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# Dendrochronological dating of geomorphic processes in the High Arctic

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**Abstract:** Dendrochronological methods were used to analyze geomorphic processes in the Arctic area. Samples of dwarf shrubs, *Salix polaris* and *Salix reticulata*, were collected from different morphodynamic surfaces: talus cones, debris flow tracks and fluvioglacial terraces. Clearly visible, countable and measurable annual growth rings (ranged from relatively wide 0.8 mm in width, to extremely narrow rings less than 0.01 mm in width) and wood anatomical changes (scars, tension wood) allow for using these species in dendrogeomorphological examinations. The age of the dwarf shrubs showed the minimum time during which the surface was disturbed by mass movements (e.g debris flow tracks developed in the early 1950s and 1970s) or the time of plant colonization which indicates disappearance of geomorphic processes (e.g. determining the age of fluvioglacial terraces in the Arie valley). Dwarf shrubs represent problems in synchronization of growth curves (discontinuous rings, missing rings, asymmetric geometry of stem). Samples taking from random surfaces can reflect only local phenomenon, which are limited to micro-topography. It is necessary to analyze material from entire area of geomorphic form.

**Key words**: the High Arctic, dendrochronology, dwarf shrubs, geomorphic processes

## Introduction

Dendrochronology including all branches of science which use the outermost tree ring to date of wood (Schweingruber 1996). One of these sciences is geomorphology. The majority of dendrogeomorphological studies have been based on data from trees growing in temperate climatic zones or on tree and dwarf shrub species growing close to the upper tree limit in different mountain regions (Alestalo 1971, Strunk 1989, McCarhy & Luckman 1993, Fantucci & McCord 1996, Gers et al. 2001, Solomina 2002, Gärtner et al. 2003, Malik 2006, Malik & Owczarek 2006, 2009, Perret et al. 2006, Bollschweiler et al. 2007, Gärtner 2007). In arctic and alpine ecosystems, where trees are rare or absent, dendrochronological research is limited. The activity of geomorphic processes in the High Arctic, based on dendrochronological method, have been investigated only in the Svalbard archipelago (Owczarek 2009, 2010, Owczarek et al. 2009), although large number of dendroecological and dendroclimatological studies have been carried out on arctic dwarf shrubs (Warren Wilson 1964, Kuivinen & Lawson 1982, Woodcock & Bardley 1994, Shaver 1986, Rayback & Henry 2005, Schweingruber & Poschold 2005, Bär et al. 2006, Zaltan & Gajewski 2006, Au & Tardif 2007). Interpretation and analysis of geomorphic processes in periglacial climatic conditions have been provided mainly on the basis of air photographs and direct field measurements or on the basis of discontinuous records ($^{14}C$, lichenometric and OSL dating) in multiple arctic sites (Rapp 1960, Åkerman 1980, Rapp & Nyberg 1981, Matsuoka et al. 2003, Kostrzewski et al. 2004). These examinations are limited due to small number of repeated air photographs, especially on the first half of 20$^{th}$ century, or, in case of field measurements, impossibility to determine the age of geomorphic forms and frequency of processes. In this paper I briefly describe to use of tundra dwarf shrubs, *Salix polaris* and *Salix reticulata*, their age and wood anatomical changes, as a poten-

Author of this article was awarded in the contest for the best doctoral thesis in geomorphology in 2005 for the thesis “Transformation of gravel-bed rivers under the influence of coarse-grained sediment supply” tial source of dendrogeomorphological data from the High Arctic area.

## Research area

The research was carried out in the Wedel Jarlsberg Land in SW Spitsbergen, Svalbard (Fig. 1). Dendrochronological methods were used to determine: (1) talus cones development, (2) the history of debris flow activity and (3) the activity of fluvial and fluvio-glacial processes. Three examples of study will be presented in this paper (Fig. 1a, b, c). Mountain massifs with elevations of *c.* 500–600 m a.s.l. aligned longitudinally and coastal plains with several marine terraces dominate in the landscape of SW Spitsbergen. The mean annual air temperature is –4.4°C, varying between –11.3°C in January to +4.4°C in July (Marsz & Styszyńska 2007). As is usual in Arctic regions, there is little precipitation, only 300–400 mm. Variations of Arctic climatic conditions, which are connected mainly with topography of the area and influence of ocean and glaciers, geology and thickness of snow cover determine vegetation development. Vegetation of tundra community is dominated by low creeping dwarf shrubs and different species of mosses, herbs and lichens. The climatic conditions result in the vegetative period being short. It starts on June and lasts to *c.* until the end of August, i.e. ranges from 40 to 70 days. Four vegetation zones can be distinguished in the Spitsbergen Island: (1) *Papever dahlianum* zone (southern part of the island), (2) *Salix polaris* zone (northern shore of Horsund and inside part of the island), (3) *Dryas octopetala* zone (middle and northern shore of Spitsbergen) and (4) *Casiope tetragona* zone (especially middle part of the island) (Rønning 1996). Tundra community is especially rich on planes. On screes, moraines and block fields the vegetation cover is generally no more than 10–15%.

## Material and methods

### Wood materials

To dendrochronological date of geomorphic processes were used two species of dwarf shrubs which belong to Willow family (*Salicaceae*): *Salix polaris* and *Salix reticulata*. These circumpolar species occurring in northern hemisphere in North America, Europe and Asia. These species have clearly visible, countable and measurable annual growth rings (Owczarek 2009). The oldest individual of *Salicaceae* analysed was 98 yr old.

