In: Annals of Glaciology 28 (1999), pp. 135 - 140

Paleoclimatic interpretation of the early late-glacial glacier in the Gschnitz valley, Central Alps, Austria

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Summary

The former glacier at the type locality of the "Gschnitz Stadial" of the Alpine Lateglacial chronology is interpreted from a paleoglaciological and paleoclimatological point of view. From the reconstructed glacier topography, the equilibrium line altitude, ice flux through selected cross-sections and mass balance gradients are calculated. They are used to determine total net ablation and accumulation and precipitation under the assumption of steady state. With various glacier-climate models, the former temperature at the ELA and temperature change is estimated. Precipitation was in the order of less than one third of today's values, and summer temperature was roughly 10°C lower than today. The climate of the Gschnitz Stadial appears to have been cold and continental, and was more similar to full glacial conditions than to the Younger Dryas climate in the Alps. This is further evidence for an older age of the Gschnitz Stadial.

Introduction

Lateglacial glaciers may provide valuable quantitative information about the climate during the time period of their existence (Maisch and Haeberli, 1982; Maisch, 1987; Kerschner, 1985). If their surface geometry can be reconstructed with a reasonable degree of accuracy, it is possible to derive various glaciological parameters, which can be climatically interpreted (e.g. Maisch and Haeberli, 1982; Haeberli and Penz, 1985). Among those parameters are the past equilibrium line altitude (ELA), ELA depression (ΔELA), basal shear stress (τ) and mass balance gradients ($\partial b/\partial z$). In this paper, the former glacier at the type locality of the "Gschnitz Stadial" of the Alpine Lateglacial chronology is interpreted from a paleoglaciological and paleoclimatological point of view. It may give some valuable insight into the climatic conditions in the Alps during an early phase of the Alpine Lateglacial, for which paleoclimatic proxy information from other sources (e.g. lake sediments, pollen analysis) is largely absent.

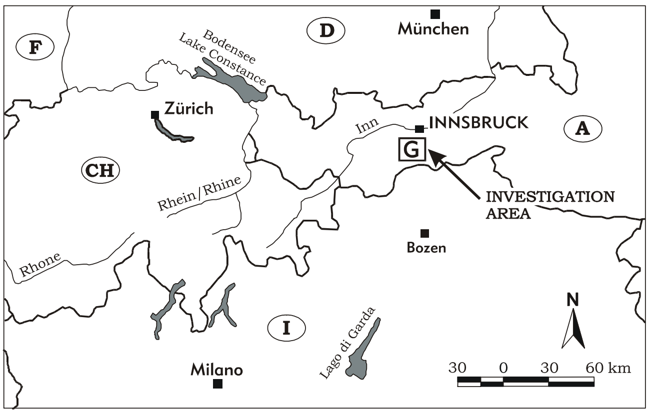

Fig. 1: Location of the Gschnitz valley (G) in the Central Alps.

The complex of lateral and end moraines in the Gschnitz valley near the village of Trins (Pichler, 1859; Kerner v. Marilaun, 1890), about 30 km to the Southwest of Innsbruck (Fig. 1) was chosen by Penck and Brückner (1901/1909) as the type locality of the "Gschnitz Stadial" of the Alpine

Lateglacial chronology. Since then, various authors studied the glacial geomorphology of the Gschnitz valley (e.g. Paschinger, 1952; Mayr and Heuberger, 1968), defining and redefining the Lateglacial chronology of the Eastern Alps in general and that of the Gschnitz valley in particular (cf. Kerschner, 1986). Today, the moraine at Trins is considered once more the type locality of the Gschnitz Stadial (Mayr and Heuberger, 1968; Patzelt and Sarnthein, 1995).

