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New insights into the 21 November 2000 tsunami in West Greenland from analyses of the tree-ring structure of *Salix glauca*

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Abstract: We test the application of dendrochronological methods for dating and assessing the environmental impacts of tsunamis in polar regions, using an example of the 21 November 2000 landslide-generated tsunami in Vaigat Strait (Sullorsuaq Strait), West Greenland. The studied tsunami inundated a *c*. 130 m-wide coastal plain with seawater, caused erosion of beaches and top soil and covered the area with an up to 35 cm-thick layer of tsunami deposits composed of sand and gravel. Samples of living shrub, *Salix glauca* (greyleaf willow) were collected in 2012 from tsunami-flooded and non-flooded sites. The tree-ring analyses reveal unambiguously that the tsunami-impacted area was immediately colonized during the following summer by rapidly growing shrubs, whilst one of our control site specimens records evidence for damage that dates to the time of the tsunami. This demonstrates the potential for dendrochronological methods to act as a precise tool for the dating of Arctic paleotsunamis, as well as rapid post-tsunami ecosystem recovery. The reference site shrubs were likely damaged by solifluction in the autumn 2000 AD that was triggered by high seasonal rainfall, which was itself a probable contributory factor to the tsunami-generating landslide.

Key words: Arctic, Greenland, tsunami, dendrochronology, *Salix glauca*, plant colonization.

Introduction

Tsunamis are long waves that pose a serious hazard to coastal environments. Their most common generating mechanisms are earthquake-induced vertical movements of the seafloor, volcanic activity and landslides. A key point in assessing tsunami hazard is the identification, size estimation and dating of former tsunami events (*i.e.* paleotsunami). The standard approach is to study tsunami deposits preserved in coastal depositional environments. However, this is a complex task, which requires multidisciplinary approaches with the application of various criteria, as well as the careful consideration of local contexts (Goff *et al.* 2012). Moreover, the tsunami deposits are usually difficult to date and provide little or no information on post-tsunami ecosystem recovery.

To date, the effects of tsunami have been mainly reported from tropical and temperate regions. The paucity of reported tsunami in polar regions may partly reflect the very low population densities, the short written history and limited coastal geological research focused on the sedimentary record of paleotsunamis (Ruffman and Murty 2006). Polar region tsunamis have been mostly recorded in fjords, which may amplify wave heights due to their constraining topography and are particularly prone to hazards associated with landslide-generated tsunamis. For instance, in 1958 in Lituya Bay (Alaska), a tsunami reached the historical worldwide maximum run-up of 516 m a.s.l. (Miller 1960). Polar regions are also affected by far-field tsunami. The best documented example of this is the Storegga tsunami about 8200 years BP that is recorded along many of the coastlines of the northern Atlantic, including east Greenland (*e.g.* Dawson *et al.* 1988; Bondevik *et al.* 1997; Wagner *et al.* 2007; Romundset and Bondevik 2011).

Dendrochronological analyses provide a valuable means to date and identify tsunami events and coastal processes (Alestalo 1971; Schweingruber 1996; Jacoby *et al.* 1997; Goff *et al.* 2004). In polar regions, trees are present in a dwarf form as tundra shrubs, *e.g.* willow (*Salix* spp.), which form annual growth rings that can be used for dating purposes (Schweingruber and Poschlod 2005; Myers-Smith *et al.* 2011b; Schweingruber *et al.* 2013; Myers-Smith *et al*. 2015). The potential of the shrub *Salix* spp. for dendrochronological studies has been known for some time (*e.g.* Polunin 1955; Beschel and Webb 1963; Savile 1979), however their broader use in studies of climate and environmental change has become increasingly common in the last two decades (Woodcock and Bradley 1994; Zalatan and Gajewski 2006; Forbes *et al.* 2010; Block *et al.* 2011; Myers-Smith *et al.* 2011a; Buchwal *et al.* 2013). For example, changes in *Salix* tree-rings growth and/or wood anatomy have been used in various dendrogeomorpholgical applications, including in the study of gelifluction lobes (Jakob 1995), rock glaciers (Gärtner-Roer *et al.* 2013), debris flows (Owczarek 2010) and flood plains (Owczarek *et al.* 2014).

