LICHENOMETRIC STUDIES ON MORAINES IN THE POLAR URALS

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ABSTRACT

Lichenomety was used to study fluctuations of six glaciers in the Polar Urals over the last millennium (viz: IGAN, Obrucheva, Anuchina, Shumskogo, Avsiuka and Berga glaciers). In order to estimate the growth rate of *Rhizocarpon* subgenus *Rhizocarpon* lichens we used recently deglaciated surfaces as calibration sites. These sites, on glacier forelands, were dated using topographic maps, aerial photographs (from 1953, 1958, 1960, 1968, 1973, 1989), terrestrial photogrammetry, field photographs (from the 1960s to 2005), and satellite images (from 2000 and 2008). We also used pits and quarries abandoned between the 1940s-1980s and a road built in the early 1980s as calibration sites. Optimum diametral growth rates of *Rhizocarpon* subgenus *Rhizocarpon* are estimated by the new curve to be ~0.25 mm/year for the last 100 years, assuming linear growth as deduced from the shape of other curves from northern Scandinavia. Due to the lack of old control points we used a reconstructed mass balance curve (from 1816-2008) to indirectly constrain the age of pre-20th-century moraines. The following moraine groups were identified near the modern fronts of glaciers: ablation moraines deglaciated during the last 40 to 60 years; lateral moraines formed in the early 20th century (largest lichen diameter (D_{LL}) = 20 mm), ice-cored moraines, probably from the 1880s (D_{LL} = 24 - 26 mm); moraines probably deposited in the middle of the 19th century and ca. 200 years ago (D_{LL} = 30-33 mm and 44-47 mm, respectively); as well as several more ancient moraines (D_{LL} = 70 mm, 90 mm and 110 - 153 mm) deposited during glacier advances of almost identical extent. According to our tentative lichenometric-age estimates most moraines were formed during the last 450 years – consistent with upper tree-limit altitude variations previously identified for this region. Glacier fluctuations in the Polar Urals are in agreement with tree-ring based reconstructions of summer temperature spanning the last millennium, and are also in tune with glacier behavior elsewhere in the Northern Hemisphere.

Key words: Lichenometry, glacier mass balance, 'Little Ice Age', climatic reconstructions, tree rings

Introduction

Reliable, multi-proxy records of climate fluctuations before and since the industrial revolution are essential to the early detection of global climate change and its attribution to specific causes. We report a valuable source of such information – fluctuations of six small glaciers in the Polar Urals over the last few centuries, dated by lichenometry. Small glaciers respond to climate changes on decadal time scales, directly relevant to human concerns. In addition to being valuable records in their own right, they provide an opportunity for comparison with other, completely independent, natural archives of climate variability.

The aims of this paper are threefold: 1) to examine the growth rates of *Rhizocarpon* subgenus *Rhizocarpon* lichens in the Polar Urals; 2) to estimate the age of moraines adjacent to six Polar Ural glaciers; and 3) to discuss the age of these moraines in the context of other climatic proxies in the region.

Study area and earlier results

The Ural Mountains are located between the East European and West-Siberian plains and extend over 2000 kms, from Yekaterinaburg in the south to Baydaratskaya Bay in the north (Fig.1). The highest peak is Mt. Narodnaya (1640 m). Most glaciers and perennial snow patches are located in the northern part of the Polar Urals (ca. N 68°10', E 67° 30'). This region forms part of an old more extensive denudation plateau eroded from the west, explaining why most glaciers are concentrated in the western side of the mountains. The present-day glaciers are very small, predominantly of cirque and niche types oriented to the east. None of them is larger than 1 km^2. The elevation of these glacier termini range from 400 to 900 m a.s.l. (Table 1). All of them are located below the present-day climatic snow line and their existence is largely dependent on preferential snow concentration in niches and cirques by wind (Troitsky 1961).

The climate of the Polar Urals is continental and quite severe. In the seasonal cold period (October-April) frequent cyclones result in abrupt changes of air temperature, strong winds and abundant precipitation. The ablation period at the glaciers lasts from the end of May to September, but its length can vary considerably. Summers in the Polar Urals are cool and rainy. The maximum precipitation totals occur in summer. The mean summer temperature at the Bolshaya Khadata station (260 m asl) for 1958-1980 was 7°C, mean winter temperature was -14.3°C; the sum of warm period precipitation is on average 70 mm; and mean annual precipitation is around 610 mm (1958-1980). The vertical precipitation gradient is ca. 100 mm per 100 m of elevation. Mean annual temperature is negative (-6.3 °C for 1958-1980) and the annual temperature range is from -29.8°C to +15.0°C.

The dominant type of vegetation in the Polar Urals is mountain tundra. Larch forests are located at the piedmonts and in the lower part of the mountains; the upper tree limit rises up to 250 m asl. The glaciers in the Urals were discovered in 1929 by Aleshkov, and in the Polar Urals in 1930 by Padalka (cited in Troitsky et al. 1966). A glaciological research programme was initiated in the Polar Urals during the International Geophysical Year and continued until the early 1980s (Dolgushin 1960; Troitsky 1961, 1966; Tsvetkov 1981), when the research base at the Bolshaya Khadata lake was closed. Since then the glaciers have been visited for monitoring purposes only sporadically (Glazovsky et al. 2005).

The morphology of the Late Pleistocene and Holocene moraines of the Polar Urals have been described in detail by Troitsky (1961, 1966) and Dolgushin (1963). However none of these moraines has been dated by radiocarbon analysis so far. Recently Mangerud et al. (2008) dated the moraines at the Chernov glacier by cosmogenic isotope (^{10}Be) analysis. They reported that during the Late Pleistocene maximum (18-22 ka) the

Chernov glacier was only 1 km longer than it is now.

Martin (1967, 1987) was the first to use lichenometry to estimate the age of moraines in the Polar Urals. He calculated the growth rate of the lichen *Rhizocarpon tinei* (later identified as *Rhizocarpon geographicum (L.)DC* using assumptions concerning the age of the young moraines, coupled with direct measurements of lichens spanning a 12 year interval. He identified numerous advances of three glaciers, generally dividing them into two major groups: 100-400 and 700 years ago. However, the growth rates of lichens were only estimates and lacked firm chronological control, hence the moraine ages reported by Martin (1967, 1987) remain tentative.

Analysis of air photographs from the Polar Urals shows that all glaciers had retreated from their Little Ice Age maxima by the mid 20th century (Troitsky 1966). The magnitude and style of the recession of individual glaciers depends very much on glacier morphology, elevation, aspect, etc. The cirque glaciers IGAN (Institut Geografii Akademii Nauk), Berga, Markova, and Kalesnika have not changed their contours much during this time, although their surface heights have considerably decreased. The Obrucheva and MIIGAiK glaciers have receded faster; their fronts had already withdrawn from their Little Ice Age moraines by 1950s. Glaciers terminating in lakes, such as the Dolgushina, Bocha, Chernogo, Shumskogo and Pareisky, have receded the fastest and have reduced in volume the most. Niche (or slope) glaciers have been more stable. Troitsky et al. (1966) estimated that the glaciers of the Polar Urals thinned between 1880s-1960s by ca. 20-30 m in their accumulation areas and ca. 40-50 m in their ablation areas. In many cirques, the glaciers have disappeared completely. Glazovskiy et al. (2005) and Ivanov (2009) demonstrated that in the second half of the 20th century and early 21st century most glaciers in this region continued to recede. The IGAN glacier was stable from 1953 to 1981, but has retreated 450 m since then. The Obrucheva glacier retreated steadily from 1953 to 2008 – a total of 450 m (see Table 1). However, some very small niche glaciers have remained stable since the 1930s due to their shaded locations.

Khodakov first reconstructed the mass balance of IGAN and Obrucheva glaciers based on direct measurements of ablation and accumulation at these two glaciers between 1957 and 1962; and temperature and precipitation measurements at the meteorological station Bolshaya Khadata (260 m asl) located close to the glaciers; alongside meteorological parameters measured at more remote stations (Vorkuta, 1926-1963) and Syktyvkar (1818-1963) (Troitsky et al. 1966). Khodakov found that in much of the 19th century, glacier mass balance in the Polar Urals was close to zero. By the end of the 19th century, it became negative, with the exception of the 1880s, when glacier volumes increased. June-August air temperature and November-May precipitation, both relevant to the glacier mass balance, registered at Salehard meteorological station showed an increasing trend from ~1890 to 1950. Since the beginning of the 1960s the temperature trend became slightly negative, while the variation in precipitation did not change significantly. This shift is reflected in the glacier's mass balance which has stabilized since 1965. The reconstruction was extended up to 2000 by Kononov, et al. (2005). Recently, Ivanov (2009) revised all available reconstructions and suggested a new version based on an updated and corrected air temperature time series from Sytktyvkar. He also used the polynomial instead of linear equation to reconstruct the ablation. We used this new reconstruction to compare with our moraine records (see "Discussion").

