 600 and 700 m higher than the nearest present-day treelines of these species. The ages all represent the early Holocene, c. 11200 to 6700 before present.

Table 1.*Radiocarbon dates of recovered megafossils. Relative elevation refers to the difference in altitude between the sampling site and the nearest present-day treeline of the concerned species.*

Altitude	Relative elevation	Species	Lab. code	Radiocarbon age	Calibrated age	Intercept	Size	Material
m a.s.l.	m			^{14}C yr BP	BP 1 SD	cal. yr BP	cm	
1410	700	Betula	Beta-474257	8330±30	9447-9273	9365	45	wood
1395	685	Betula	Beta-474258	8400±30	9495-9397	9450	40	wood
1380	690	Pinus	Beta- 474259	8020 ±30	9010-8848	8900	37	wood
1320	630	Pinus	Beta- 474254	8380±30	9779-9371	9435	19	wood
1295	585	Betula	Beta-474255	5850±30	6743-6603	6665	21	wood
1275	565	Betula	Beta-474252	7910±30	8791-8602	8780	18	wood
1370	630	Picea	Beta-474251	9760±30	11 238-11 167	11 200	14	Cone + peat

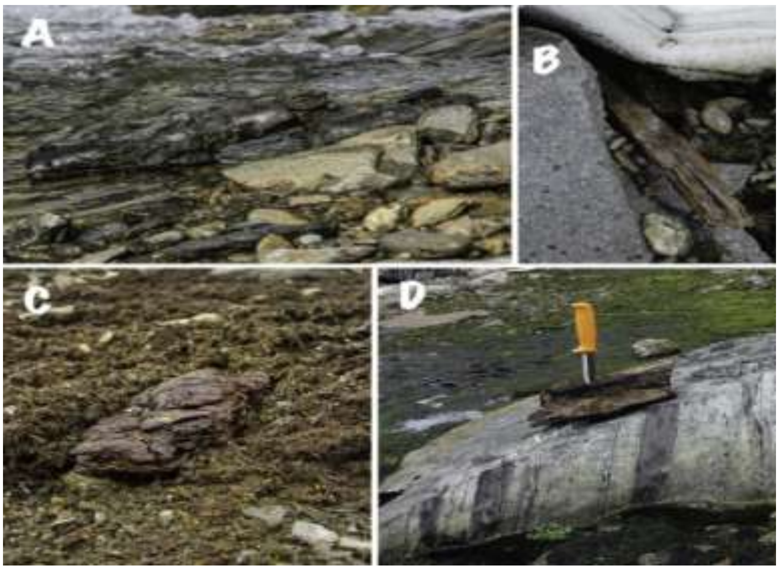

Fig 5. *Recovered and dated megafossils of Betulapubescens. **A**. 9365 cal. yr BP. **B**. 9450 cal. yr BP. **C.** 6665 cal. yr BP. **D**. 8780 cal. yr BP*

Fig6. *Recovered and datedmegafossils of Pinussylvestris. **A**. 8900 cal. yr BP. **B**. 9435 cal. yr BP.*

A cone of *Piceaabies*, contained in a peat cake, was dated 11 200 before present at an elevation, almost as high as the uppermost dated birches and pines (Fig. 7).The cone contained a few heavily decayed seeds.

This is the highest position, relative to its modern treeline, ever recorded for postglacial spruce. In addition, this peat sampleshowed macrofossils of the following identifiable ground cover taxa: *Empetrumhermaphroditum, Vacciniummyrtillus, Vacciniumvitis-idaea, Rhododendron tomentosum, Hylocomiumsplendens, Pleuroziumschreberi*, *Dicranum*sp., *Sphagnum* sp. All samples of *Betula* and *Pinus*displayed a size and form which indicated that they originated from tree-sized individuals. In the case of *Piceaabies*(a cone) no such inference could be made.

Fig7. A.*Peat cake which contained macrofossils of ground cover species, 1370 m a.s.l*. **B**.*Cone of Piceaabies dissected from the peat cake.*