Here we provide an example of the first application of dendrochronological analysis for tsunami research in the Arctic. We use *Salix glauca*, a common tundra

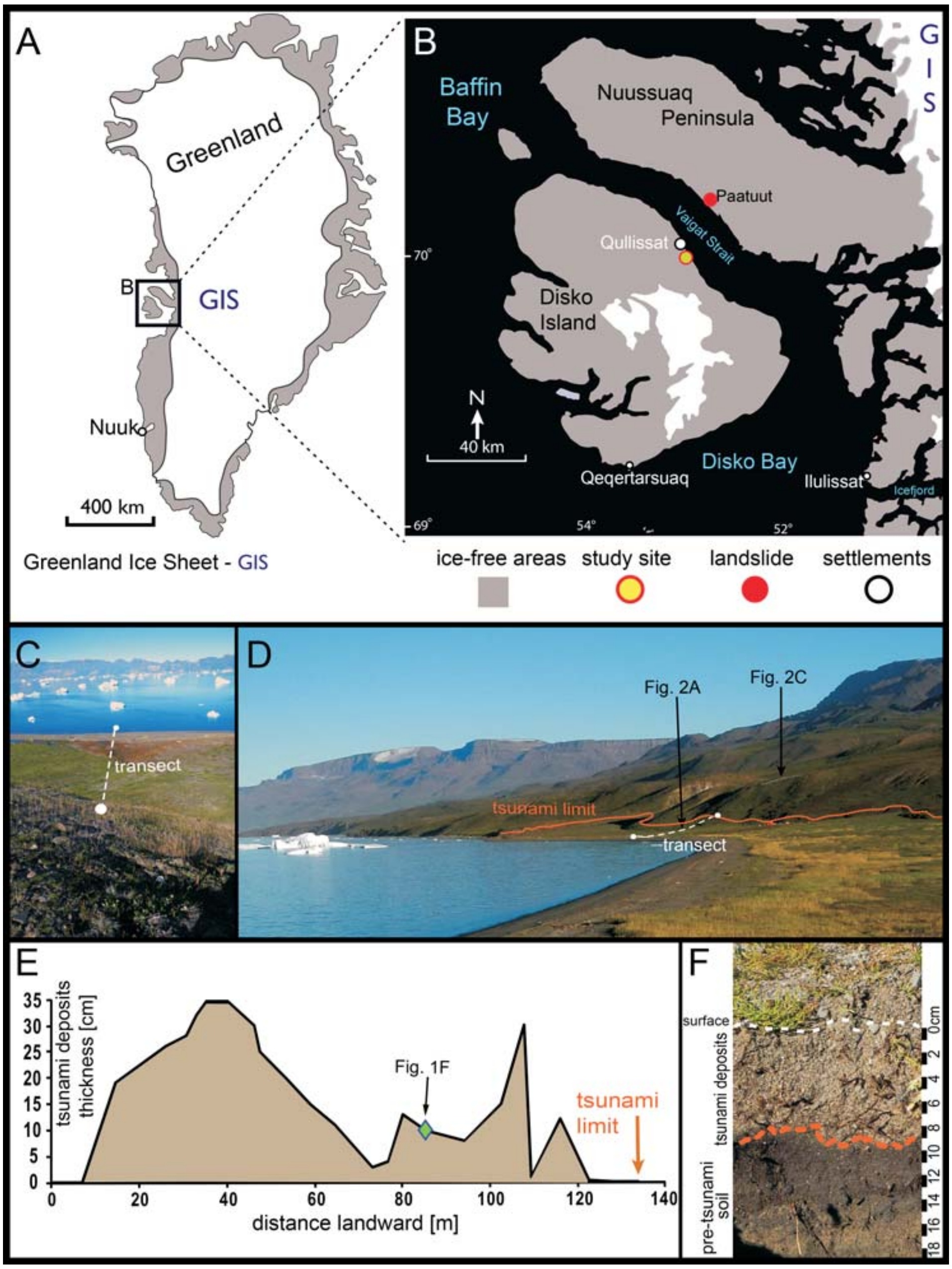

Fig. 1. Study area and tsunami deposits from the 21st November 2000 AD tsunami. **A**. Location of the study area in west Greenland. **B**. Location of the study site within Disko Bay, with the site of the Paatuut landslide marked. **C**, **D**. Photographs of the studied site with marked transect line for tsunami deposits analyses, tsunami run-up limit and shrub sampling locations (see Fig. 2). **E**. Tsunami deposits thickness along the coast-normal transect line. **F**. Example of tsunami deposits, next to the shrub sampling site, composed of *c.* 10 cm-thick poorly sorted gravelly coarse sand with lower erosional contact.

shrub, collected from a coastal plain that was inundated by a landslide-generated tsunami in November 2000, which occurred in Vaigat Strait, west Greenland. The objectives of this pilot study are twofold: (1) to test the potential usefulness of *Salix glauca* growth rings in paleotsunami studies in arctic regions and; (2) to assess the natural recovery of arctic coastal plain ecosystems following extreme seawater flooding.