Materials and methods

In order to reconstruct the glacier margin positions we used a range of historical imagery: oblique photographs; field drawings (the earliest from 1938); orthotransformed aerial photos for glaciers Anuchina (1953), IGAN (1958), Obrucheva (1953), Shumskogo (1953), Avsiuka (1953), Berga (1960); and orthotransformed satellite images IRS-P5 Cartosat 2008.

A large amount of information concerning the geomorphology, geology and glaciology of the Polar Urals obtained in 1950s-1970s is available for these glaciers (Troitsky et al. 1966, Khodakov 1978, Glazovsky et al. 2005 etc.) but it is published in Russian and is largely inaccessible to the general scientific readership. We draw on it here, where possible, with respective references. In particular, we find the attempts to reconstruct the Polar Urals glacier mass balance, basing on the long meteorological records, very useful. Taking into consideration the small sizes of the glaciers in this region the mass balance excesses of the decadal length can be directly compared to the glacier advances and, hence, the age of moraines without any significant time lag.

In order to estimate the ages of moraines in the Polar Urals we used the “classical” version of the lichenometric method (Innes 1985, Bradwell 2009). This involved measuring all large lichens on an entire surface, which given the small size of the moraines in this area was not a problem. We used both the single largest lichen (maximum diameter) and the mean of the five largest lichens as predictors of moraine age. The single largest lichen approach is probably more effective in the case of small (i.e. Polar Urals) moraines, while the mean of the five largest diameters and the standard deviations provide supplementary information, which is especially useful when the number of measured lichens is limited. Unusually large lichens were considered “anomalous” if their diameter exceeded the next largest lichen by >20% (Innes 1985).

Martin (1987), a professional lichenologist, identified the most common lichens on the Polar Urals moraines as *Rhizocarpon geographicum (L.) DC, R. alpicola (Hepp.) Rabenh., R. sublucidum Ras., R .lindsayanum Ras, R. concretum (Ach.) Elenk*. The first two species are the most widespread and closely resemble each other. *R. geographicum* is more abundant on young moraines, whilst *R. alpicola* appears later in the colonization sequence, but grows faster – exactly as it was described by Innes (1985) in other regions. We did our best to distinguish the two species but we cannot exclude the possibility that these two species were confused especially on the youngest and oldest moraines. Thus, following to the recommendation of Innes (1985) and Benedict (2009) we refer here to the yellow-green *Rhizocarpon* species collectively as ‘*Rhizocarpon* subgenus *Rhizocarpon*’.

The size spread of the largest lichens of both *R. geographicum* and *R. alpicola* species increase at diameters ca. 70 - 80 mm (mean of five largest lichens). At the same time the number of measurements decreases due to the small number of measurable discrete large lichens. If the surface of a moraine is not large enough the number of measurable large lichens become critical; as a result the accuracy and reliability of the age estimates decreases dramatically. This means that on surfaces where the largest lichens exceed 70-80 mm, age estimates are uncertain.

To construct the lichen ‘growth’ curve we used both repeated measurements and control points to calibrate growth rates (see below: “Lichen growth rates”). In total, our dating (age-size) curve is based on eight control points, but none dates back further than the early 20th century. In order to correctly extrapolate beyond the period of calibration we used *Rhizocarpon geographicum* dating curves from regions with a similar climate to guide our curve, and constrain reasonable limits of growth. This method is far from ideal, but is the best possible solution at the moment due to the lack of old control surfaces in the field area.

Unfortunately, owing to logistical reasons, our Polar Urals field season in 1999 was shorter than hoped and in several locations we were limited to rather brief studies (e.g. Avsiuka glacier).

Results

Growth rates of Rhizocarpon *subgenus* Rhizocarpon *in the Polar Urals*

In his earliest publication concerning lichenometry in the Polar Urals (Martin 1967) indicated the diametral growth rate of *Rhizocarpon tinei* (= *Rhizocarpon geographicum*) as 0.14 to 0.20 mm per year. He based his estimate on the assumption that the ice-cored moraines then adjacent to the glaciers were deposited in the 1880s. This assumption was based in turn on the mass-balance reconstruction curve of Troitsky et al. (1966), which showed the major increase of ice-mass accumulation was during the 1880s (for the period of available meteorological records at Syktyvkar (1820s to present, with some gaps). Martin measured *R. geographicum* lichens in 1965 on the first prominent moraines near the glaciers and obtained his first tentative growth rate estimates. He re-measured lichens on the same moraines twelve years later (in 1977). The mean difference between the lichen sizes in 12 years was 2.12 mm (Fig. 2). Taking into consideration both estimates (0.14-0.20 mm per year and 0.19 mm per year), and suggesting that the growth rate remained relatively constant through time, he accepted the growth rate as 0.16 - 0.19 mm per year to calculate the age of Polar Ural moraines.

In 1999 we repeated the measurements of lichens on the moraine of Obrucheva glacier. This glacier has a distinctive isolated ice-cored moraine ridge, which was easy to identify and increased our certainty that this moraine was used as a control point both times by Martin. We used the same method as he did: we measured all large lichens (a single ‘largest’ lichen per large boulder, 642 lichens in total) at 12 stations 25 m away from each other (see Fig. 2). We found the largest lichen was 25 mm in diameter (mean of five largest thalli = 24.4 mm). Thus, we infer that the growth rate of *Rhizocarpon* subgenus *Rhizocarpon* was similar, but 50% greater (0.3 mm/year) than the growth rate determined for the period 1967-1977 by Martin (1987).

The second method used to constrain the dating curve was the indirect approach – where lichens were measured on surfaces of known age. We investigated the potential to find control points at two cemeteries in Salekhard (former Obdorsk) and Labitnangy village. Unfortunately, no suitable surfaces were found which could be used as control points. The first descriptions of the Polar Urals glaciers before the Second World War (1930s) are too general to be useful for our purposes. Eight control points for the potential dating curve have been obtained from: topographic maps of IGAN and Obrucheva glaciers; aerial photographs taken in the 1953, 1958, 1960, 1968, 1973; terrestrial photogrammetry, and field photographs from the 1960s through 1999; as well as pit and quarry abandonment from the 1940s to the 1980s (Table 2). When plotted as an age-size graph these control points, covering 50-60 years, can be approximated by a straight line (r^2=0.85). The lichen growth rate estimated from this indirect approach is about 0.5 mm per year, i.e. growth appears to be even faster than identified by our repeat measurements on the Obrucheva glacier moraine.

It is clear at the moment that despite some progress in the calibration of lichen growth rates in this region, the problem is still far from resolved. Due to the young age of control points in the study area a satisfactory *Rhizocarpon* subgenus *Rhizocarpon* dating curve spanning the last few centuries is unobtainable. However, lichenometry can be a very useful tool for relative age estimates and for the identification of isochronous surfaces in a range of glacial settings.

Lichenometry of moraines

The generalized results of our lichenometric surveys on the young moraines of six Polar Urals glaciers are displayed in Table 3.

Anuchina Glacier

This small glacier occupies a part of the wide valley at the elevation of 530-900 m. The cirque walls consist of dark schists and quartzite and sandstone rocks. One kilometer down valley there are deposits of unclear genesis generated either by glaciers or by a rockfall (Troitsky 1962).

The glacier was discovered in 1938 by Khabakov, and later visited by a number of researchers. The comparison of oblique, aerial and satellite images (Fig. 3) shows that the size of the glacier remained almost the same during the period 1953 to 2000. The picture drawn by Khabakov shows that the glacier was of a similar size in 1938 (see Fig. 3). Tiuflin and Perevoshikova (1986) compared the photogrammetric results of the years 1961 and 1981 and showed that the south-western margin of the glacier had retreated by 5-15 m over this time, whilst the thickness of the glacier did not change.

During our visit on 12 July 1999 the glacier and its forefield were snow covered and it was impossible to exactly determine the glacier limits. The contours of the area covered by snow were the same as the glacier area in the aerial photos of the 1950s-1960s, though the periphery of this area was flat, and most probably the snow here was not covering the glacier surface, but the valley floor.