Moraines of the Gschnitz Stadial as presently defined have been found at various other localities in the Alps (e.g. Mayr and Heuberger, 1968; Patzelt, 1975; van Husen, 1977; Gross and others, 1977; Maisch, 1987). Minimum radiocarbon ages suggest that they were deposited during the Oldest Dryas. They show that large parts of the Central Alps were already ice-free and only covered by local glaciers some time before the beginning of the Lateglacial Interstadial (Bølling - Allerød). No reasonable minimum ages could be obtained for the type locality, but recent surface exposure dating (^{10}Be, ^{26}Al) of the end moraine (Ivy-Ochs and others, 1997; for the sampling and dating methodology see Ivy-Ochs and others 1996, 1998) suggests a preliminary age of ca. 15000 cal. BP for its deposition.

Geomorphology

A prominent end moraine occurs in the Gschnitz valley close to the village of Trins at an altitude of 1200 m, marking the end of a former local glacier. The lateral moraines are well preserved on both sides of the valley (cf. Kerner v. Marilaun 1890, Paschinger 1952) for a distance of more than three kilometres up to an altitude of 1410 m. From the morphology of the moraines it can be concluded that the left-hand part of the former glacier tongue below 1300 m (ca. 1% of the glacier surface) was covered with rockfall debris. Above the village of Gschnitz, 6-6.5 km from the end moraine, remnants of moraines at an altitude of 1520 - 1540 m can be traced to the lateral moraines downvalley.

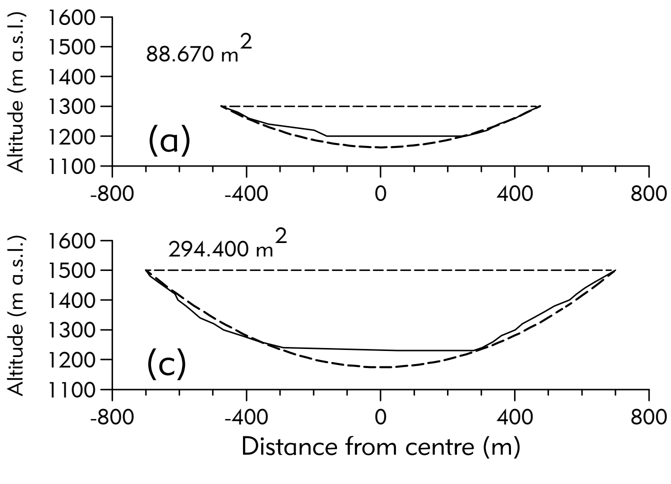

Fig. 2.: Cross-sections of the lower part of the Gschnitz valley. Solid lines represent the actual topography, dashed lines the parabolic cross-sections. Letters a - d refer to the position of the cross profiles in Fig. 3. Surface areas of the parabolic cross profiles are indicated in the upper left.

The valley is almost straight and its width varies only slightly for the entire length of the former glacier tongue (ca. 12.5 - 13 km). The lower parts of the valley walls are covered with scree slopes, morainic material and alluvial cones from small tributaries. Wherever bedrock is exposed, the cross-section is almost perfectly parabolic (Fig. 2). Between the end moraine and the present-day end of the public road at Gasthaus Feuerstein, the valley floor rises for 100 m on a distance of 9 km (1.1%). From there to Lappones Alm it is somewhat steeper (7.6 %). Farther upvalley, a step leads 400 - 500 m up to the cirque areas, which are presently glacierized (Fig. 3). The surrounding peaks are in the order of 2800-3200 m. The comparatively simple morphology of the lower part and the large number of preserved moraines makes the Gschnitz valley well suited for reconstructing a glacier tongue.