***Salix polaris*** (Wahlenb.) is a commonly known as polar willow (Påhlsson 1985). This dwarf shrub re-

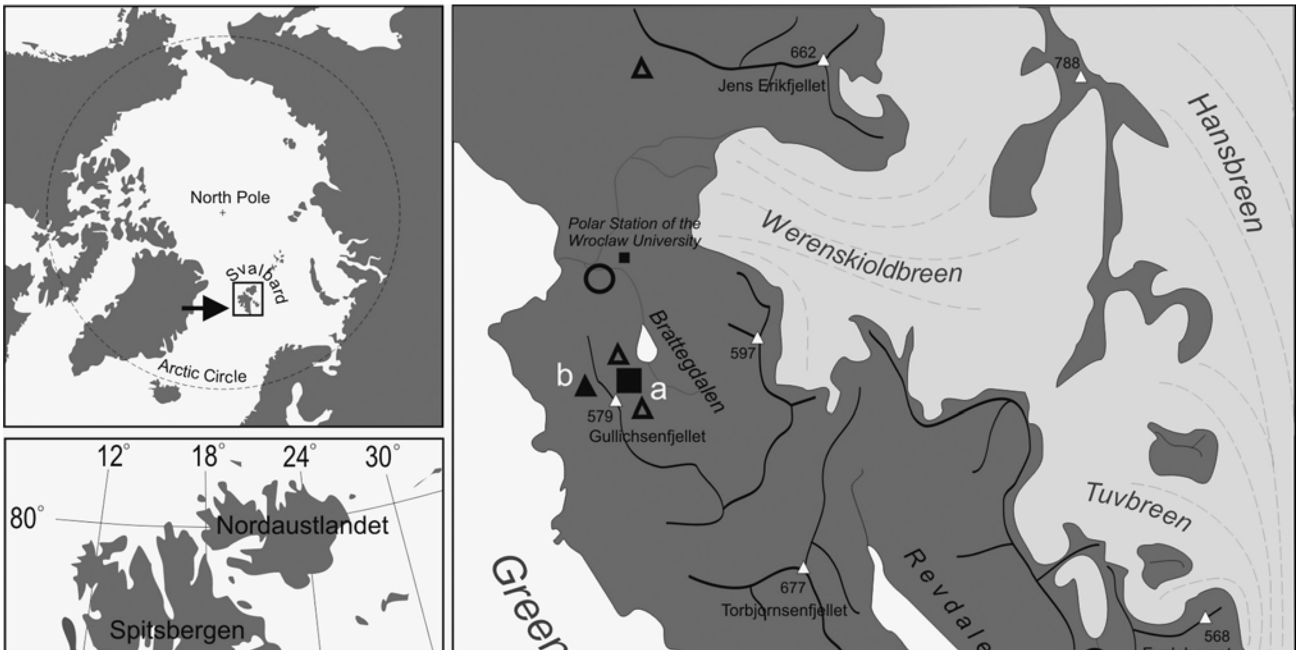


**Fig. 1.** Location of the study area with places of detailed research: 1 – talus cones (a – the Brattegdalen talus cone), 2 – debris flows (b – the Gullichsenfjellet debris flow), 3 – valley bottom analyzed (c – the Arie valley)

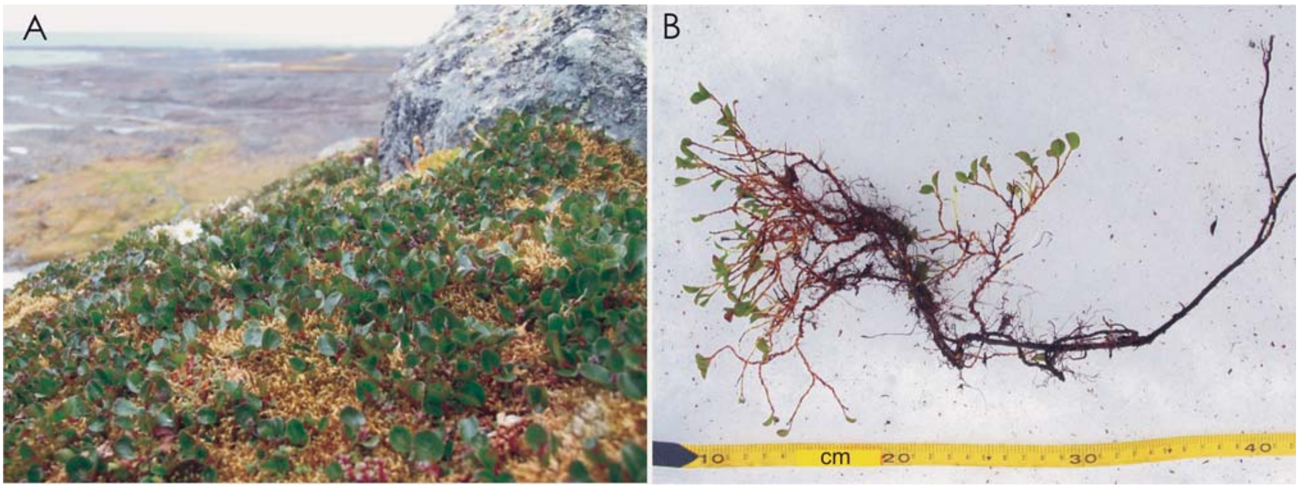


**Fig. 2.** (A) *Salix polaris* Wahlenb. – Polar willow, (B) complete individual of *S. polaris* including leaves, branches and root system

produces by seed and also vegetatively by rooting at the nodes of stems. This deciduous, prostrate, trailing shrub is usually less than 8 cm tall and forms mats (Fig. 2A). *S. polaris* is a creeping shrub with long shoots. Only small oval, dark green leaves with fresh branches are visible above the ground level. Wooden branch and root system are located underground in the uppermost of active layer of permafrost (Fig. 2B). *S. polaris* is common in south part of Spitsbergen. This species can be meet in different conditions, both on moraines and dry screes as well as on wetlands. ***Salix reticulata*** (L.) is called net-leaved willow (Påhlsson 1985). It is low (8–10 cm) creeping shrubs and reproduces vegeatatively. In compare to *S. polaris*, *S. reticulata* has larger oval green leaves. The branch system is located marginally subterranean. This dwarf shrub usually doesn't form mats. *S. reticulata* grows on dry, sunny, gravel slopes. It's common on screes.