Troitsky (1962) described a prominent ice-cored moraine ridge up to 15-20 m high and 350 m long located along the southern margin of the glacier in 1959, which can still be seen today (see Fig. 3). We identified five surfaces of different age at this glacier forefield (Fig. 4, see table 3). The youngest surface, ablation moraine (M I) at the left side of the glacier, became ice free after 1960s – yet on the air photo taken on 30 July 1960 this surface is still covered by ice. On this surface lichens measured up to 9 mm in diameter (D_{LL}); this surface was used as a control point for the dating curve (see Table 2). At that time the glacier was adjacent to its left moraine (M II, D_{LL}= 20-24 mm). One can see this moraine on the photos of 1960 and on the drawing of Khabakov in 1938, i.e. in 1999 this moraine was more that 61 years old. The distal part of this moraine (M III) is probably slightly older, according to the size of the largest lichen (D_{LL}=28 mm). The crest of the highest moraine (M IV) is considerably more ancient, as evidenced by the size of the largest lichens growing on it (D_{LL}=85 mm). In the center of the valley a small fragment of an even older moraine (M V; D_{LL}=140 mm) is also preserved.

IGAN glacier

IGAN glacier was the focus of research during the International Geophysical Year (1957). It is located at the eastern slope of the mountain Khar-Naurdy-Key in a cirque consisting of grey chlorite slates, grey and lilac cericite shists, quartzitic sandstones, and grey to green diabases (Troitsky 1962).

The glacier retreat in the second part of the 20th century and early 21st century is documented by oblique photographs (Fig. 5) and is reconstructed from the aerial and satellite images (Fig. 6). In the second half of the 20th century the glacier retreated by 450 m (see Table 1). A part of the surface between the end of the glacier and the young moraines is covered by a lake, which often changes its shape. Owing to these changes and substrate instability, lichens did not colonize this surface in 1999: we did not find any yellow-green *Rhizocarpon* lichens between the end of the glacier and the moraine damming the lake (see Fig. 6, table 3, M It).

A sequence of well-shaped distinct end moraines of various ages is located at the left side of the valley, while the lateral moraines are better preserved to the right. Between the terminal and end moraines is located a chaotic landform assemblage with an uneven surface strongly modified by thermokarst processes and meltwater channels. These interrupt the transition between the end moraines and lateral moraines. However, in some cases an equivalent-age surface in the lateral and frontal moraine complexes can be identified by a lichenometric survey.

The youngest unvegetated moraine (M IIt) supports lichens of the same size as the first ice-cored moraine at Anuchina glacier (M II; D_{LL}=24 mm). The surface of this moraine is very fresh and it can be easily identified in the field and from aerial photos (see Fig. 7).

The older moraine (M IIIt) marked by a geodetic point can be linked to the higher level of the right lateral moraine (M IIIr) both geomorphologically and by correlation of largest lichen sizes (D_{LL}=31 and 33 mm, respectively). The moraines of the previous generation (both end and lateral moraines) differ markedly from the stage M III moraines by their darker color on air photographs. The lichens growing on both lateral and terminal moraines M IV are about 10 mm larger than those on moraines of stage M III (D_{LL}=43-45 mm). This moraine is bordered by a field of grey hills (M V), again distinctively different by their color and surface morphology from the previous stage. The maximum diameter of lichens on this surface (D_{LL}=60 mm) differ significantly from those of the corresponding lateral moraine (M Vr), however the mean of the five largest lichens on these surfaces are almost identical (D_{5LL} =50 and 51 mm). It is of interest that the well-shaped push moraine arc delimiting this surface supports much smaller and far less numerous lichens than on the flat surface adjacent to this wall. The same pattern is seen in the two older stages. None of the older lateral moraines supports enough lichens suitable for a dating assessment. Two old terminal moraines (VI and VII) differ from the grey moraine M V in their yellow-green appearance – probably due to the higher coverage of subgenus *Rhizocarpon* lichens. The dating assessment is tentative because we are approaching the confidence limits of our lichenometric methodology in this area. The oldest moraine at the IGAN glacier supports lichens of similar size (D_{LL}=153; D_{5LL} =120) to those on the oldest moraine in front of the Anuchina glacier (D_{LL}=140; D_{5LL}=127).

Obrucheva glacier

The Obrucheva glacier was first described by Khabakov (1945), and this glacier along with the IGAN glacier (described above) became the main research focus during the International Geophysical Year. The Obrucheva glacier is surrounded on three sides by a high cirque wall composed of pink and grey quartz sandstones, green chlorite-sericite shiest and greenish effusive rock (Troitsky 1962). Snow and ice accumulation on the glacier depends mostly on avalanches from the steep slopes of the cirque. The glacier has retreated gradually in the last half century (Fig. 7). Between 1963 and 1973 retreat was interrupted and the glacier was close to the stationary position. Since 1953 the glacier's surface area has decreased by around 50%, and by 2008 it had become a niche type glacier.

Lichens on surfaces occupied by the glacier in the 1960s (MI) (Fig. 8) are up to D_{LL}=10 mm (see Table 2 and 3 (MI)). On the NE side, the glacier is bordered by an ice-cored moraine ridge up to 40 m high. Martin (1967) suggested that this moraine was formed in the 1880s during the last period of positive mass balance, and he used it to estimate lichen growth rate. Lichen sizes on the proximal side of this moraine are up to D_{LL}=21 mm (MIIt l) (the level that one can see at the proximal slope of the moraine); on the distal slope lichen sizes increase up to D_{LL}=27 mm (MIIIt). This moraine partly overlaps a fragment of an older moraine (MIVt; D_{LL}= 47 mm).

Shumskogo glacier

The Shumskogo glacier is located in the neighboring valley, in a cirque oriented to the east. On 17 July 1999 when we visited the valley the glacier was covered by snow, so unfortunately we could not ascertain its exact size. The glacier terminates in a lake, which is dammed by a prominent end moraine complex (Figs. 9, 10). Moraine deposits of unknown age can be found up to 1 km downvalley of the present-day glacier margin. The highest and most prominent ridge on the left side, probably with an ice core, includes three stadial moraines (M I-III). The two (oldest) moraines can be traced to the end moraine complex damming the lake. The maximum diameters of *Rhizocarpon* subgenus *Rhizocarpon* lichens on these three moraines correspond very well to those located adjacent to the IGAN glacier (see Table 3). The older moraines behind the terminal moraine M IV support lichens of a smaller size.

Avsiuka glacier

Only a very brief study of the moraines at this glacier was made. We identified three advances, with lichen sizes: D_{LL}=27, 42 and 72 mm. Unfortunately there was insufficient time to study the older surfaces (see Table 3 and Fig.11).

Berga glacier

This glacier was first described by Parkhanov, a geologist, in 1949. The cirque backwall of this glacier is composed of the same pink quartzite, sandstone, schist and grey-green effusive rocks. Moraines of various ages occupy the cirque floor. Roughly 1 km from the glacier terminus an old vegetation-covered end moraine dams a lake. The comparison of oblique photos taken in 1959, an aerial photograph in 1960 and a satellite image from 2008 show that the glacier retreated 330 m during this time. Presently, the glacier tongue still terminates in a proglacial lake but the lake has enlarged since the 1960s becoming slightly longer and wider (Fig. 12, 13).

The lake in front of the Berga glacier is surrounded by recent ice-cored moraines. Most surfaces are unstable because the debris layer covering the buried ice is very thin. The youngest surface colonized by lichens was the terminal moraine (M It) (see Fig. 14 and Table 3). Below this moraine there are numerous ridges with chaotic expression and unclear outlines – several different generations are preserved here (see Fig. 13, 14). These glacial deposits are probably partly overlapped by debris originating from the left slope of the valley. The moraines are grey in color because their surface is only sparsely lichen-covered (M IIl — M IIIt). The moraines M IVt and M Vt are much older and have a greenish color owing to the size and density of *Rhizocarpon* lichens. Only a few large thalli 90 - 150 mm in diameter were measured on these surfaces – the majority of the lichens at these surfaces are of much smaller sizes.

A small depression occurs between the moraines M IV and V, which probably once hosted a pond. An excavation in the sediments in this depression revealed clay and silt deposits interlayered with sand and vegetation detritus, underlain by till. The whole thickness of the clay-silt-sand deposit was 1.4 m. The surface of this depression is covered by ice-wedge polygons. At a depth of 0.40-0.42 m, the most organic-rich horizon was sampled for radiocarbon analysis. The radiocarbon age of the sampled sediment (bulk organic material) is 340±110 years BP (GIN-10720).