Study area and tsunami

A large rock avalanche and landslide of approximately 90 million m^3 of rock took place at Paatuut (Vaigat Strait or Sullorsuaq Strait, Fig. 1) in the mid-afternoon of 21st November 2000 and triggered a tsunami with a reported maximum local run-up height of up to 50 m (Dahl-Jensen *et al.* 2004). Tsunami generated damage was described by local authorities from sites as much as 180 km from Paatuut. Anomalous weather conditions, notably warming followed by cooling that caused water freezing in cracks during the days prior to the slide are thought to have caused failure of the steep mountain side (Dahl-Jensen *et al.* 2004). Although rock avalanches and landslides are common in the area, the size of the tsunami was considered to be the largest during at least the last 500 years (Dahl-Jensen *et al.* 2004).

The impact area of the tsunami studied in this paper is the *c.* 100 m-wide coastal plain of northeast Disko Island, which is characterized by sand and gravel beaches that are backed by relatively steep vegetated slopes (Fig. 1). The present coastal plain was formed during the mid and late Holocene as relative sea-level fell tens of meters to reach present due to glacio-isostatic rebound (Long *et al.* 2011). The area is located in the arctic maritime climate zone and the nearest meteorological station Qeqertarsuaq (Fig. 1) recorded an average annual air temperature for the period 1991–2000 of -4.4°C (Nielsen *et al.* 2001) and an average annual precipitation (1991–2004) of 436 mm (Hansen *et al.* 2006). The area is in the permafrost zone and the maximum thickness of the active layer observed in sandy coastal sediments, as measured at Qeqertarsuaq (Fig. 1), was reported to reach 180 cm in late September (Humlum 1998). The site is located in the Southern Arctic Tundra Zone (Elvebakk *et al.* 1999; Walker *et al.* 2002).

Methods

We conducted a field survey to document the impacts of the Paatuut tsunami in July 2012 along *c.* 20 km of the Vaigat Strait. For the purpose of this study we use a representative shore-normal transect to document the extent and nature of tsunami deposits and to assess the impacts of the tsunami on vegetation communities. We describe the tsunami deposits from 28 closely spaced trenches that were hand-dug.

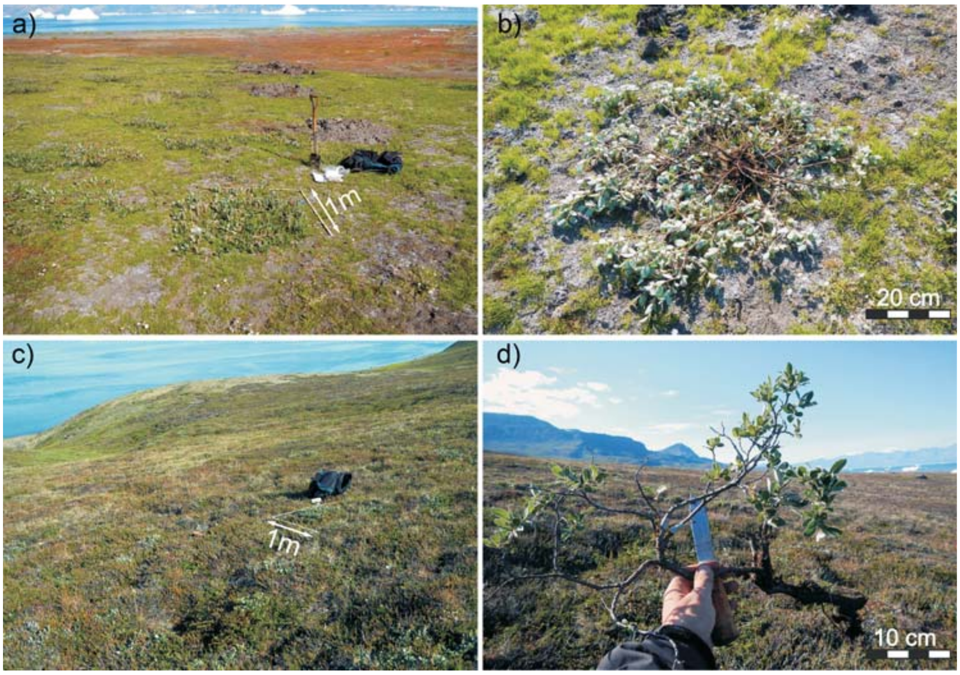

Fig. 2. Shrub sampling sites in NE Disko Island and examples of the collected specimens. (a) Sampling site in the tsunami inundated area covered by *c.* 10% with recently established *Salix glauca* shrubs and (b) one of the analysed specimens from the tsunami-affected site. (c) Reference site and one of the *Salix glauca* specimens (d) collected from area not affected by the tsunami.