*Geomorphic mapping and samples collection*

The study sites were selected according to accessibility of *Salicaceae* species and their location within on the typical periglacial land forms. The samples collection and field research were carried out during two arctic summers 2007 and 2008. Simple geodesic methods were used to mapping of land forms (debris flows, fluvio-glacial terrace edges) drown to a scale of 1:500.

The two major dendrogeomorphological approaches applied here use the age of dwarf shrubs and event-response dating using ring patterns and wood anatomical changes in the shrubs affected. Complete individuals of *S. polaris* and *S. reticulata* including the root and branch systems were collected in the field (Fig. 2B). Minimum of ten samples were collected from each debris flow tracks. Samples from debris cones and terraces were taken along several transects. Each individual was documented by digital photos.

### Laboratory analysis and measurement of tree-ring structures

The samples were sectioned with GSL 1 sledge microtome, taking 15–20 $\mu$m cross-sections from 4 to 7 different locations along the length of the individuals (Fig. 3). This cutting was necessary, because the oldest part is located on the border between wooden branch system and root (Schweingruber & Poschold 2005). This part isn't visible on the basis of physiognomic structure of *Salicaceae*. Microtome sections were prepared from the whole diameter of selected segments. Maximum stem diameters ranged from 0.5 cm to 1.1 cm. After staining with 1% solutions of safranin and astrablue, digital photographs of the micro-sections were taken for tree-ring analysis and measurements. Ring widths were measured along two or three radii using the programs OSM 3.65 and PAST4. The samples were visually crossdated using skeleton plots. The accuracy was verified using COFECHA program.

## Wood anatomy characteristics

### Growth-rings

Woody plants with tree rings can be found in all climates on Earth, but the frequency of species with clear visible of tree rings is directly related to the seasonality of climate (Schweingruber 1996). Growth-ring boundaries in arctic *Salicaceae* have been variously reported especially for *Salix arctica* (Beschel & Webb 1963, Warren Willson 1964) and *Salix alexensis* (Zaltan & Gajewski 2006). *S. polaris* and *S. reticulata* are semi ring-porous and have well-defined growth-rings whose boundaries are delimited by one or more rows of cells (Owczarek 2009) (Fig. 4AB). Cells, rectangular in cross section, are usually smaller in *S. reticulata* in compare to *S. po-*

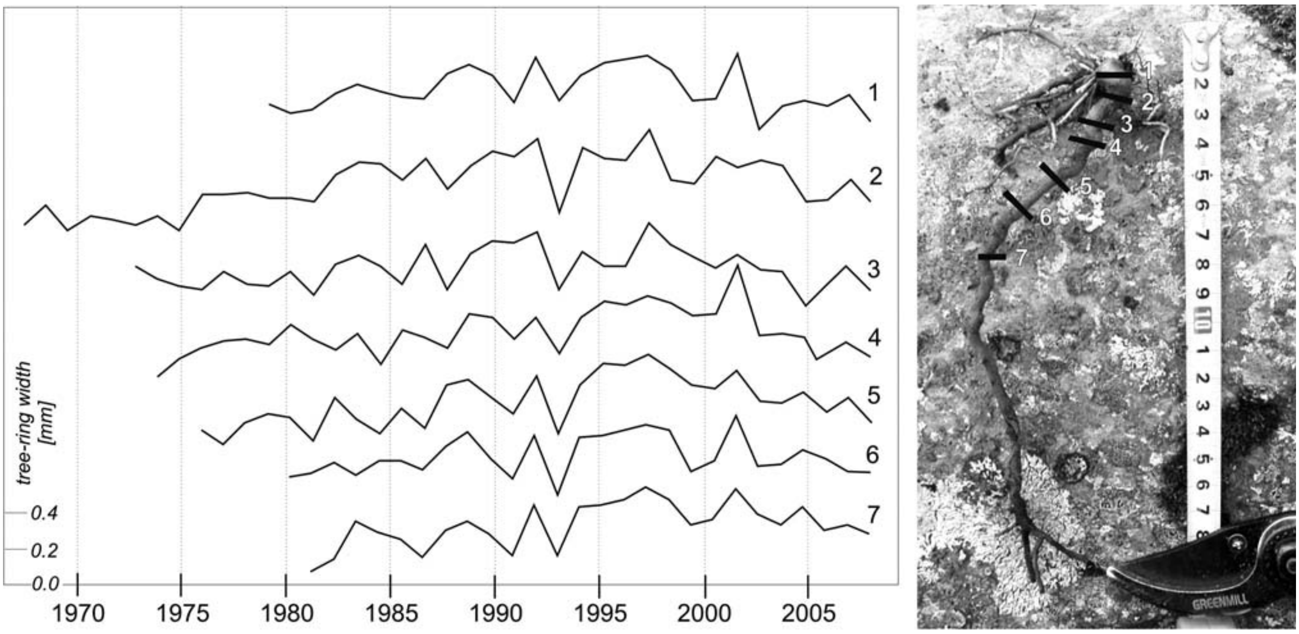


**Fig. 3.** Serial sectioning of *S. polaris* shows the high variability of growth ring formation within one individual plant; the oldest part in cross-section no. 2

*laris,* thus boundaries of *S. reticulata* tree-ring are better visible and easily countable. Growth-rings in the individuals ranged from relatively wide 0.8 mm in width, to extremely narrow rings less than 0.01 mm in width, usually meet in *S. polaris*. Discontinuous growth rings are very common in analysed species (Fig. 4C). Partially absent tree rings appear due to e.g. climatic conditions (frost year, absence of water), mechanical stress connected with periglacial processes or partly limitation of root and branch system growth space. The age of samples is used to determine minimum age of geomorphic form or processes (Stoffel & Bollschweiler 2008).

*Reaction wood*

Reaction wood, called tension wood in angiosperms, is often visible in analysed dwarf shrub species. This type of wood is only found in upper side of tilting stem and root and indicate the change in stem position. Tension wood cells exhibit irregularly shaped secondary walls, so-called gelatinous fibers (Fig. 4D) (Schweingruber 1996). This parameter plus geomorphological features gives possibility of reconstruction of the spatial and temporal patterns of slope movements, e.g. debris flow events or solifluction movements. Reaction wood was analysed in the samples, which grow on the debris flow trucks. Branches and stems of *S. polaris* and *S. reticulata* are very flexible and so they can survive during high energy geomorphic events.