Relative age estimate of moraines

Several moraines within the Polar Urals can be grouped on the basis of their largest-lichen sizes, position relative to the glacier margin, and similar morphology. We identified the following groups: surfaces deglaciated after the 1950s-1960s with lichens up to D_{LL}=10 mm; proximal “shelves” of the lateral moraines (Obrucheva, Anuchina and Shumskogo glaciers) and recent ice-cored end moraines (Shumskogo glacier) (D_{LL}=20-24 mm); the distinctive ice-cored end moraines of Anuchina, Avsiuka and Berga glaciers (D_{LL}=25-28 mm); the moraines of IGAN, Shumskogo and Berga glaciers with lichen sizes up to D_{LL}=30-33 mm. At most of the glaciers the highest moraines support lichens up to D_{LL}=44-47 mm (Berga, Obrucheva); at Shumskogo and Avsiuka glaciers lichen sizes on the highest moraines are somewhat smaller (D_{5LL}=36-38 mm), but the largest single lichens still measure up to D_{LL}=42-44 mm. The highest lateral moraine of IGAN glacier seems to be even older (D_{LL}=53 mm). We did not find any analogues of this moraine at the other glaciers. Older moraines are not clearly discriminated using lichenometry due to the large spread (standard deviation) of lichen sizes. With this in mind, the moraines at the Avsiuka and Berga glaciers (D_{5LL}=57±10 mm 63±4 mm, respectively) probably represent the same event. Two older moraines at the IGAN and Berga glaciers differ in age according to the mean of the five largest lichens (D_{5LL}=87±2 mm and D_{5LL}=77±14 mm, respectively), but interestingly support single largest lichens of the same size (D_{LL}=90 mm). The age of the oldest moraines is the most uncertain: they could be of the same generation or could possibly be separated in time by hundred of years – although the means of the five largest lichens are close (D_{5LL}=127±14 mm for Anuchina glacier; D_{5LL}=120±25 mm for IGAN glacier), the single largest lichens measured differ significantly (D_{LL}=140 mm and D_{LL}=153 mm, respectively). In general, we identified a large group of moraines with yellow-green *Rhizocarpon* lichens D_{LL} = 20-90 mm, separated in time from a second smaller group of moraines with lichens up to D_{LL}=120-153 mm.

Discussion

Our lichenometric control points in the Polar Urals were restricted to the second half of 20th century; hence the shape of the dating curve prior to this time, unfortunately, cannot be estimated independently. A single radiocarbon date from the Berga glacier forefield relates to a broad time interval, after calibration (AD1440 – AD1660; at 68,2% significance level). This date cannot be specifically linked to moraine ridge formation, but merely constrains the minimum age of the moraine ridges (MI-MIV) adjacent to Berga glacier.

Using the ‘indirect’ lichenometric approach, we estimate the optimum diametrical growth rate of *Rhizocarpon* subgenus *Rhizocarpon* in the Polar Urals to be c. 0.25

mm/yr over the 20th century. Comparison with other high-latitude studies shows that these growth rates are faster than in Spitsbergen (cf. ~0.15 mm/yr; Werner 1990) but considerably slower than in the southern Norway (cf. ~0.7 mm/yr; Bickerton and Matthews 1992) (Fig. 15). Growth rates of *Rhizocarpon* lichens in the Polar Urals estimated for the 20th century seem to be similar to, but slightly slower than, those in Swedish Lapland (Karlen and Denton 1975). The two regions are similar in climatic severity (Table 4), although the Polar Urals' climate is a little more continental.

The reconstruction of glacier mass balance in the Polar Urals (Fig. 16) is quite important to help identify the periods of possible glacier advance and retreat. Owing to the small size of glaciers in the Polar Urals, ice mass fluctuations should show a direct correspondence to mass balance anomalies on a decadal scale. The reconstructions based on the same direct mass balance measurements, but somewhat different meteorological records, agree well for the 1890s-1970s but diverge at both the beginning and the end of the records. Discussing the differences between the reconstructed mass balance curves is beyond the scope of this paper. What is most important for the purpose of this study is to identify the moraines which may correspond to the peaks in positive mass balance during the 19th century.

According to the reconstructions of Khodakov (1978) and Ivanov (2009), the period of most prominent positive balance in the 19th century occurred in the 1880s. Taking into account the estimated lichen growth rates in the 20th century, the most realistic candidate for formation during the 1880s are the prominent ice-cored moraines with largest lichens D_{LL}=24-26 mm. This is also the moraine suggested by Martin (1987) to have formed in the 1880s. Using a linear approximation of the 'age-size curve' similar to that of Karlen and Denton (1975) (see Fig. 15) the next oldest moraine group (D_{LL}=30-33 mm) best corresponds to the period of positive mass balance in the 1850s. The large moraines supporting yellow-green *Rhizocarpon* lichens up to D_{LL}=44-47 mm, assuming a linear extrapolation, are probably about two centuries old. Under this age-size lichen model these moraines are a little too old to match the first period of positive mass balance in the 1820s, however the date is close to the cold spell at the beginning of the 19th century, according to the curve of reconstructed summer temperatures (Briffa et al. 1995) (Fig. 17). These tree-ring-based summer temperature reconstructions from the Polar Urals (Briffa et al. 1995) and upper tree-line variations recording the lower frequency temperature variability (Shiyatov 2003) are useful to discuss the potential correspondence of moraine ages and climatic changes in the region, especially for the period preceding the mass balance measurements and reconstructions (see Fig. 17).

Although the mass balance of glaciers depends on two parameters (summer temperature and winter precipitation), summer temperatures often play a more crucial role in controlling glacier dynamics – with strong climate cooling events corresponding to glacier advances. Two summer cooling events are evident in the tree-ring temperature reconstructions of Briffa et al. (1996) – one in the early 19th century, and one in the late 19th century. They both roughly correspond to the reconstructed mass balance peaks that we used to tentatively estimate the age of moraines (Fig. 16). The mid 19th century was relatively warm according to the tree-ring reconstruction, so we speculate that the small mass balance increase at that time (ca.1845-1860) most probably stemmed from a positive precipitation anomaly. Summer air temperatures in the 18th century were close to the mean for the whole millennium, while in the 16th and early 17th centuries summer temperatures were generally cold with two major ‘troughs’ at the beginning and the end of this period. If we estimate the age of moraines using our tentative extrapolated curve, we will see that most lichens that we measured, located close to the modern glaciers (up to D_{LL}=90mm), were probably deposited in the last ~450 years (see Fig. 17). Shiyatov’s (2003) curve reconstructing upper tree limit variability over the last millennium clearly shows the period of lowest tree line altitude in the Polar Urals occurred in the period from AD 1600 to 1900.

From AD 850 to AD 1580, the upper treeline altitude was higher than today. We found very few moraines with lichen sizes relating to this time interval, which is to be expected considering the general warming in the area and likely glacier retreat at this time. However the scatter within maximum lichen sizes increases significantly on these older surfaces; consequently, using a linear age-size relationship to estimate the age of these moraines is probably not applicable (shown in Fig. 17 in gray).

The following moraine groups were identified adjacent to 6 Polar Urals glaciers (IGAN, Obrucheva, Anuchina, Shumskogo, Avsiuka, and Berga), largest subgenus *Rhizocapon* lichen measurements are shown in brackets: surfaces deglaciated during the last 40-60 years (D_{LL}=10 mm); narrow ‘shelves’ of lateral moraines deglaciated at the beginning of the 20th century (D_{LL}=20 mm); ice-cored moraines presumably formed during the 1880s (D_{LL}=24-26 mm); probable mid-19th century moraines (D_{LL}=30-33 mm); distinctive arcuate, but well-established, moraines c. 200 years old (D_{LL} = 44-47 mm); as well as several more ancient moraines deposited by glacial advances to a similar position, all probably formed within the last 450 years (D_{LL}=70-72 mm and 90 mm). The oldest surveyed moraines support lichens up to 120-140 mm in diameter, but any age estimates for this moraine group would be very weakly constrained due to the large spread (standard deviation) in largest lichen diameters.