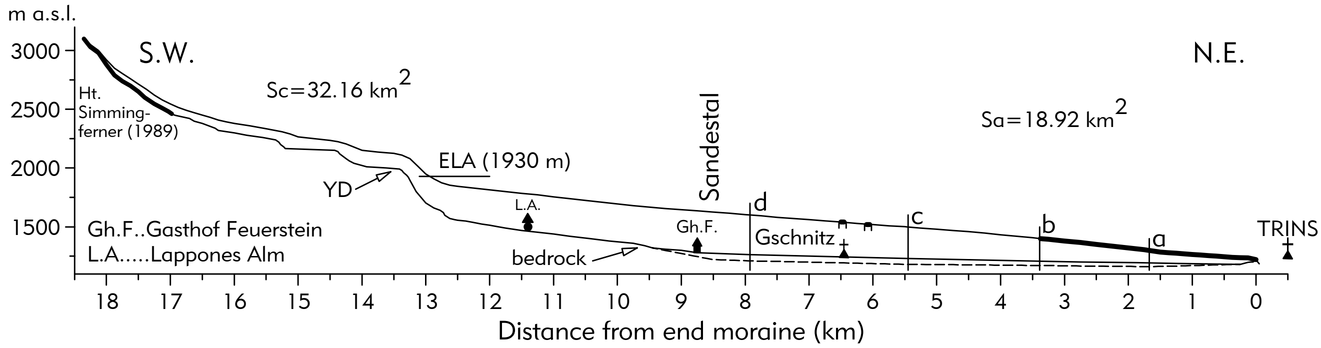

Fig. 3: Long profile of the Gschnitz valley and the Gschnitz Stadial glacier. Thick lines at the glacier tongue and above the village of Gschnitz represent preserved moraines. Sc: accumulation area, Sa: ablation area, YD: position of the Egesen Stadial (Younger Dryas) glacier end.

Reconstruction of the glacier topography

Due to the favourable morphologic situation, the surface topography of the glacier tongue can be reconstructed with a high degree of accuracy.

In a first step, the basal shear stresses in the lowest 3 km of the tongue are calculated as

$$\tau = \rho * g * h * \sin\alpha * f$$

with ρ as the density of glacier ice (900 kg m^{-3}), g as the acceleration due to gravity (9.81 m s^{-2}), h as the thickness of the glacier at its centreline, α as the slope of the glacier surface and f as shape factor for a channel with parabolic cross-section (Nye, 1965). Glacier thickness h is calculated from the altitude of the moraine crests under the assumption of a parabolic cross-section of the valley (dashed line in Fig. 2). The surface slope α is calculated from the lateral moraines over a horizontal distance, which is five times the glacier thickness. As the frontal part of the glacier tongue becomes increasingly steeper upvalley, the basal shear stress rises from ca. 18 kPa at 500 m from the glacier tongue to 77 kPa at a distance of 3000 m from the glacier tongue (Fig. 4).

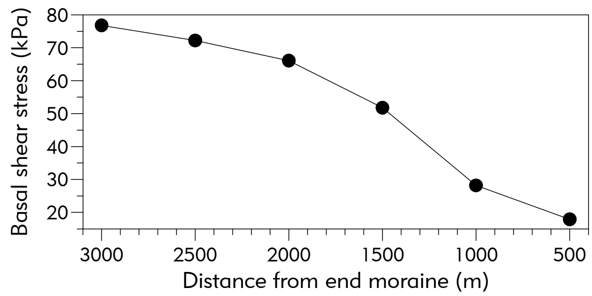

Fig. 4: Basal shear stress at the glacier tongue .

The surface profile between the upper end of the moraines (1410 m a.s.l., km 3.4, Fig. 3) and the point, where the bedslope steepens significantly (km 8.3, Fig. 3) was calculated with the theoretical long profile of a glacier tongue (Nye, 1952). Under the assumption of steady state, it relates glacier length (x) and thickness (h), if the difference between bedslope β and surface slope α is small, as

$$x = \frac{h'_0}{\beta^2}\left(\ln\frac{h'_0}{h'_0 - h\beta}\right) - \frac{h}{\beta}$$

with

$$h'_0 = \tau'/(\rho * g) \quad \text{and} \quad \tau' = \tau/f.$$

By connecting the lowest points of the parabolic cross-sections, a bedslope of 0.88 % can be calculated. With h'_0 = 12.8 m, the reconstructed glacier surface passes through the ice marginal features above the village of Gschnitz. With a shape factor f=0.68, as it can be determined from the topography, this is equivalent to a shear stress of 76.8 kPa, which is similar to the value farther downvalley.