5. DISCUSSION

The present study sustainsa generic pattern for the entire Swedish Scandes (cf. Öberg & Kullman 2011a; Kullman & Öberg 2013, 2015). As evident from Fig. 5A, the highest date of *Betula* (1410 m a.s.l,) is obtained from an outwash stream protruding from beneath the glacier.Obviously it originates from a primary growing site further up valley, more than 700 m above today´s treeline. Conservatively drawing on the latter figure and a summer temperature lapse rate of 0.6 °C per 100 m elevation (Laaksonen 1976), could *apriori* mean that, summer temperatures were at least 4.2 °C warmer than present around 9500 year before present. However, glacio-isostatic land uplift by at least 100 m since that time (Möller 1987; Påsse & Anderson 2005) implies that this figure has to be reduced to 3.6 °C higher than present-day levels, i.e. first decades of the 21st century. Evidently, this was the warmth peak of the Holocene, hitherto. This inference concurs with paleoclimaticre constructions from Europe and Greenland (Korhola et al. 2002; Bigler et al. 2003; Paus 2013; Luoto et al. 2014; Väliranta et al. 2015) and complies with theoretical calculations based on variations in Earth´s orbital parameters and associated gradual change in summer insolation (Berger &Loutre 1991; Esper et al. 2012). It contrasts with commoninterpretations suggesting a much later thermal optimum (Berglund et al. 1996; Seppä& Birks 2002). The latter inferences are based on pollen analyses, which in some cases are proved to deliver less reliable vegetation history details and temperature estimates (Paus 2013; Elven et al. 2013; Luoto et al. 2014; Kullman 2017a).

The youngest megafossil date, 6665 cal. yr BP, suggests that the concerned glacier, like many others, did not exist prior to that date (cf. Bakke et al. 2005). Dated peat remains indicated that neoglacial instatement of this particular glacier ice took place after 3890 cal. yr BP (Kullman&Öberg 2013).

Available dates are too few to allow any firm conclusions as to the zonation patterns during the early Holocene. Anyhow, *Betula* appears to have been the highest ascending tree species. Such a pattern also emerges from earlier more extensive megafossil studies, although a distinct subalpine birch forest belt, as we know it today, appears to have formed later on (Kullman 2013). In that context, it is of some interest to note that the nearest living birches (tree-line markers), in the form of a dense and isolated copse, are located within the main outwash stream furrow from the glacier here concerned (Fig. 4). This pattern is compatible with an earlier inference, based onmegafossil performance, that trees (and possibly other plant species, have in general spread downslope from primary“occurrence sites” at high elevations, e.g. empty glacier cirques (Kullman 2002).

Information from ground cover macrofossil plant species contained in a peat cake (Fig. 7A), indicate that the recovered megafossils grew in a matrix of dwarf shrubs and bryophytes with present-day quite ordinary boreal forest affinities. Predominance of *Sphagnum* spp. could indicate that the megafossils were preserved by peat growth prior to the final burial by glacier ice.

Recent data on early Holocene presence of *Piceaabies* at high elevations in the Scandes comply temporally with megafossil and some recent pollen studies from different parts of the Scandes (Kullman 1996, 2000;Segerström& von Stedingk 2003;Öberg&Kullman 2011b; Paus et al. 2011; Kullman & Öberg 2013, 2015).This pattern contrasts with traditional inferences from pollen data,suggesting a mid- or late Holocene wave-like spread of spruce from the east (e.g. Moe 1970; Hafsten 1992; Huntley & Birks 1983;Giesecke 2005;Seppä et al. 2009).Recent DNA analyses in lake sediments andemergent patterns ingenetic structure of extant spruce populationssupport the contention ofLate-glacial andearly Holocene presence of spruce enclaves in western and northern Scandinavia (Parducci et al. 2012). Furthermore, multimillennial old prostrate spruces, prevailing high above the current treeline in some mountain areas, provide support to the latter option (Öberg & Kullman 2011b; Kullman 2015).

Apparently, these peripheral spruce occurrences wereconfined to restricted, widespread and particularly favorable habitats, acting as dispersal nodes during later parts of the Holocene. This option was originally inferred from megafossil spruce data gathered along the entire Swedish Scandes (Kullman 1996, 2001, 2008, 2017a; Kullman & Engelmark 1997), a mechanism reiterated by Väliranta et al. (2011) on evidence from north-eastern European Russia.

Importantly, megafossil data of the kind accounted for above, in combination with DNA analyses in soils and lake sediments, urge pollen analysts to adopt a less conservative attitude when interpreting trace amounts of pollen.Evidently, much of the commonly narrated pollen-based postglacial history of subalpine/alpine regions has to be reconsidered in the light of emerging megafossil evidence .These latter results, in combination with those, analogously derived, from other Swedish glaciers, provide a new view on the early postglacial landscape and climate in high-altitude Swedish Scandes. Paleoecologists are forced to reconsider standard views on Late-Glacial and early Holocene environments in the high mountains (cf. Anderson et al. 2009; Horáček et al. 2015). This view is strongly substantiated by the present paper.

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