*Scars*

Scars appear when falling or flowing rock particles collide with root, stem or branches of dwarf shrubs. Injures are callused over by bordering cambiums (Fig. 4EF), thus it is possible precisely to determine geomorphic events according to the position of the scar from cross-section (Hupp et al. 1987, Shroeder & Butler 1987, Stoffel & Bollschweiler 2008). Stem and branches of arctic *Salicaceae* are very flexibility. This feature allow to survive of wounded shrub. Wounded arctic shrubs can be found both in valley bottoms and on steep screes, but injured shrubs, which grow only on steep slopes, can be used in dendrochronological analysis. Wounds on dwarf shrubs growing in valley bottoms and other flat areas can not to be analyzing, because large number of injures is connected with animals (polar bears, reindeers).

## Examples of dendrogeomorphological research

*Talus cone development*

The talus cones are formed by rock weathering, rock fall and by further downslope transport caused by creep, slide, debris flow or snow avalanches (Luckman 1977). They are very common, characteristic geomorphological features of periglacial, arid and high-mountain environments (Albjär et al. 1979). Depending on the active geomorphic process, the supply of talus material may be either a continuous or a periodic process. The structure, morphology and sources of material of talus cones in the Arctic areas have been reported in many papers (Rapp 1960, Jahn 1967, Church et al. 1979, Åkerman 1980 1984, Rudberg 1986, Ballantyne 2003). Owczarek (2010) used arctic dwarf shrubs for analysis of talus cones activity in southern part of Spitsbergen. The age of the dwarf shrubs showed the minimum time during which the cones were disturbed by mass movements. One of the talus cone analyzed is located in the Brategg valley on the eastern slope of the Gullichsenfjellet massif (579 m a.s.l.) (Figs 1c, 5). The cone is situated below narrow rock-fall chutes, which refer to schist beds within a complex of Middle Proterozoic white and green quartzites (Manecki et al. 1993). The cone has a distinct lower convex margin with an angular block-rich surface. The talus cone analyzed is 110 m in height with an average slope gradient of 33° (Fig. 6A). In the steep upper and middle part of cone are observed two debris flow channels with distinct visible levees (Fig. 6B). Irregu-

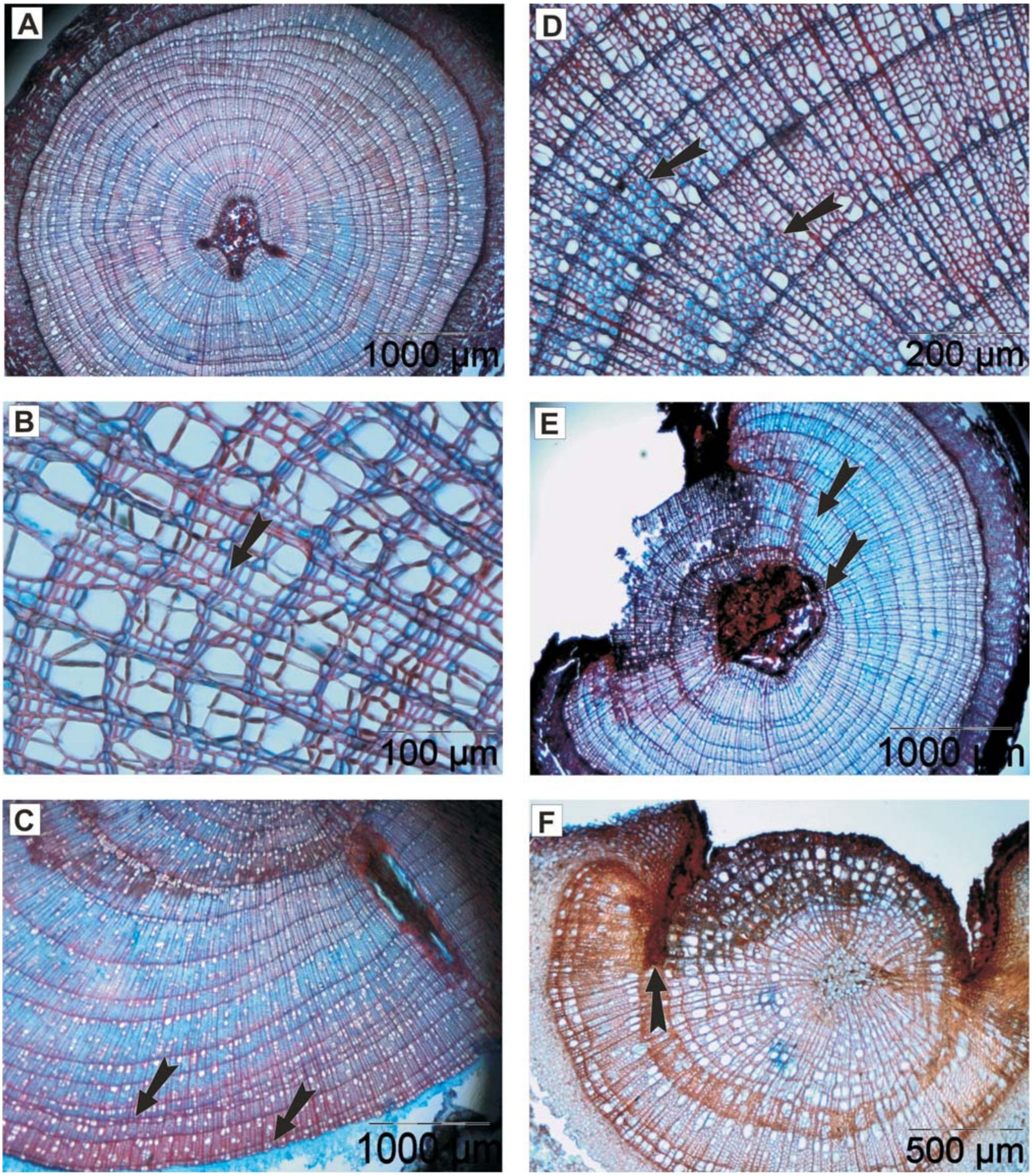


**Fig. 4.** Examples of wood anatomy features of *Salix polaris* and *Salix reticulata*. (A) growth rings, estimated age of the sample is 14 years, (B) ring boundaries, which consist of two or more rows of rectangular cells and are indicated by arrows, (C) portion of the section that includes two discontinuous growth rings, (D) tension wood, arrows indicate on the irregular gelatinous fibers, (E) two generation of scars, 12 years old and 9 years old, (F) 4 years old scar, overgrowth starting from the lateral edges of the injury is distinct visible