In the upper part of the valley, moraines are missing. There, the glacier received considerable amounts of ice from the large cirque areas at both sides of the valley and from the Sandestal tributary. Hence it is reasonable to assume that the glacier thickness decreased somewhat upvalley (Fig. 3). At the step, which leads up to the cirque areas, the ice thickness was calculated with a shear stress of 400 kPa, as it was typical for the steep part of the Little Ice Age Rhone glacier (Haeberli and Schweizer, 1988). In the cirque areas, which are very wide compared to the ice thickness, a constant shear stress of 100 kPa was used.

With the help of the long profile, the topography of the glacier tongue was drawn with contour lines with 100 m equidistance up to an altitude of 2200 m. Higher up, no contour lines were drawn, as it was quite clear from earlier studies (Paschinger, 1952; Gross and others, 1977) that the ELA of the glacier was situated between 1800 m and 2000 m a.s.l. Steep and serrated rock areas in the uppermost part of the glacier were excluded.

Equilibrium Line Altitude

The ELA of modern and lateglacial glaciers in the Alps is usually calculated with an accumulation area ratio (AAR) of 0.67. It yields reliable results for glaciers with a typical "alpine" area-altitude distribution with large and comparatively flat surface areas in the vicinity of the equilibrium line (Gross and others, 1977; Kerschner, 1990). In the case of the Gschnitz glacier, the ELA was situated in the steepest part of the glacier. Therefore, it seemed to be reasonable to bracket it with AAR values between 0.67 and 0.6 (Fig. 5). The respective ELAs are between 1860 m and 1990 m. As a compromise, an AAR of 0.63 and an ELA of 1930 m are chosen for the subsequent calculations. The average Little Ice Age (1850) ELA in the catchment basin was at 2630 m (Gross and others, 1977), resulting in an ELA depression of the Gschnitz Stadial of -700 m against 1850 or ca. -800 m against modern values.

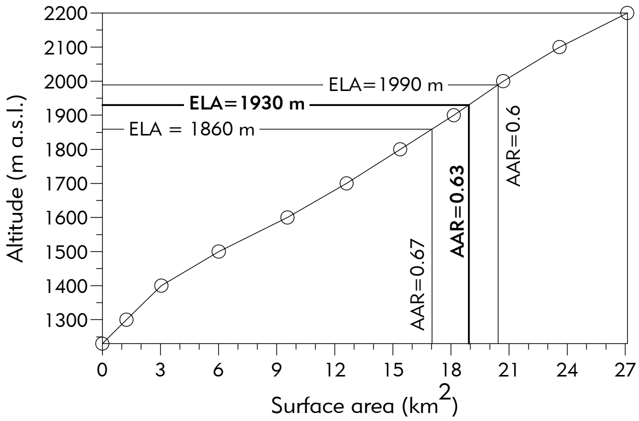

Fig. 5: Area-altitude distribution of the Gschnitz glacier tongue and ELAs for different AAR-values.

Balance gradients

From the topography of the glacier and its bed, the ice-flux through selected cross-sections and balance gradients along the glacier tongue can be calculated. They are an important tool for qualitative and quantitative paleoclimatic interpretations.

To calculate the ice flux, we must first know the mean velocity over a cross-section. If only ice deformation is assumed, the surface velocity u_s of an infinitely wide parallel sided slab of ice is

$$u_s = 2A\,(\rho g \sin\alpha)^n \,\frac{h^{n+1}}{n+1}$$

with A as the temperature dependent parameter (in this case $5 \cdot 10^{-15}$ kPa^{-3} s^{-1}; Paterson, 1994) and n=3 as the exponent in Glen's flow law. The mean horizontal velocity over a parabolic cross-section $u_{m,p}$ can then be calculated from u_s with a correction factor, which depends on the relation between glacier width and ice thickness. It was determined from Table IIIA in Nye (1965: 677). Then, the total horizontal velocity u_t of the glacier is the mean velocity due to ice deformation $u_{m,p}$ plus the contribution of basal sliding u_b (Tab. 1). As the amount of basal sliding is unknown, scenarios were calculated with basal sliding contributing 80% and 50% of u_t.