Concluding remarks

Six major advances during the last millennium have been identified by geomorphological mapping and supplemented by lichenometric surveys. Using a combination of 'direct' and 'indirect' lichenometric methods we estimated the optimum diametrical growth rate of *Rhizocarpon* subgenus *Rhizocarpon* in the Polar Urals to be c. 0.25 mm/year for the last 100 years – close to, although slightly slower than, *Rhizocarpon* agg. growth rates in northern Sweden (0.29 mm/year) (Denton and Karlen 1973). According to our preliminary lichen-dating curve, extrapolated in a linear fashion, moraine ages are estimated as: AD 1880s, AD 1850s, early 19th century, and, more approximately, mid 17th century, and mid 16th century. Our lichenometric age estimates are in agreement with the earlier chronology of Martin (1967, 1987) who subdivided the moraines of 3 glaciers (IGAN, Obrucheva and Berga) into 4 general groups, deposited about 100, 200, 340-370 and 700-740 years before present.

The end moraines located in front of the modern glaciers bear witness to repeated glacier advances of approximately similar amplitude. Presently, the total glaciated area in the Polar Urals is up to 50% smaller than it was at the "Little Ice Age" maximum (roughly from c. AD 1550 to AD 1800). These glacier advances correspond well with other Northern Hemisphere glacier fluctuations, for example in Norway, Sweden, Iceland, the Swiss Alps, Alaska and Kamchatcka (e.g. Denton and Karlen 1973; Grove 1988; Holzhauser 1997; Matthews 2005; Bradwell et al. 2006; Solomina and Calkin 2003), and they are in general agreement with tree-ring-reconstructed temperature trends from the Polar Urals (Briffa et al. 1995). Being small, sensitive to climatic perturbations, and having short response times, we find the Polar Urals glaciers a geographically important but under-used source of palaeo-environmental data.

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Table captions

Table 1. Morphological characteristics of studied Polar Urals glaciers.

Table 2. Control points for the *Rhizocarpon* subgenus *Rhizocarpon* lichen-dating curve obtained in the Polar Urals in 1999.

Table 3. *Rhizocarpon* subgenus *Rhizocarpon* maximum diameters on the moraines of the Polar Urals measured in 1999. Indices in the second column: a - ablation moraine, t - terminal moraine, l - left lateral moraine, r - right lateral moraine.

Table 4. Climatic parameters in subpolar regions where lichenometry was applied. The

regions correspond to those in Fig. 15.

Figures captions

Fig. 1. Location of the Polar Urals Glaciers.
1 – Anuchina; 2 – IGAN; 3 – Obrucheva; 4 – Shumskogo; 5 – Avsiuka; 6 – Berga

Fig. 2. Maximum diameters of *Rhizocarpon* subgenus *Rhizocarpon* on the moraine of Obrucheva glacier: according to our measurements in 1999 (indicated as Solomina, 1999), according to the measurements of Martin in 1977 (1987), and in 1965 (Martin, 1967).

Fig 3. Anuchina glacier. 1938 – drawing by A.V.Khabakov; 1960 – Photo courtesy of L.S.Troitsky; 2005 – Photo courtesy of G.N.Nosenko. The changes in glacier shape are not discernible. The same moraine is marked in all three photos with an arrow.

Fig. 4. Aerial photograph (1953) of Anuchina glacier and moraines. No changes in glacier shape and size are observed between 1953 and 2008. The numbers of moraines correspond to those in the Table 3. A clear moraine (without number), too old to be dated by lichenometry, and a trimline visible at the left side of the valley define two stages of glacier advances – when Anuchina glacier was much larger than during the last millennium.

Fig. 5. IGAN glacier in 1963 (photo courtesy D.G.Tsvetkov) and in 2005 (photo courtesy G.A.Nosenko). Between these two dates the glacier retreated and thinned.

Fig. 6. Aerial photo of IGAN glacier in 1960 with the numbers of studied moraines (see Table 3). The moraine without number outlines the whole complex of the advances of similar amplitude. The external part of the complex is undated due to the insufficient number of large lichens.

Fig. 7. Obrucheva glacier in 1963, 1981 (photos courtesy D.G.Tsvetkov) and in 2005 (photo courtesy G.A.Nosenko) showing that the surface of the glacier was gradually lowering.

Fig. 8. The dramatic retreat of the front of Obrucheva glacier between 1953 and 2008 is clearly seen in the aerial photo taken in 1953. The moraine number III (outlined by points) was used by Martin and later on by Solomina to estimate the *Rhizocarpon* subgenus *Rhizocarpon* growth rates by repeated measurements (see explanations in the text). The undated moraine, without number, damming the lake outlines a previous stage of advance of Obrucheva glacier.

Fig 9. Shumskogo glacier in 1999 (photo courtesy V.A.Zhidkov) and its lake dammed by two moraines (stages II and III in Figure 10).

Fig. 10. Aerial photo of Shumskogo glacier in 1953. The area occupied by ice in 1953 is now covered by the enlarged lake. The moraines without numbers outline the older stages of glacier advances clearly seen in the forefields of the glacier.

Fig. 11. Aerial photo of Avsiuka glacier in 1953. Unlike many other Polar Urals glaciers the Avsiuka glacier has not changed much since 1953. The bleached surface below the marked moraines and the trimline outline the shape of the formerly, much larger, glacier.

Fig. 12. Berga glacier in 1959 (photo from Khodakov 1978) and in 1999 (photo courtesy V.A.Zhidkov).

Fig. 13. Moraines of Berga glacier in the 1970s (Khodakov 1978). 1 and 2 – “Little Ice Age” moraines, 3 – Khodakov’s reconstruction of glacier size during an older glacier advance.

Fig 14. Moraines of Berga glacier (aerial photo, 1960). The open white circle marks the site of ^{14}C sample collection. The outermost moraine (without number) is a well-shaped moraine ridge at the contact of the cirque of Berga glacier and the main valley.

Fig. 15. *Rhizocarpon* subgenus *Rhizocarpon* growth rate in several subpolar regions: Spitsbergen (gray circles) (Werner 1990), St.Elias and Wrangell Mts, Southern Alaska (open circles) (Denton, Karlen, 1973), Sarek Mountains (gray squares) (Karlen and Denton 1975), Southern Norway (open squares) (Bickerton and Matthews 1992), Polar

Urals (black squares) – this paper. The point with the question mark is the moraine presumably deposited in the 1880s. The assumption is based on the mass balance reconstruction (see also Fig. 16 and explanations in the text).

Fig 16. Measured (1) and reconstructed glacier mass balance in the Polar Urals by Troitsky et al. 1966; (2), Kononov and Ananicheva 2004 (3), and Ivanov, 2009 (4). The upper panel shows the control points from the *Rhizocarpon* subgenus *Rhizocarpon* dating curve (gray circles) and the maximum diameters of lichens (open circles) at two moraines next to the surfaces deglaciated in the 20th century. The moraines are tentatively attributed to the two periods of positive mass balance in the 19th century.

Fig 17. Tree-ring summer temperature reconstruction from the Polar Urals (gray area) (Briffa et al. 1995) and upper tree-line variations (black line) in the same region (Shiyatov 2003) in comparison with the number of moraines tentatively dated by lichenometry. The distribution histogram of single maximum diameters is shown in the upper panel, where the number of moraines are averaged for each ten-millimeter interval. In the Polar Urals the glacier fluctuations, the upper tree-line variations and the tree-ring width are all largely controlled by summer temperature (Ivanov 2009). The figure shows a certain agreement between all three lines of evidence. The tree line was lower than now in the last five centuries and this period corresponds to numerous glacier advances, when the glaciers exceeded their present day sizes. The first half of the millennium was warmer according to the tree-line altitude. This statement agrees well with a small number of moraines. The decrease of the number of moraines in the last century corresponds to the summer temperature rise recorded by the tree-ring width proxy. The long-term cooling recorded in tree-ring widths in the 16th and first half of the 17th century corresponds to the beginning of the major period of moraine deposition. The accuracy of the dating of the individual moraines is insufficient to allow for comparison of these dates with the high-frequency summer temperature variations reconstructed from the tree-ring data.

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Table 1. Morphological characteristics of studied Polar Urals glaciers

Glacier	N	E	Type	Orientation	Length 1953, km	Length 2008, km	Front elevation, m in 1950s
Anuchina	67.62	66.05	slope	E	0.60	0.60	530
IGAN	67.58	66.03	valley-cirque	E N-E	1.45	1.00	830
Obrucheva	67.63	65.8	cirque	E	1.1	0.65	390
Shumskogo	67.65	65.87	cirque	E N-E	0.57	0.45	560
Avsiuka	67.65	65.9	cirque	N N-E	0.75	0.70	800
Berga	67.65	65.72	cirque	E	0.93	0.60	400

Table 2. Control points for *Rhizocarpon* subgenus *Rhizocarpon* growth curve obtained in the Polar Urals in 1999.