**Fig. 5.** The Brategg valley and eastern slopes of Gullichsenfjellet massif (579 m a.s.l.). Arrow indicates on the talus cone analyzed

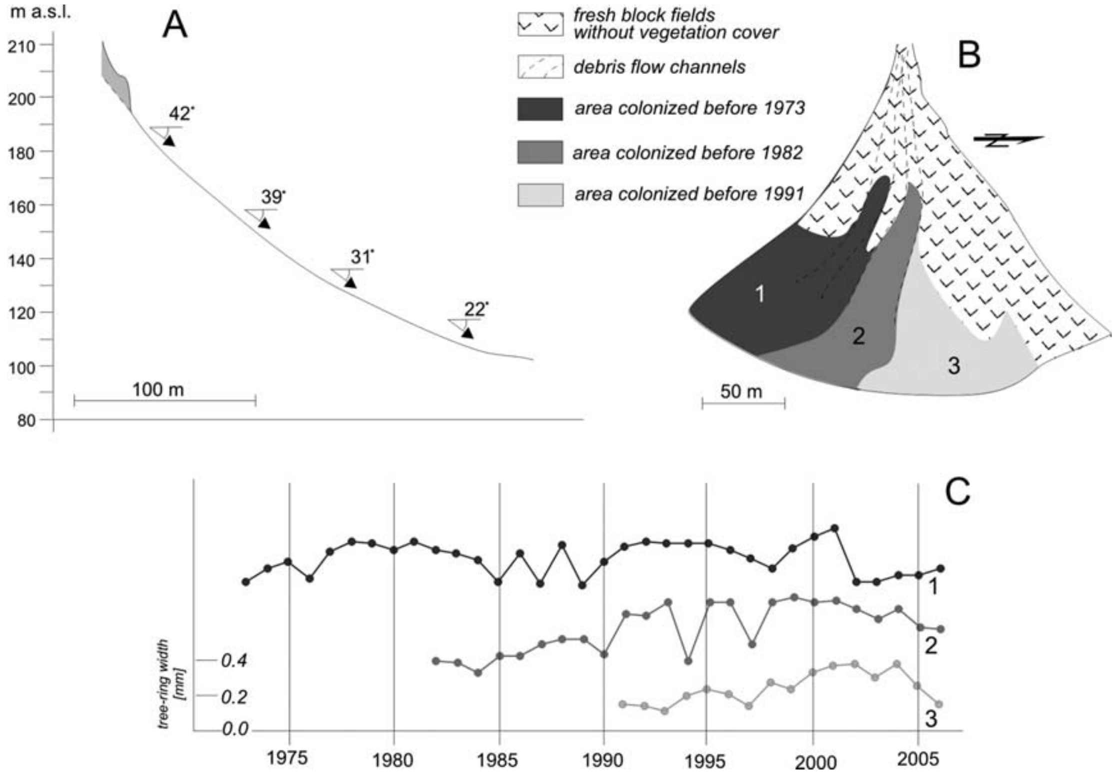


**Fig. 6.** The Brateggdalen talus cone: (A) longitudinal profile, (B) morphological sketch, (C) tree-ring diagrams of the oldest samples of *Salicaceae* collected from the distal part of the cone

lar solifluction lobes are characterized for the lower part. The rock material is angular and the grade finer at the top and coarser in the distal part. In the marginal areas are blockfields. Fresh blockfields, without vegetation cover, are observed in the upper part and the north-facing side of the cone. 12 samples of *S. reticulata* and *S. polaris* were collected from the middle and distal part. Tree-ring analysis indicates that the cone started being colonized by vegetation in the early 1970s. In the first phase, the vegetation started appearing on the south-facing side of the cone (Fig. 6B, C). At present only the north side of the cone is active. The cone is being developed here through debris creep and slide.

*Debris flows*

Debris flow is an event during which a large volume of a highly concentrated viscous water-debris mixture flows downstream a slope. This with rock falls is the most important process, which shapes and upbuilts debris cones. Talus cones with large debris flow tracks are one of the most common and characteristic features of the periglacial area. Debris flows in the Arctic region are triggered by rainfall during short arctic summer or fast snow melt (Rapp & Nyberg 1981, Larsson 1982, André 1995) . Field observations demonstrate, that the largest intensity of this process take places in the first phase of the short arctic summer. Owczarek & Latocha (2009) presented the first results of debris flow investigations by using dendrochronological methods in the High Arctic area. One of the most interesting research site with debris flow tracks is located on the western slope of the Gullichsenfjellet massif (Figs 1b, 7). Debris flow forms are located on the talus cone (80 m in height) with average slope gradient about 35°. Lower part of the cone is located on the flat marine terrace on the height about 15 m a.s.l. The material is angular and grade finer at the top and coarser near the margin. Distinct visible three debris flow tracks are observed on the cone area (Figs 7, 8). The track G0 is present shaped by periodic debris flows and is used by flowing water. The tracks G1 and G2 are fossil and are partly covered by vegetation. The length of these two debris flow is about 155 m. These fossil debris flows have well defined leveés varying in hight from 0.4 to 1.5 m (Fig. 8). Lower parts are occupied by accumulation forms, fan like in G1 and finger-like in G2, with particle size ranging from fine sand to coarse angular rock blocks.