Table 1: Ice thickness (h), surface slope (α), surface velocity (u_s), correction factor for a channel with parabolic cross-section (fc), mean velocity for a parabolic cross-section ($u_{m,p}$), sliding velocity for 80% basal sliding (u_b) and total velocity (u_t) for selected cross-sections. Letters (a) - (d) refer to Fig. 2 and 3.

Cross-section	h (m)	α (deg)	u_s (m a^{-1})	fc	$u_{m,p}$ (m a^{-1})	u_b (m a^{-1})	u_t (m a^{-1})
a	140	4.29	8.7	0.27	2.4	9.5	11.9
b	230	2.99	21.5	0.24	5.2	20.7	25.9
c	320	2.29	36.4	0.20	7.1	28.4	35.5
d	390	2.15	66.2	0.14	9.3	37.1	46.4

The ice-flux Q through a cross-section can be determined by multiplying u_t with the area of the cross-section (Fig. 2). From the difference in ice-flux ΔQ between two neighbouring cross-sections and the surface area S between them, net ablation can be calculated as ΔQ/S, which has finally to be corrected for water equivalent. The resulting b(z)-curves for the glacier tongue are shown in Fig. 6. For comparison, the b(z)-curves of various other glaciers for years with zero net balance (Kuhn, 1984) are added to Fig. 6.

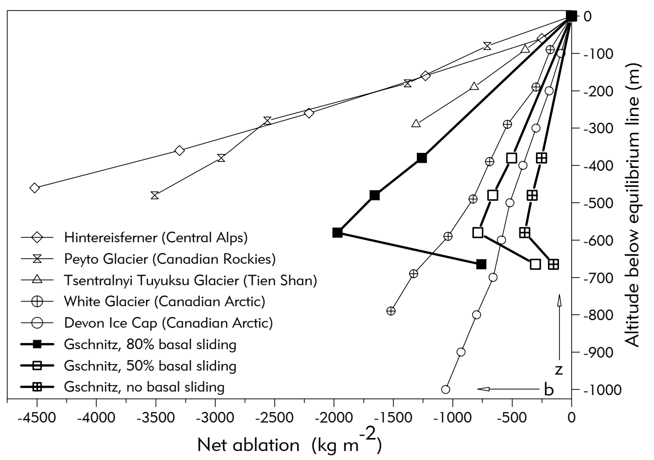

Fig. 6: Steady-state balance gradients along the glacier tongue of the Gschnitz glacier and various other glaciers.

Under the assumption of 80% basal sliding, the balance gradient is somewhere in-between that of Tsentralnyi Tuyuksu Glacier (Tienshan) and White Glacier (Canadian Arctic), whereas for 50% basal sliding, it is rather similar to that of White Glacier. If we (unrealistically) assume that there was no basal sliding at all, the balance gradient is even steeper than that of Devon Ice Cap (Canadian Arctic). Depending on the amount of basal sliding, the balance gradients $\partial b/\partial z$ on the glacier tongue between 1350 m and 1550 m a.s.l. vary between -3.55 kg m^{-2} m^{-1} (80% basal sliding) and -0.71 kg m^{-2} m^{-1} (0% basal sliding). These values are typical for glaciers in a cold and continental climate. They can be cross-checked with the activity index of a stationary glacier (Kuhn and Hermann, 1990: 307). It relates the balance gradient $\partial b/\partial z$ with the length of the glacier tongue X and the maximum velocity in the x direction $u_{x,max}$ as

$$\partial b/\partial z = -\rho * u_{x,max} / X$$

Assuming a value of 50 m a^{-1} for $u_{x,max}$ and taking the length of the glacier tongue as 12.8 km (Fig. 3), $\partial b/\partial z$ is -3.55 kg m^{-2} m^{-1}, which is similar to the result obtained for 80% sliding.