We selected the greyleaf willow (*Salix glauca)* species for dendrochronological analyses since it is the only shrub species presently growing in the tsunami affected area. We collected four shrub individuals from representative sites, one covered with tsunami deposits (samples BH1, BH2; see Fig. 2a, b) and the second, a reference site, that was not affected by the tsunami (samples BR1, BR2; see Fig. 2c, d). Two complete shrub bodies (*i.e.* including below- and above-ground parts) were carefully excavated from each site.

Shrub specimens were prepared for analysis using a sledge microtome, with the tree-ring structure analysed in at least three cross-sections per individual shrub, including the root collar and the main branches segments. We prepared thin-sections using the methods detailed in Schweingruber and Poschlod (2005) and undertook dendrochronological analyses by measuring tree-ring widths (TRW) within the cross-sections to assess the age and the annual growth rate of the sampled shrubs. Within a single cross-section a number of annual growth rings were studied within four radii in order to identify partially missing rings. Ring widths were manually traced using the path analyses mode in the WinCell software (Regent Instruments, Canada). To enable the precise determination of a shrub age, we visually cross-dated growth series of different shrub parts, first within one individual and then between the sampled plants. Each cross-section was carefully inspected and wood anatomical features such as cambial injuries and reaction wood (*i.e.* tension wood) were noted.

Results

Field observations. — The Paatuut tsunami inundation extended inland at the study area by at least 135 m, as marked by driftwood and salt-damaged vegetation that was clearly visible in the field, albeit 12 years after the event itself. Tsunami deposits extended inland from the present coast by *c.* 120 m (Fig. 1). The deposits were sheet-like and massive in structure, composed of gravelly sand and sandy gravel that are typical of present-day beach and beach ridge sediments. Their lower contacts with the pre-tsunami soil were sharp and in most cases erosional, with very rare occurrences of pre-tsunami plants. The deposits thickness had two maxima, the first (35 cm) *c*. 40 m from the shoreline and the second (30 cm) in front of the steep slope at the landward limit of the coastal plain (Fig. 1e). The total volume of tsunami deposits along a 1 m wide transect line was about 18 m^3.

The tsunami deposits were sparsely vegetated with *c.* 10% of average plant coverage density compared to areas not impacted by the event (Fig. 2b). The only shrub species present within the site flooded by tsunami was *Salix glauca*, which is represented by semi-erect canopies <15 cm of height. The diameter of an individual shrub patch typically ranged between 0.5 to 1.5 m, with shrubs being dispersed, healthy and characterized by flexible branches.

The investigated shrubs that were impacted by the tsunami were at about 4 m a.s.l., and the reference site was located about 40 m a.s.l.. The latter sample was collected from a densely vegetated area, supporting a diversity of species that included shrubs of *Salix glauca* and *Betula nana* (Fig. 2c). The patches of *Salix* here were smaller (<0.25 m, Table 1), less frequent and some specimens were characterized by rigid branches.

Dendrochronological analyses. — Two *Salix glauca* specimens (Table 1) from the tsunami affected site revealed relatively wide growth ring widths of 0.15 to

Table 1

Summary of the shrub samples characteristics with the mean, maximum and minimum ring width (RW) and wood anatomical features identify at root collar base of *Salix glauca* shrubs sampled within tsunami-affected and reference sites.

shrub ID	sampling site	tsunami deposits thickness [cm]	shrub patch diameter [m]	shrub age [years]	mean RW [mm]	max RW [mm]	min RW [mm]	wood injury	tension wood
BH1	tsunami-affected site	8–10	0.5	12	0.286	0.496	0.150	no	yes
BH2		4–13	1	12	0.392	0.695	0.233	no	yes
BR1	reference site	0	0.2	26	0.119	0.239	0.052	yes	yes
BR2		0	0.25	69	0.042	0.109	0.017	no	little