*Salix polaris* and *Salix reticulata* samples were collected from levees, debris flow tracks and accumula-

**Fig. 7.** Debris flow tracks on the talus cone in the Gullichsenfjellet massive

tion forms (Fig. 8). The age of dwarf shrubs shows minimum time, when the cone was disturbed by debris flow events. The sampled dwarf shrubs started growing from 1955 in G1 and from 1972 in G2 (Fig. 9). So the debris flow G1 event must have happened earlier than G2. Interesting information is yielded by wood anatomical features such as tension wood and scars. These features show age of debris flow events on relatively smaller energy without surface-clearing disturbances. Analyses of these growth reactions resulted in an accurate dating some event years, which are especially marked in the 1990's and second half of 1980's (Fig. 9). These results are correlated with meteorological data. Extraordinary precipitation events were observed during this time.

*Reconstruction of fluvio-glacial processes activity (the Arie valley)*

The fluvial processes in periglacial environment differ than another regions. Hydrologic regime of the rivers is connected not only with precipitation or snow and glacial melts during summer season as well as with thawing of permafrost and thermo-erosional phenomenon. The Arie valley is located in the northern shore of the Hornsund Fjord. The Arie River is a right tributary of the Revelva River (Fig. 1c). The length of the valley is 5.5 km and maximum width – 1.1 km. The upper part is occupied by small Arie Glacier (Fig. 10A), which is separated from flat valley bottom by large and wide lateral moraine (Fig. 10B). The steep slopes of the valley are free face in

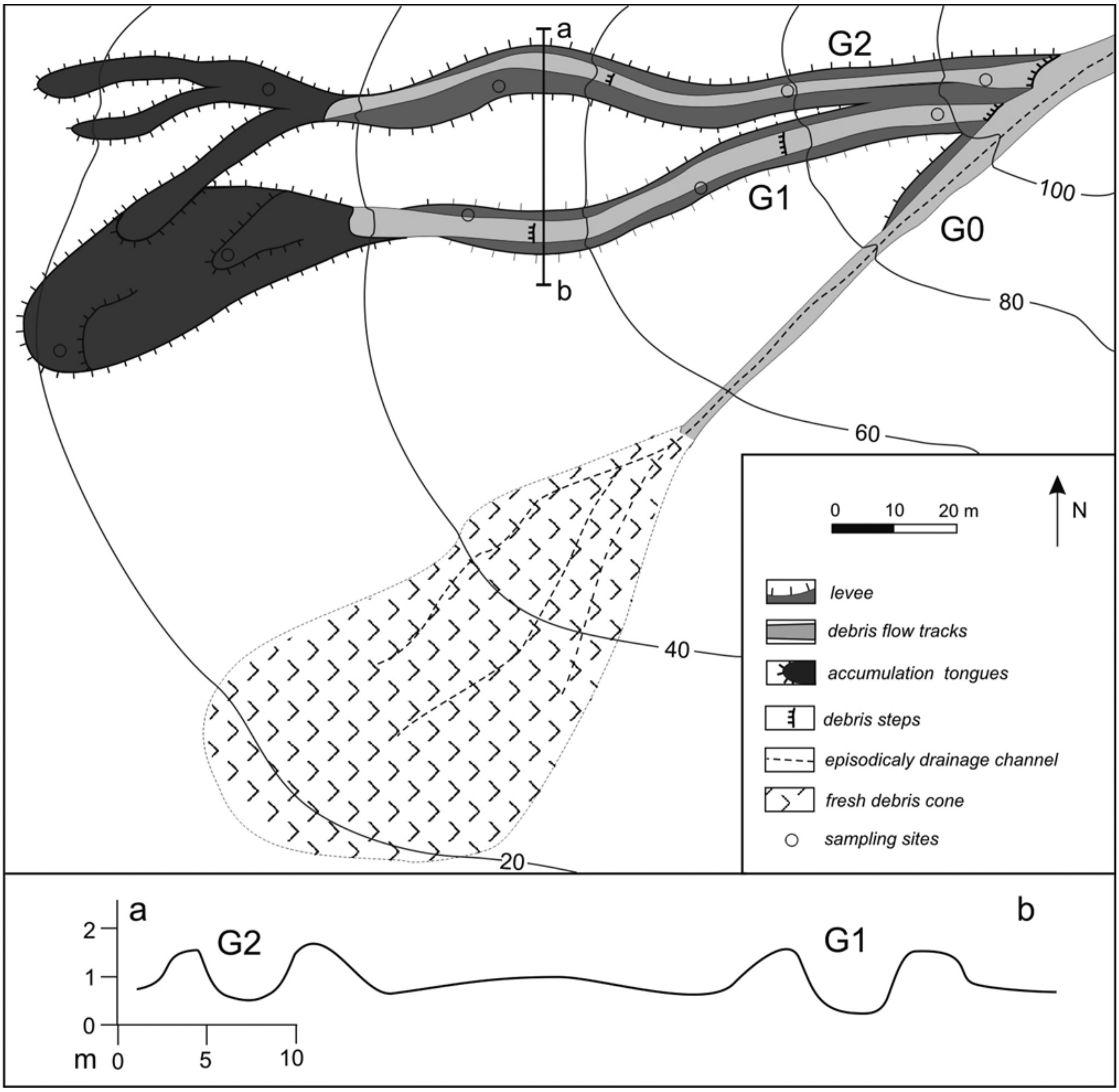


**Fig. 8.** Geomorphic sketch of the debris flow tracks on the talus cone in the Gullichsenfjellet research site with an example of cross-section

the upper- and debris in lower part. They are built of Middle Proterozoic paragneisses and schists. Two levels of fluvio-glacial terraces are distinct visible in the morphology of the valley bottom. 29 samples of *Salicaceae* were collected from lateral moraine and fluvio-glacial levels T2 (higher level) and T1 (lower level) (Fig. 10C). On the basis of the amount of annual rings, there was a possibility of determining the age of the main geomorphic forms in the Arie Valley and hence reconstruction of the course of geomorphic processes (Owczarek et al. 2009). In the light of dendrochronological analysis can be distinguish tree stages of the Arie Valley development during last 100 years: (1) before 1930 – aggradation phase – development of higher level of the fluvioglacial terrace (Fig. 11A), (2) form the turn of 1930 and 1940 – intensive erosion phase, connected with the Arie glacier retreat (Fig. 11B), (3) from the 1970–1975 – sta-