Possible Errors

This way of calculating ice discharge and balance gradients is sensitive to various parameters. The influence of the temperature dependent parameter A is linear. The chosen value of $5*10^{-15}$ kPa^{-3} s^{-1} is for ice with a temperature of ca. -1° C (Paterson, 1994). Smaller values for colder ice lead to correspondingly lower discharge rates. Values for surface slope α are determined as exactly as possible from the moraines, and, therefore, from topographical maps. Errors in the order of several metres can easily occur during such a procedure. As the surface slope enters the velocity equation with the third power, this may finally lead to a distortion of the b(z)-curves. However, the overall shape of the b(z)-curve is not altered significantly, even if the assumed errors are larger than necessary (>±10 m). A systematic error in the determination of the surface slope is unlikely due to the large number of preserved moraines. Errors in the determination of the ice thickness h may also occur. As the actual glacier bed remains unknown, h is determined from the parabolic cross-sections and only speculations can be made about the size of the errors. An error in h does not only influence the area of the cross-sections, but also the surface velocity, because it enters the velocity equation with the fourth power. On the other hand, the effects of changes in h are somewhat counterbalanced by corresponding changes of the shape factor. Changes in h do not affect the surface topography, as it is largely fixed by the moraines. The results of some calculations with different values of h (±20 m) showed fairly similar results as compared to those with changes of α. The b(z)-curves were distorted, but the principal shape remained the same. In any case, the balance gradients remain typical for glaciers in a cold and continental climate.

Paleoclimatological interpretation

This section provides some more quantitative ideas about precipitation and summer temperature during the Gschnitz Stadial. They are to some extent speculative and the figures should not so much be seen as absolute values but rather as orders of magnitude.

By extrapolating the b(z)-curve towards the ELA, we may calculate the total net ablation A_n on the glacier tongue. If we assume steady state, A_n must be balanced by total net accumulation C_n. Thus we may calculate the mean specific accumulation over the accumulation area S_c as $c = A_n / S_c$. Even for 80% sliding, calculated values are quite low (Tab. 2). Only this case, which is already rather "humid" and "warm", is discussed in more detail below. All other scenarios (lower values for A under the assumption of lower ice temperatures, smaller contributions of basal sliding to the velocity of the glacier) represent drier and colder conditions.

Tab. 2: Mean specific accumulation of the Gschnitz glacier

sliding	mean specific accumulation (kg m^{-2})
80%	600
67%	360
50%	240
0%	120

From the data in Fliri (1975) we may estimate present-day (i.e. 1931 - 1960) precipitation at the ELA (ca. 2730 m) as 1700 mm a^{-1} and summer (June-August) temperature as 3.3°C. Similar precipitation values can be obtained from the (P,T)-relation of Ohmura and others (1992: 401). If we assume that accumulation is 1.5 times precipitation (Kuhn, 1981), it should be in the order of 2550 kg m^{-2} a^{-1}. Assuming further that the mean specific accumulation during the Gschnitz Stadial is correct at the median altitude of the accumulation area (2580 m), and using an accumulation gradient of 1 kg m^{-1}, accumulation at 2730 m was then about 750 kg m^{-2} (29 % of the present accumulation). The change in accumulation was -1800 kg m^{-2}. We may therefore conclude that accumulation and probably also precipitation during the Gschnitz Stadial was less than one-third of the present-day values.

Inferring temperature change is even more prone to errors. The glacial-meteorological model by Kuhn (1981) should only be used with extreme caution, because ΔELA is large (-800 m) and the results for the summer temperature change δt_S are strongly influenced by the (unknown) accumulation gradients, the (unknown) duration of the ablation period, the (unknown) change of the temperature lapse rate, possible (unknown) changes of the short-wave radiation balance and the (unknown) contribution of the latent heat flux to ablation. Despite these uncertainties, some cautious calculations show that temperatures might have been lowered in the order of -7.5 to -11°C.