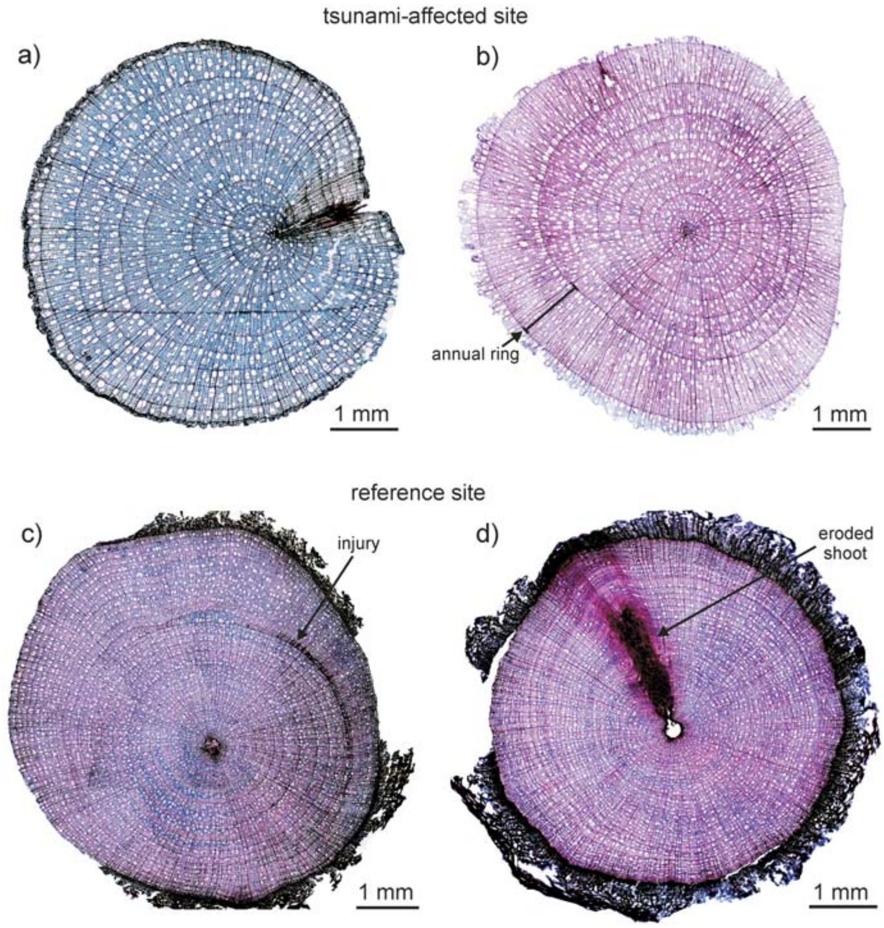

Fig. 3. Cross-sections of the *Salix glauca* shrubs sampled in NE Disko Island, W Greenland. (a) and (b) show 12-year old specimens sampled from the tsunami-affected site. (a) main root cross-section (shrub BH1) with common tension wood (blue colour); (b) root section (shrub BH2) with wide annual ring of 2011 (marked). (c) and (d) present tree-ring structure of shrubs sampled from the reference site. (c) a 26-year-old stem part from the control site (shrub BR1) with a wood injury dated to 2000/2001; (d) a 69-year-old stem part (shrub BR2) with the narrowest rings and an overgrown trace of an eroded adventitious shoot (marked).

0.69 mm and complete annual increments (Fig. 3a, b), suggesting vigorous growth. The age of the two specimens sampled is 12 years, indicating immediate re-sprouting in early summer of 2001 AD, after the tsunami event. Despite the young age of these specimens no partially or completely missing rings were observed. The rings were characterized by a high porosity, which explains the observed flexibility of their branches. The most common anatomical feature recorded was tension wood, which is a type of reaction wood that comprises unlignified (*i.e.* appearing blue after staining, Fig. 3a) gelatinous fibers within the growth ring. Tension wood was traced within the shoots, as well as in the main root of the shrubs.