Site description	Age of surface stabilization/ exposion	Number of measured lichens	Maximum diameter, mm	Average of 5 maximum diameters	Standard deviation, mm
Paipudina valley, 490 m asl, dump and entrance to the gallery	1940's-early 1950's	61	12	11.8	0.45
Second dump at the same location	1940's-early 1950's	14	9	7	1.41
Road leading to to Khanmey, 240 m asl., open mines	before early 1950's	107	15	14.2	0.45
Nemur-Egan mine, cores	1959-1962	53	8	7.2	0.45
Kharbey village, molibdenum mine	before early 1950's	88	14	12.4	1.14
Quarry at 37 km of Balanenkov' road, 130 m asl	early 1980's	absent			
Anuchina Glacier, ablation moraine	1960's	103	9	8.2	0.45
Obrucheva Glacier, ablation moraine	1953-1966	34	10	9	1

Table 3. Lichenometric data from moraines in the Polar Urals (surveyed in 1999).

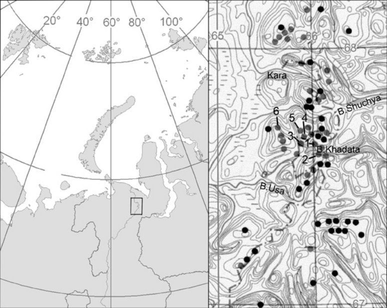
Glaciers	Number and index * of moraine	Number of measured lichens	Maximum diameter, mm	Mean of 5 maximum diameters, mm	Standard deviation, mm
Anuchina	I a	103	9	8	0.45
	II a	186	24	20	2.49
	IlI a	102	28	24	2.35
	II t	98	20	17	1.67
	IV t	186	85	66	13.90
	V t	149	140	127	13.65
IGAN	I t	absent			
	II t	70	24	24	0.00
	III l	77	31	29	2.28
	III r	19	33	29	3.90
	IV l	37	43	42	1.22
	IV t	130	45	43	1.52
	V t	21	60	51	5.41
	V r	81	53	50	1.52
	VI t	40	90	87	1.92
	VII t	10	153	120	25.19
Obrucheva	I a	34	10	9	1.00
	II l	52	21	19	1.67
	IlI a	55	26	25	0.71
	III l	642	25	24	0.89
	Ill t	13	27	23	3.11
	IV t	110	47	44	2.28
Shumskogo	I I	нет			
	II I	14	18	14	2.39
	II t	18	20	19	0.84
	Ill t	50	33	32	1.41
	IV 1	45	44	38	4.15
	IV t	9	42	34	4.76
Avsiuka	I l	23	27	26	0.89
	I t	30	27	26	0.89
	II t	25	42	38	2.88
	III t	9	72	57	9.86
Berga	I t	17	30	26	3.05
	II l	69	44	42	1.58
	Ill t	47	70	63	3.90
	IV t	16	90	77	13.89
	V t	15	120	104	11.72

*Index of moraines: t- terminal, a-ablation, l – left lateral, r – right lateral

Table 4. Climatic parameters of the sub-polar regions used for comparison with the Polar Urals

Number and name of regions	Latitude	Elevation, m asl	Mean annual temperature, ºC	Mean July temperature,ºC	Mean annual precipitation< mm
1. NW coast of Spitsbergen	79°	<50	-4.7 – -5.8	5.2	385
2. St.Elias and Wrangell Mts, Southern Alaska	61°	1200-1500	-5.5	13.9	360
3. Northern Sweden	67°	900-1250	-4.3	12.5	900
4. Southern Norway	62°	250-285	5	13.7	1000-1500
5. Polar Urals	67°-68°	800-1200	-6.3	12.0	610