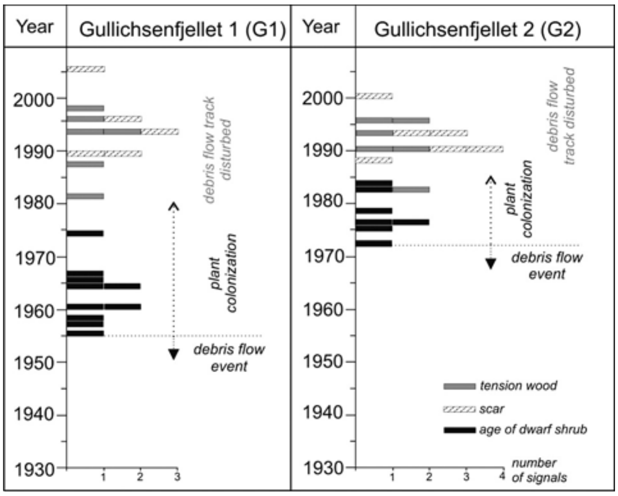


**Fig. 9.** Diagram showing the age of samples and the number of debris-flow event years derived from dendrochronological analysis

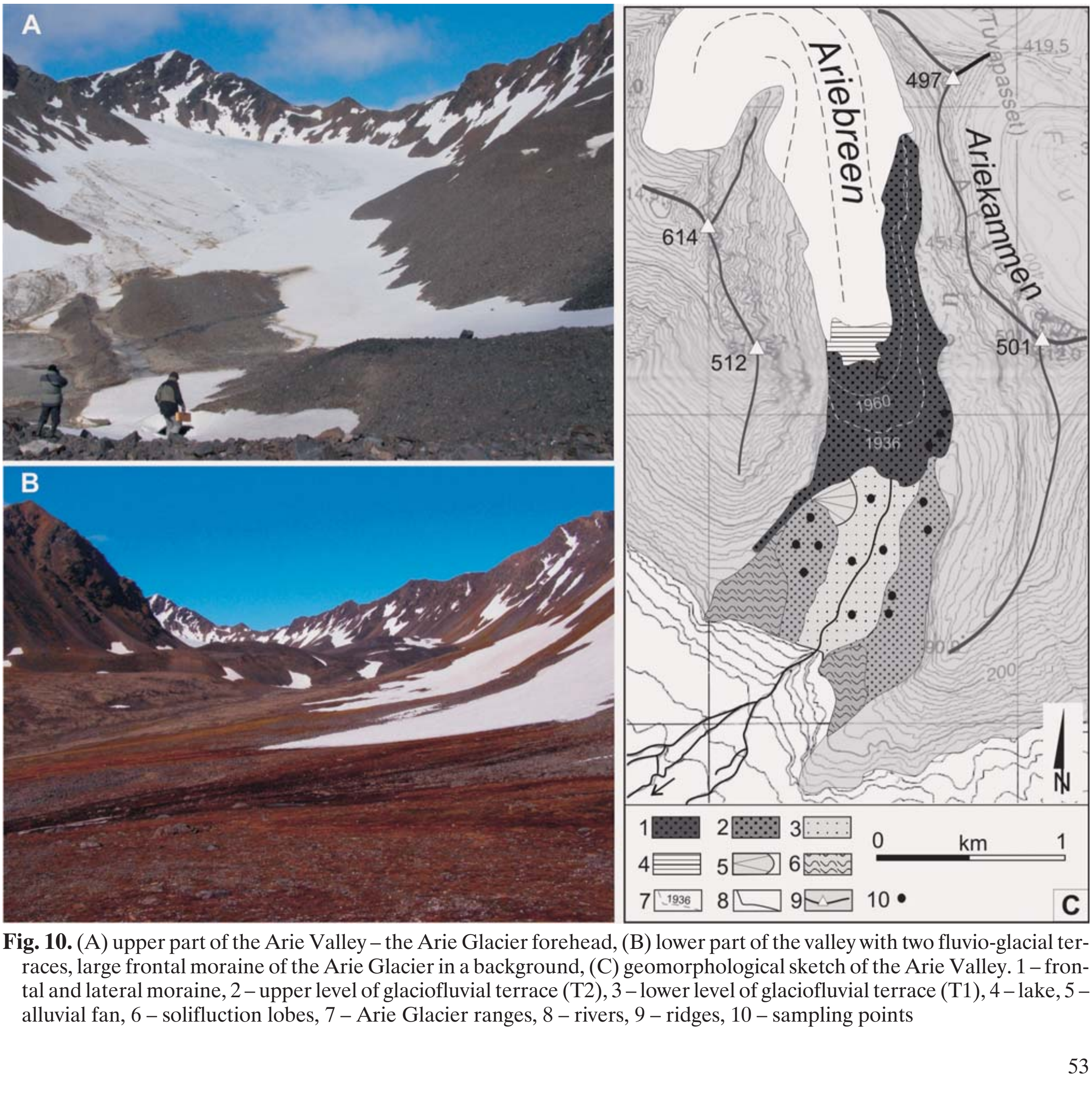


**Fig. 10.** (A) upper part of the Arie Valley – the Arie Glacier forehead, (B) lower part of the valley with two fluvio-glacial terraces, large frontal moraine of the Arie Glacier in a background, (C) geomorphological sketch of the Arie Valley. 1 – frontal and lateral moraine, 2 – upper level of glaciofluvial terrace (T2), 3 – lower level of glaciofluvial terrace (T1), 4 – lake, 5 – alluvial fan, 6 – solifluction lobes, 7 – Arie Glacier ranges, 8 – rivers, 9 – ridges, 10 – sampling points