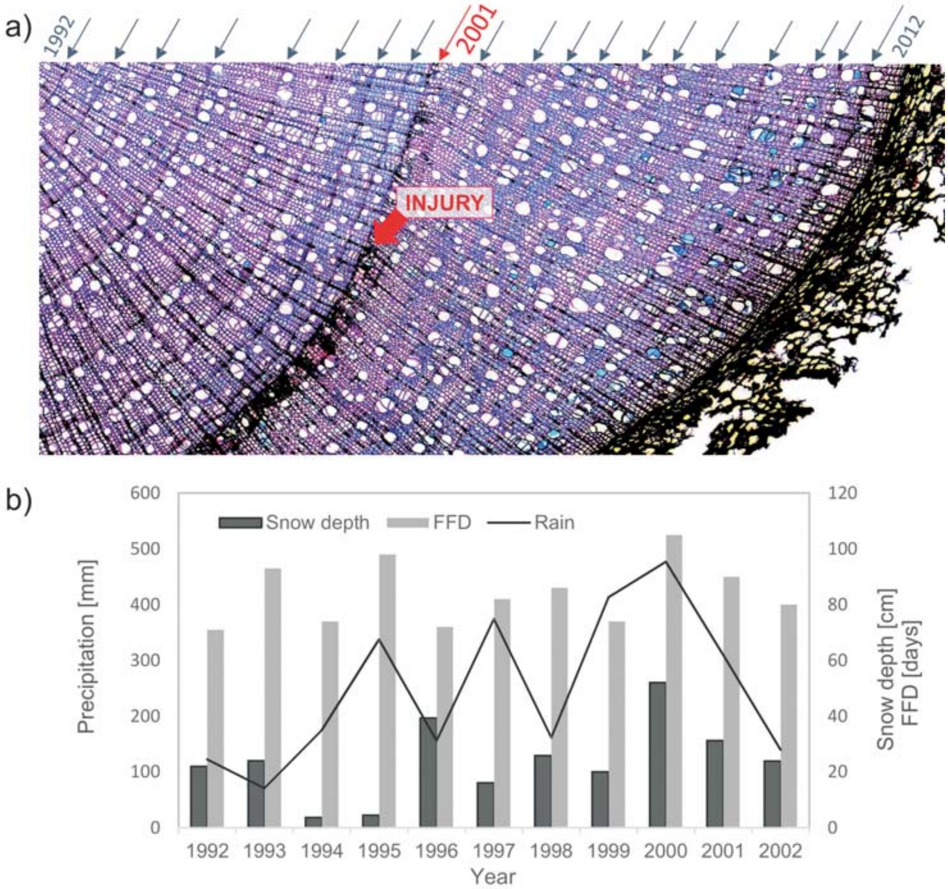

Fig. 4. *Salix glauca* tree-ring structure from the reference site (shrub BR1) with a wood injury and tension wood suggesting mechanical disturbance and shrub bending (a) compared to meteorological records of rainfall, snow depth and frost free days (FFD) from Qeqertarsuaq (b), see Hansen *et al.* 2006.

The shrubs from the reference site (Fig. 3c, d) were at least twice as old (ages of 26 and 69 years) than those from the tsunami affected area. These specimens had narrower growth rings with mean width of 0.119 and 0.042 mm, respectively (Table 1). They also revealed tension wood and in one of the shrubs (BR1, Fig. 3c) an annual ring with an injury (dated to post 2000 AD) was detected, likely as a response to physical disturbance (Fig. 4a).

Discussion

Paleotsunami identification and dating. — Identification and robust dating of event layers are critical issues in palaeotsunami research and may be addressed using dendrochronological methods. The Paatuut tsunami left a clearly defined sand and gravel layer in the coastal sequence (Fig. 1). The dominant sediment source was the immediate beach and storm ridge, since pre-tsunami soils and offshore sediments (as documented in grab samples analysed by the authors) comprise finer-grained sediments. However, the presence of such a deposit without supporting evidence, on a coast with fluctuating relative sea level, could be explained in a variety of ways.

Our data show that dendrochronological analysis of the age structure of shrubs that rapidly re-colonize a stratigraphic unit may be a good indicator of its origin. In this case, the common age of the shrubs from the tsunami-affected site (*i.e.* 12 years) points to the immediate colonization of the sediment layer following the 2000 AD tsunami.