In a different approach, various statistical (P,T)-models can be used. The basic assumption is that precipitation at the Gschnitz Stadial ELA was proportionally lowered like accumulation. In that case, precipitation at 1930 m (ELA of the Gschnitz Stadial glacier) during the Gschnitz Stadial is estimated at 400 mm. Then we may calculate the corresponding summer temperature at the ELA from the (P,T)-models. Finally, the present-day summer temperature at 1930 m has to be subtracted from the Gschnitz Stadial summer temperature at the ELA to obtain δt_S. The results are summarised in Table 3. They show that temperature was roughly 9 - 11°C lower than today with an average value of -10.2°C. This agrees surprisingly well with the results from the glacial-meteorological model. It should be kept in mind though that a summer temperature depression of ca. -10°C is quite large and should be evaluated in further studies.

Table 3: Temperature at the ELA of the Gschnitz glacier (T_{ELA},G), present-day (1931-60) temperature at the altitude of the Gschnitz Stadial ELA (T_{31-60},ELAG) and changes of summer temperature (δt_S).

source	T_{ELA}, G	T_{31-60}, ELAG	δt_S	
Ohmura and others (1992)	-0.8	8.7	-9.5	June-August
Kerschner (1985)	-2.4	8.2	-10.6	June-September
Listøl in Sissons (1979)	-2.4	8.2	-10.6	June-September
Khodakov (1975)	-1.0	9.3	-10.3	July-August
Krenke (1975)	-1.1	8.7	-9.8	June-August

By comparison, climate during the Younger Dryas in the Alps was much warmer (δt_s -2.5 K - -3 K) and more humid (δP ±0 - -40 %), as can be inferred from timberline and ELA fluctuations in the Austrian and Swiss Alps (e.g. Kerschner, 1985; Ivy-Ochs and others, 1996). During the Gschnitz Stadial, climate was more closely resembling full glacial conditions. This strongly supports an early age of the Gschnitz Stadial.

Conclusions

From the above, we may draw some interesting conclusions for paleoclimatological research:

- In valleys with simple topography (flat valley bottoms, no significant changes in the geometry of the valley), it is possible to reconstruct the topography of glacier tongues with simple glaciological models to a high degree of accuracy, if a sufficient number of moraines is preserved to calculate reliable shear stresses.
- From the topography of the glacier tongue, it is possible to calculate ice-flux through selected cross-sections and mass balance gradients on the glacier tongue, which give at least realistic

orders of magnitude. In the case of the former Gschnitz glacier, they are similar to those from glaciers in Central Asia and the Canadian Arctic, thus indicating a cold and continental climate.

- Under the assumption of steady-state, it is possible to estimate net accumulation, and, with some further assumptions, precipitation. Even under the assumption of 80% basal sliding, accumulation and precipitation are calculated at less than one third of present-day values in that area.
- Changes of summer temperature can be inferred with standard glacier-climate models. For earlier parts of the Alpine Lateglacial (i.e., older than the Younger Dryas), statistical models seem to be more robust than glacial-meteorological models, which require too many assumptions. They show that summer temperature was roughly 9 - 11° lower than today. These results are at least realistic orders of magnitude.
- The paleoclimatic interpretation of balance gradients is independent of non-glacial paleoclimatic information (e.g. from timberline fluctuations). Therefore, it allows quantitative paleoclimatic inferences for earlier periods of the Alpine Lateglacial, for which such information is unavailable.

Acknowledgements

We sincerely thank Gernot Patzelt (Institut für Hochgebirgsforschung, Innsbruck) and Georg Kaser (Institut für Geographie, Innsbruck) for critically reading the manuscript and for many valuable suggestions. The comments of two reviewers (Nick Hulton and Andrew Mackintosh) were most helpful during the final stages of the manuscript. The project was partly supported by the Swiss National Science Foundation under grant No. 21-043469.95/1. This support is most formally acknowledged.

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