See references in Fig. 15.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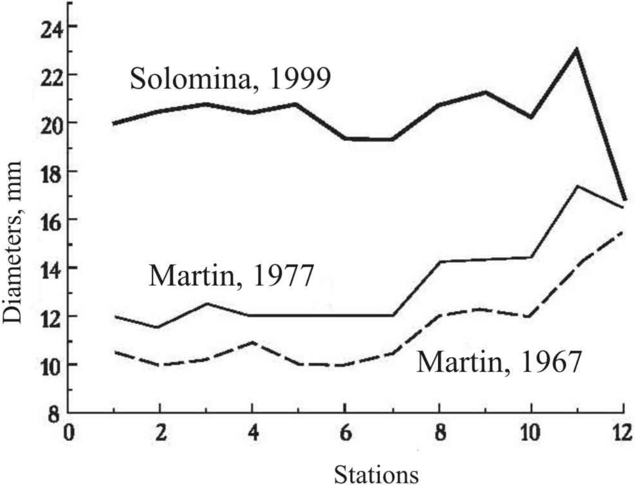
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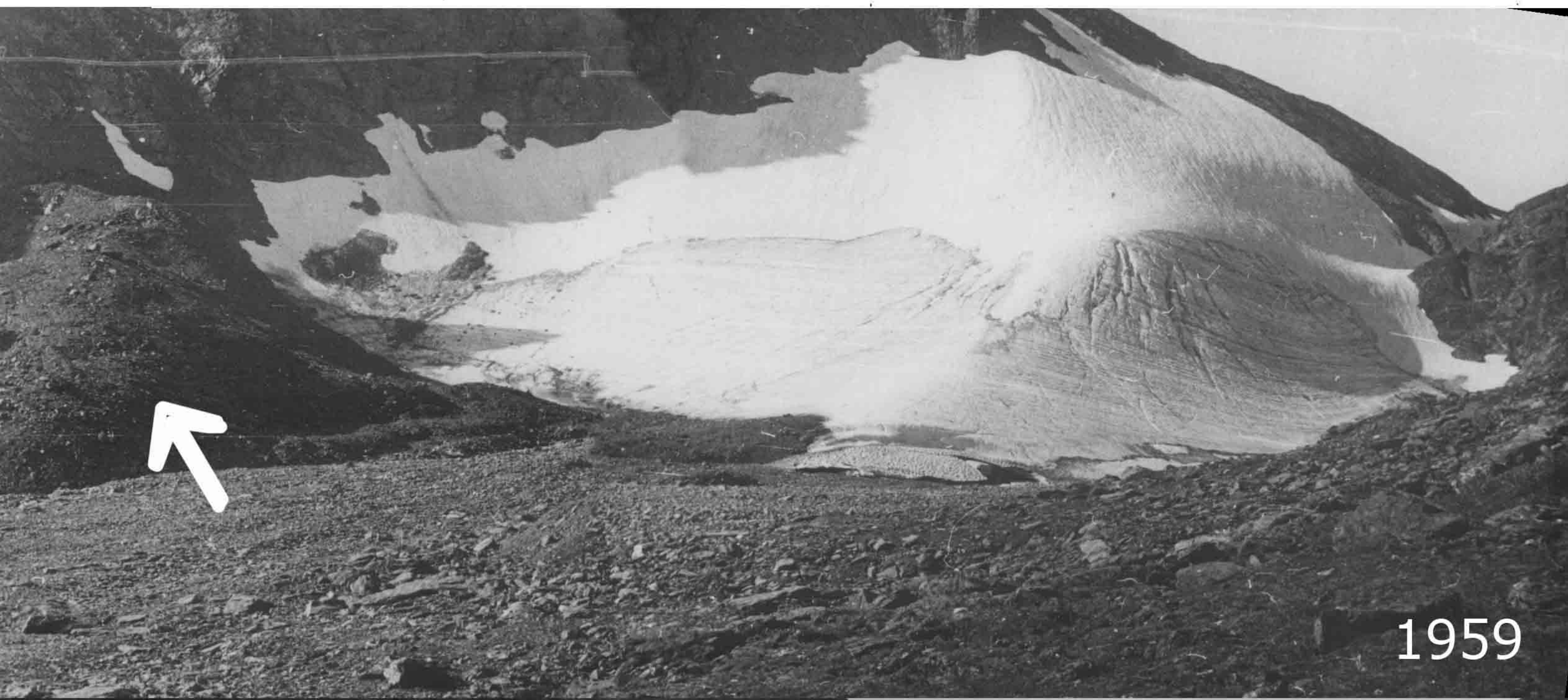
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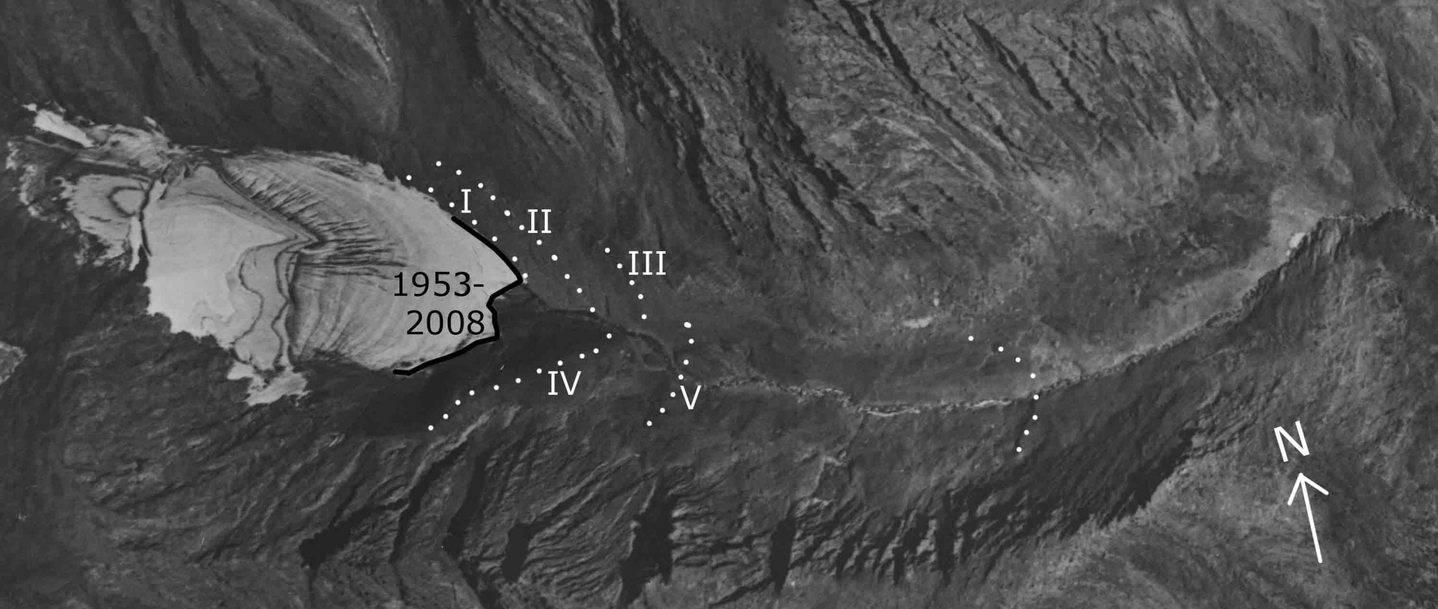
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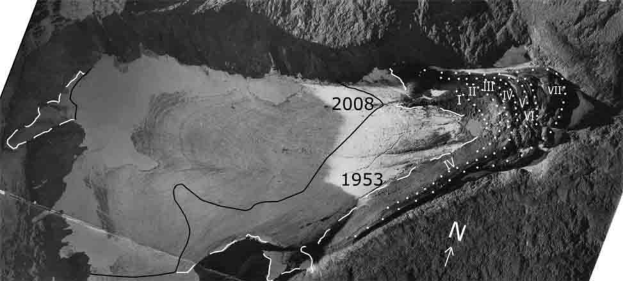
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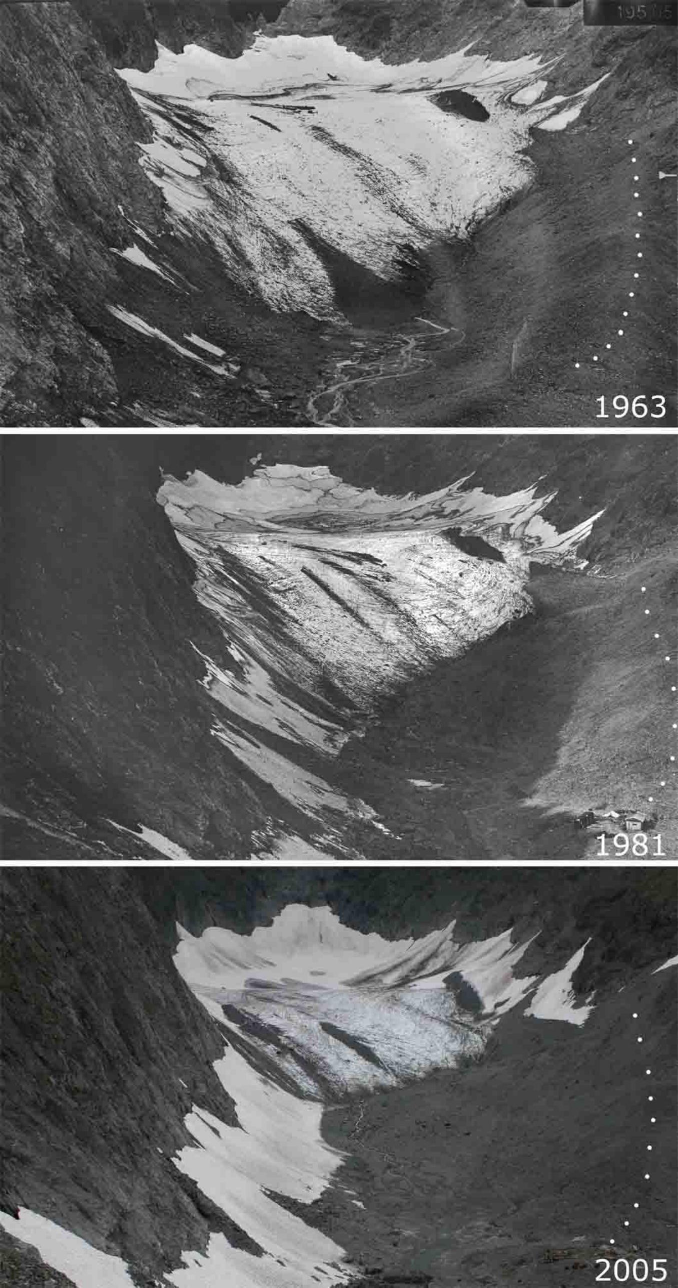
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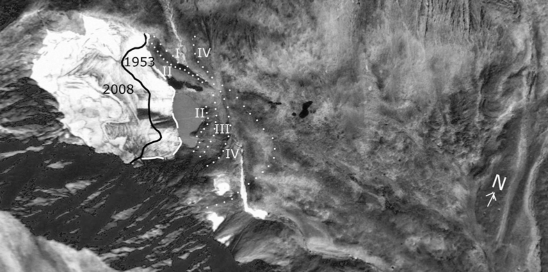