There are several ways to establish paleotsunami chronologies (see Goff *et al.* 2012 for a review), which are key in identifying event layers and establishing tsunami frequency analysis. In coastal plain settings, one may assess the age of an event by dating the pre-tsunami soils and associated plants remains, the tsunami deposit itself, or the post-tsunami soils and plants. The age of a pre-tsunami soil provides a maximum event age since the top soil layer is frequently eroded by the tsunami, as is observed here. Only in rare cases are pre-tsunami vegetation preserved and suitable for dating (*e.g.* Bondevik *et al.* 2012). The sediments that form the tsunami deposits are redeposited and therefore contain material that is sometimes much older than the event itself. A potentially more accurate approach is to date the tsunami using Optically Stimulated Luminescence (OSL) methods based on the bleaching process during a tsunami. However, studies of recent tsunami deposits have shown that this method can provide ages from less than 40 to about 250 years older than expected due to incomplete bleaching (Murari *et al.* 2007; Brill *et al.* 2012). Moreover, new soils and plants that may develop on tsunami deposits can do so with a significant delay and thus provide much younger ages for the event. In the case described here, although 12 years had elapsed after the tsunami, an organic soil layer was not observed in most of the surveyed sites and the tsunami deposit is still remarkably fresh. However, our study shows that *Salix glauca* shrubs are able to colonize a tsunami deposits within a year of the event and potentially may therefore be very useful for its dating. This species is dominant on Disko Island (Callaghan *et al.* 2011) and *Salix* spp. shrubs are one of the most common in the moist coastal habitats across the Arctic. Therefore the method detailed here has the potential to be applied across other polar regions.

In the case of the relatively recent events (less than a century old), the tree-ring analyses of tundra shrubs may date an event with an annual resolution. However, arctic shrubs may not form a complete ring every year or may not grow evenly in all parts of the plant (Polunin 1955; Wilmking *et al.* 2012; Buchwal *et al.* 2013). Thus a local tree-ring chronology should be developed to ensure a precise event dating. This step should be validated by cross-dating of growth series within multiple sections per individual shrub (*i.e.* serial sectioning, Kolishchuk 1990) sampled from non-affected sites.

The presence of shrub wood remains within and at the surface of buried paleotsunami deposits may be very useful for radiocarbon dating. The plants studied here are rapidly colonizing the new surface and are characterized by much thicker tree-rings than those developing beyond the tsunami impact (Fig. 3, Table 1). This is one characteristic that may help identify shrub remnants that started to grow shortly after the occurrence of a paleotsunami.

Ecosystem recovery after tsunami in the Arctic. — The recovery of coastal ecosystems following tsunami events have thus far been studied in tropical (*e.g.* Cochard *et al.* 2008; Szczuciński 2012; Kaiser *et al.* 2013) and temperate (*e.g.* Chagué-Goff *et al.* 2012) climate zones. The rate of the recovery is varied and depends on many local factors including precipitation, slope gradients, drainage efficiency, soil permeability, thickness and the nature of the tsunami deposits.

The Paatuut tsunami flooded the study site with seawater, caused erosion of the beach and top soil, the death of pre-tsunami flora, and the deposition of up to 35 cm-thick tsunami deposits. However, following the event there was an immediate colonization by *Salix glauca* shrubs across an area that was covered by at least several cm thick tsunami deposits. The occurrence of these shrubs shows that seed availability was not a limiting factor and that flower buds were buried by the tsunami deposits. Rapid colonization by *Salix glauca* may also have been facilitated by an absence of competition in the freshly cleared habitat, as well as by favorable microclimate conditions (low site elevation and adequate moisture), which are typical requirements for this species (Uchytil 1992). The available space and lack of competition from other species probably also contributed to the greater radial growth of the new seedlings in comparison to those growing on sites unaffected by the tsunami (Table 1).

The observed re-colonization within the tsunami-affected site is much faster than in cases of plant succession on recently deglaciated areas. For instance, Nakatsubo *et al.* (2010) reported that *Salix* colonization started *c.* 70 years after glacier retreat in NW Spitsbergen. They attributed the slow rate of colonization here to low seed availability, difficulties in germination and/or seedling establishment. In contrast, the Paatuut tsunami deposits are of high porosity and extend across former soils that are rich in nutrients and likely contain an abundance of seeds of *Salix glauca*. These factors contributed to the recruitment and rapid development of *Salix* seedlings within a tsunami-affected area.

One of the major limiting factors in post-tsunami plant recovery is the increased salinity of soils and tsunami deposits (*e.g.* Chagué-Goff *et al.* 2012; Szczuciński *et al*. 2005). The Paatuut tsunami took place in the late autumn and left porous deposits on a gently inclined slope, facilitating relatively rapid water percolation and drainage. Moreover in the following spring, before the onset of the growing season, the tsunami deposits would have been flushed by freshwater from melting snow.