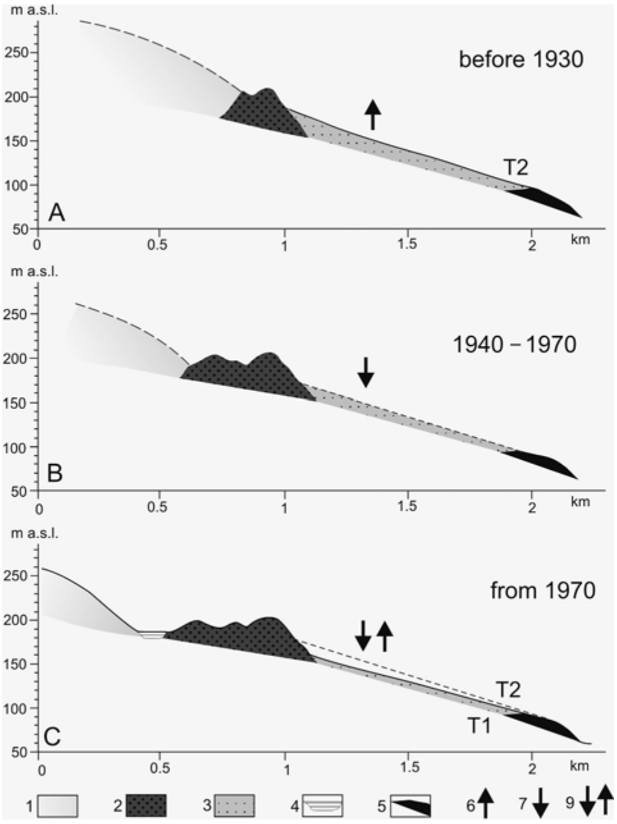


**Fig. 11.** The diagram showing the Arie valley development during last 100 years, reconstruction on the basis of the age of dwarf shrubs. 1 – the Arie Glacier, 2 – frontal moraine, 3 – glaciofluvial terraces (T2 – upper, T1 – lower), 4 – lake, 5 – knickpoint, 6 – aggradation, 7 – erosion, 8 – equilibrium phase

bilization of the valley bottom and development of the lowest part of the valley (Fig. 11C).

## Discussion

No detailed dendrogeomorphological studies were conducted so far on arctic *Salicaceae* and therefore a comparison with other regions is presently not possible. It is common that Arctic dwarf shrubs have narrow growth rings consisting of only few cell rows (Warren Wilson 1964, Woodcock & Bradley 1994, Schweingruber & Dietz 2001, Bär et al. 2006). The age of the oldest known individual of *Salicaceae* from the Arctic which has been analysed dendrochronologically was 87 yr (Beschel & Webb 1963). I found individuals from the Arie Valley, to the north of Hornsund Fjord, reaching the age of 98 yr. I indicated the age of dwarf shrubs and hence the minimum age of the geomorphic forms. It is difficult to estimate the time which passes between a geomorphic event and a dwarf shrub germinating. This time is dependent on the site conditions: soil composition, slope declination, insolation, snow/water conditions, runoff dynamics etc. Birks's (1980) is showing that *Salix* is starting colonization of ice-cored moraines already after 6–10 years. Moreau et al. (2008) and Ziaja (2006) delivered similar results of examinations of the rates of plants succession in the Arctic. The research conducted in the Lovén glacier forefield and Sørkapp Land (Spitsbergen) indicates, that vascular species appeared very quickly after deglaciation, usually earlier than lichens.

Discontinuous rings, missing rings as well as asymmetric geometry of the stem constrict the synchronisation of growth curves. The eccentric growth, connected with locally absent rings, and lobate growth form is typical for *Salicaceae* analyzed. It can be caused by pressure, e.g. by stones in active layer (Schweingruber & Poschold 2005). Microscopic analysis showed also numerous damages associated with reindeer grazing, especially on a flat fluviogalcial areas. These disadvantageous features caused that many of the sections were difficult to crossdate. Other researchers of dwarf shrubs notice similar difficulties (cp. Bär at al. 2006, Zaltan & Gajewski 2006). These factors cause that dendrogeomorphological analysis in the Arctic is completely different compared with the studies in temperate climatic zone. Micro-site conditions, e.g. slope inclination and exposition, active layer thickness, period of snow beds lying, are playing the huge role in growth-ring formation. These site-related differences and features of wood anatomy must be taken into consideration during dendrogeomorphological analysis in the High Arctic area.

## Conclusions

1. *Salix polaris* and *Salix reticulata* demonstrate excellent potential for use in dendrogeomorphological analysis in the Arctic conditions where trees are absent. Microscopic analysis of collected samples indicated that these species have clear visible growth rings which ranged from relatively wide, 0.8 mm in width, to extremely narrow rings less than 0.01 mm in width.
2. The two major dendrogeomorphological approaches applied here use the age of dwarf shrubs and event-response dating using ring patterns and wood anatomical changes in the shrubs affected. The features of *S. polaris* and *S. reticulata* wood anatomy, such as tree-ring variations, reaction wood and a distinctly visible layer of cambium cells which grow over the injury, enable to determine the minimum age of the land form (e.g. minimum age of fluvio-glacial terraces development, the age of debris flow tracks) and the frequency of natural geomorphic events in the past (e.g. debris flow frequency, activity of talus cones).
3. Dwarf shrubs like *S. polaris* and *S. reticulata* growing in difficult climatic conditions during

short arctic summer represent problems in synchronization of growth curves (discontinuous rings, missing rings, eccentric growth). The most important is a good strategy of sample collection. It is necessary to analyze material from entire area of geomorphic form (e.g. along debris flow tracks). Samples taking from random surfaces, can reflect only local phenomenon, which are limited to micro-topography.

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