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V
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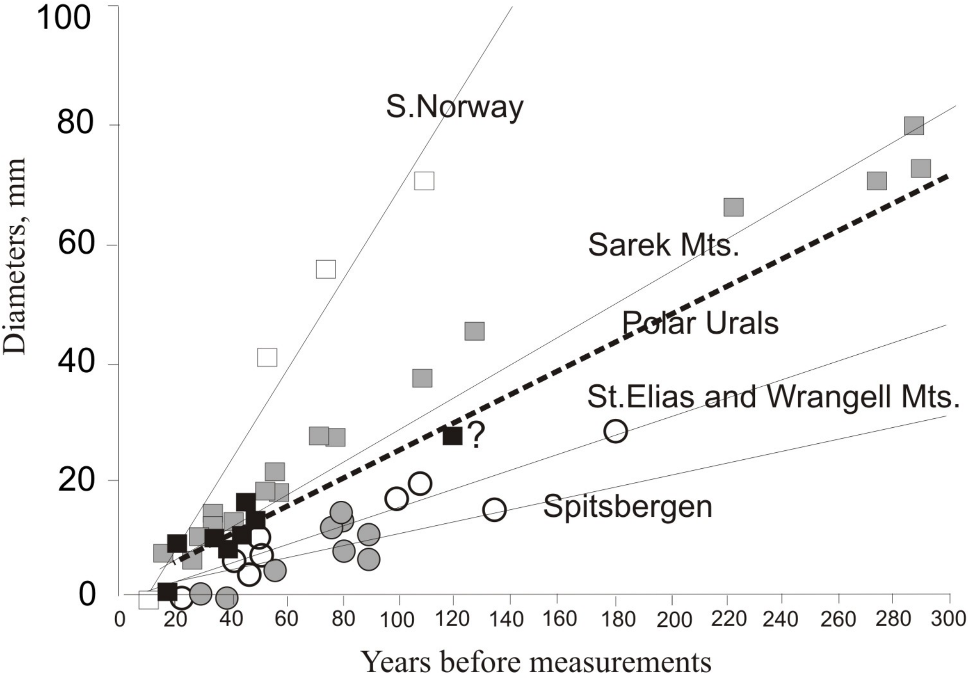
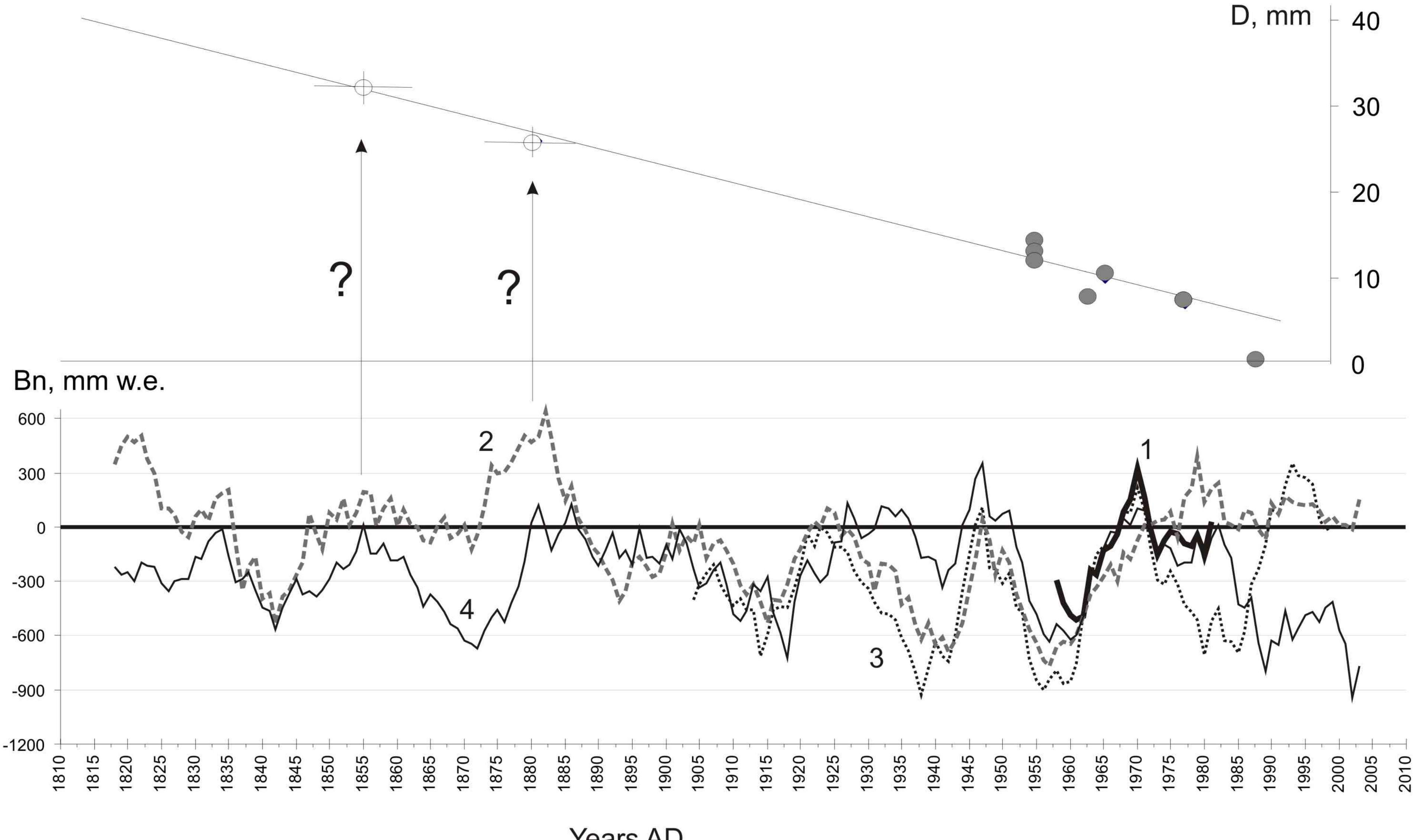
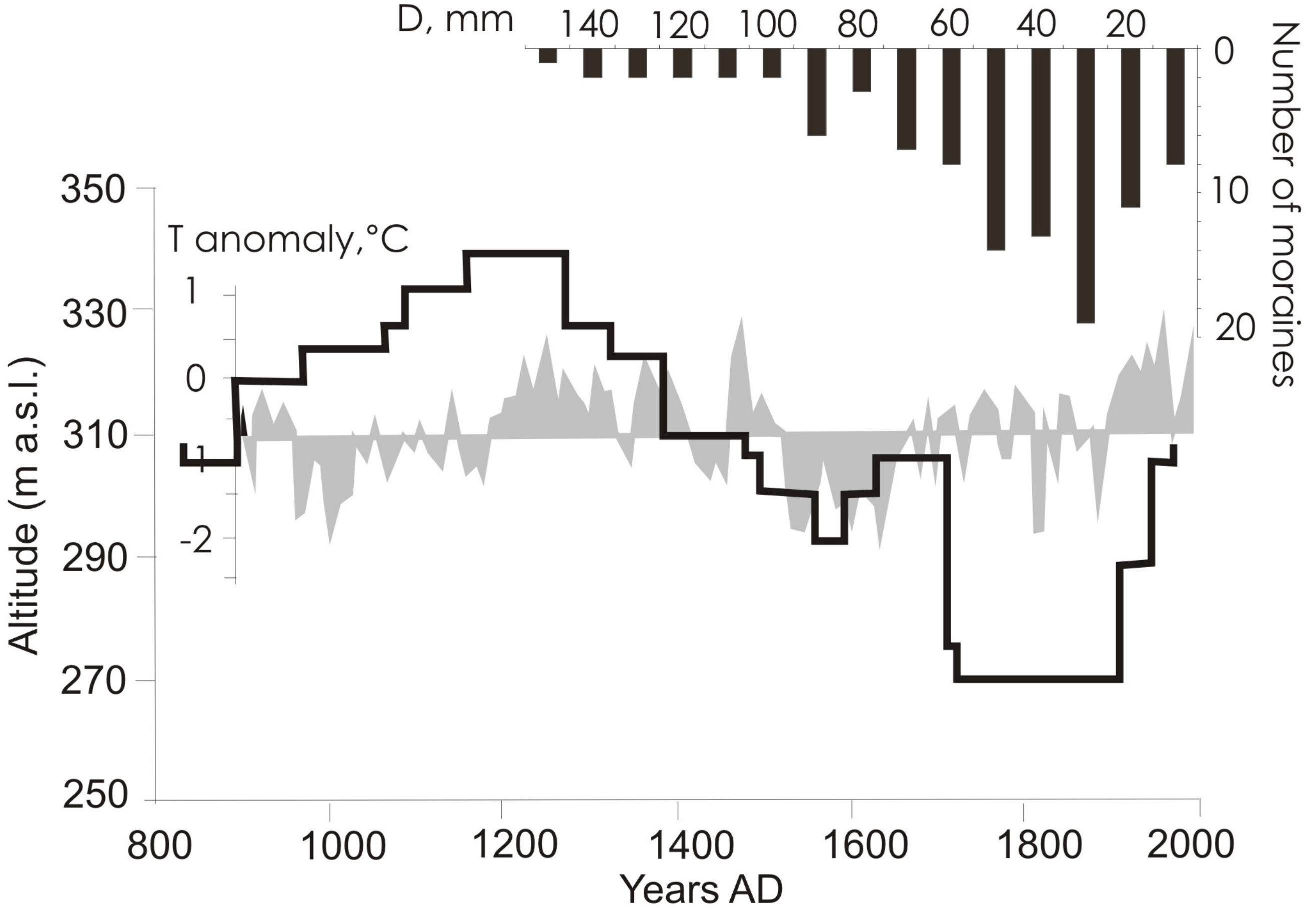


100
80
60
40
20
0
Diameters, mm
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
Years before measurements
S.Norway
Sarek Mts.
Polar Urals
St.Elias and Wrangell Mts.
Spitsbergen
?


D, mm
40
30
20
10
0
?
?
Bn, mm w.e.
600
300
0
-300
-600
-900
-1200
2
1
4
3
1810
1815
1820
1825
1830
1835
1840
1845
1850
1855
1860
1865
1870
1875
1880
1885
1890
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Years AD


D, mm
140
120
100
80
60
40
20
0
10
20
Number of moraines
T anomaly,°C
1
0
-1
-2
350
330
310
290
270
250
Altitude (m a.s.l.)
800
1000
1200
1400
1600
1800
2000
Years AD