Insights into the origin of the 2000 AD events. — The Paatuut tsunami was generated by a rock avalanche and landslide (Fig. 1). According to Dahl-Jensen *et al.* (2004) the direct cause was melting and refreezing of water in surface cracks due to air temperature fluctuations during the days prior to the event. After several days with cold temperatures and some snowfall the temperature rose to 5 to 6°C for two days, causing some snow melt, followed by temperatures just below freezing on the 20th and 21st of November 2000. However, it is important that this event is put into a longer-term climatic context, something that is possible using the tree-ring analysis of our control specimens of *Salix glauca* (Fig. 2b). One specimen sampled within a reference site revealed a wood injury (Fig. 3c), which is likely a result of a physical disturbance during the dormant period (autumn and winter) of late 2000, as it visible right at the beginning of early wood formation within the growth ring of 2001 (Fig. 4a). Although several triggers may be listed as a potential reason for this single wood injury at the study site, the most likely disturbance is related to solifluction processes which are prevalent in permafrost terrains. However, the site does not reveal features typical for frequent solifluction activity, such as well-developed solifluction lobes or garlands. Also, the wood injury is the only one within the studied cross-section, so it may suggest that the conditions during that season were notably different from the average. Indeed, a comparison with available meteorological data (Fig. 4b) reveals that 2000 was exceptional in terms of the number of days with temperatures above 0°C and the highest rainfall and snowfall at least since 1990 (Hansen *et al.* 2006). This suggests that the active layer at the time of the tsunami was relatively thick and soaked with water, and this may have facilitated solifluction movements and shrub bending that is seen in asymmetric growth of last 12 annual rings followed by wood injury of our control sample BR1. These conditions may also have influenced the slopes at Paatuut and helped trigger the landslide.

Remarks on the dendrochronological application of tundra shrubs in tsunami studies. — Our results suggest that tree-ring studies of *Salix glauca* shrubs, along with careful recognition of tsunami deposits, have the potential to identify and assess the timing of paleotsunami. Thanks to the formation of annual growth rings and specific site conditions (*i.e.* a high abundance of seeds and immediate plant colonization) it was possible to confirm the age of the Paatuut tsunami deposits. However, the present pilot study is based on a small number of samples and focused on a well known, young, historical tsunami event. In order to identify and estimate the precise date of so far unknown paleotsunami events (*e.g.* which occurred in inhabited areas) we recommend the application of a combination of research approaches (*e.g.*, sedimentological, micropaleontological, geochemical); the application of dendrochronology alone is not sufficient for the unambiguous identification of a tsunami event.

Moreover, in the case of older events, where their occurrence is not obvious from field studies, a larger and more representative sample for dendrochronological analyses should be collected and cross-dated. Coastal areas affected by paleotsunamis that occurred several years or decades ago, may support several shrub species of various ages. Thus, the shrub sampling should ensure a sufficient replication of dendrochronological material which is old enough to cover the reconstruction period. In order to confirm a regional signal of the studied tsunami event a site-specific tree-ring chronology should be established and compared with the reference chronology.

Our study also provides an example of the importance of reference samples being taken from areas not directly impacted by the tsunami. They provided the reference for dendrochronological dating, but may provide insights into local paleoenvironmental changes. The meteorological data from the year of the Paatuut landslide suggests that it was remarkable warm and wet period (Fig. 4b). These conditions may have helped trigger the landslide, but they were probably also responsible for intensification of other geomorphological processes. Some of them (*e.g.* solifluction) may be also recorded in the shrubs wood anatomical characteristics, such as those documented in the present study as cambial injuries or reaction wood formation. However, it should be stressed that the interpretation of wood anatomical characteristics, such as cambial injuries or reaction wood, is not straightforward, as they can result of various exogenous disturbances, such as soil instability, long-lasting snow cover and other processes. At the same time, the environmental settings of shrub growth should be carefully analyzed in order to exclude other possible natural disturbances which might result in the formation of the same anatomical features (*e.g.* browsing by herbivory and formation of cambial injury).

Conclusions

This pilot study has demonstrated the potential application of the dendrochronological analysis of *Salix* spp. shrubs, which are common throughout the Arctic, for various aspects of paleotsunami studies. They may help in the identification and dating of tsunamis and in assessments of post-event ecosystem recovery. Although the direct impact of Paatuut tsunami was significant, the *Salix glauca* shrubs have re-occupied the tsunami deposit surface soon after the event and demonstrated high growth resistance and plasticity. The results of this study will serve as a guide for further studies of palaeotsunami in the Vaigat region and elsewhere in the Arctic.

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