LATEGLACIAL PALEOTEMPERATURES AND PALEOPRECIPITATION AS DERIVED FROM PERMAFROST: GLACIER RELATIONSHIPS IN THE TYROLEAN ALPS, AUSTRIA

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Numerous fossil rock glaciers in the Alps, situated 450-550 m below the presently active rock glaciers, can be correlated with the Egesen Stadial cold phase (11,000 to 10,000 BP). Fossil rock glaciers of Daun and Senders age (probably older than 13,000 BP) are situated 650 m below the active rock glaciers. From the lowering of the Egesen rock glaciers, a lowering of the mean annual air temperature in the order of -3.5°C against modern values is inferred. The lowering of the summer temperature, as inferred from the lowering of timberline, was in the order of -2.5°C during this period. For the Daun and Senders Stadials, a lowering of the MAAT in the order of -4.5°C is estimated. With the help of a permafrost-glacier-precipitation relationship, paleoprecipitation is estimated. During the Egesen Stadial, precipitation was reduced by 30% in the sheltered valleys of the Tyrolean Alps, whereas precipitation was about equal to present-day values along the northern slope. During the Daun and Senders Stadials, precipitation was reduced by 40% and 25% respectively in some valleys of the northern slope.

INTRODUCTION

In the past paleoclimatic studies in the Alps were concerned with the inference of summer temperature fluctuations from snowline and timberline fluctuations (Patzelt 1975, 1980). A first attempt to derive fluctuations of the annual temperature from rock glacier altitudes was made by the present author (Kerschner 1978). Statements on paleoprecipitation had been qualitative, relying mainly on paleobotanical information. For the last cold phase of the Alpine Lateglacial, the Egesen Stadial (Younger Dryas cold phase, 11,000 to 10,000 BP), a quantitative estimate of the precipitation could be given on the basis of equilibrium line altitudes and timberline altitudes (Kerschner 1982a). As paleobotanical information on timberline fluctuations is limited for various reasons, the distribution of lateglacial fossil rock glaciers is used as a source of paleoclimatic information in this paper. This attempt is largely based on the permafrost-glacier-precipitation model developed by Haeberli (1982, 1983), which relates the mean annual air temperature at the equilibrium line of glaciers with precipitation.

STRATIGRAPHY

The Alpine Lateglacial covers the period of the final recession of the large valley glacier systems

Table 1 Lateglacial glacier and rock glacier data, Tyrolean Alps, Austria

AGE	STADIAL	D ELA (m) M	D ELA (m) C	GLACIERS	BASAL SHEAR STRESS (GLACIERS)	ROCK GLACIERS, PUSH MORAINES M	ROCK GLACIERS, PUSH MORAINES C	D PF (m)	PRECIPITATION % M	PRECIPITATION % C	D MAAT °C	D MST °C
10.000 B.P. YOUNGER DRYAS	KROMER	-200	-180	MANY CIRQUE GLACIERS SOME VALLEY GLACIERS	LESS THAN 1 BAR	ABUNDANT, BUT HARD TO DIFFERENTIATE FROM OLDER DEPOSITS		?	POSSIBLY LESS THAN 50 %		-3,0- -3,6 ?	-2,5- -3,0
	LATE EGESEN	-300	-200	MANY CIRQUE GLACIERS SOME VALLEY GLACIERS	LESS THAN 1 BAR	ABUNDANT	ABUNDANT	-450- -550	75 %	50 % OR LESS	-3,0- -3,6	-2,5- -3,0
11.000 B.P.	EGESEN MAXIMUM	-400	-300	MANY CIRQUE GLACIERS SOME LARGE VALLEY GLACIERS	CA. 1 BAR	ABUNDANT	ABUNDANT	-450- -550	100 % OR MORE	LESS THAN 70 %	-3,0- -3,6	-2,5- -3,0
	BØLLING - ALLERØD - INTERSTADIAL COMPLEX											
13.000 B.P. OLDEST DRYAS	DAUN	-450- -500	-300- -400	VALLEY GLACIERS MORE FREQUENT	0,6-0,8 BAR	SOME	RARE	-650	60 %	LESS THAN 60 %	-4,5	-3,5- -4,0
	SENDERS	-600	-500- -400	VALLEY GLACIERS	CA. 1 BAR	RARE	?	-650	75 %	LESS THAN 75 %	-4,5	-4,5 ?
	GSCHNITZ	-750	?	LARGE VALLEY GLACIERS	CA. 1 BAR	?	?	?	?	?	?	?
	STEINACH	-750- -800		LARGE VALLEY GLACIERS	?	?	?	?	?	?	?	?
	BÜHL	-1200 OR MORE		VALLEY GLACIER SYSTEMS ("EISSTROMNETZ") INTACT	?	?	?	?	?	?	?	?

D ELA: LOWERING OF THE EQUILIBRIUM LINE ALTITUDE AGAINST MODERN VALUES, D PF: LOWERING OF PERMAFROST (ROCK GLACIERS), D MAAT: LOWERING OF THE MEAN ANNUAL AIR TEMPERATURE, D MST: LOWERING OF THE MEAN SUMMER TEMPERATURE, C: CONTINENTAL AREAS, M: MARITIME AREAS from approximately 16,000 BP until 10,000 BP. By 9,500 BP, glaciers had already readvanced within their mid-19th century limits (Patzelt 1973). This period of general downwasting of the glaciers was interrupted several times by periods of readvance ("stadials"). These stadials, which are named after type localities near Innsbruck (Tyrol), have been described in detail by Mayr and Heuberger (1968), Heuberger (1966) and Kerschner and Berktold (1982).

During the past decade, extensive mapping by several authors showed that the stratigraphical system developed in the Tyrolean Alps is equally applicable in other areas of the Austrian and Swiss Alps (bibliographies in Müller et al. 1981, Maisch 1981). These readvance periods were usually not single phased but consisted of a series of advances and retreats, each one smaller than the preceding. The correlation with the lateglacial stratigraphy of northwestern Europe still presents some problems, mostly for the older stadials. The most likely correlation is given in Table 1.

In the course of mapping lateglacial deposits, a large number of fossil rock glaciers of lateglacial age was found. These rock glaciers developed from talus as well as from morainic debris. Their average length is in the order of 300 to 500 m, but some are more than 1,000 m long and several hundred metres wide. From the collapse structures, a former ice content in the order of 50 to 70% is estimated. A transition from rock glaciers to push moraines (Haeberli 1979a) and vice versa can be observed at numerous localities. Rock glaciers with a core of glacier ice are presently uncommon in the Alps. This is also true for lateglacial rock glaciers. In most cases the transition between the former glacier and the rock glacier can be clearly delineated in the field or from aerial photographs. The period of activity of these rock glaciers can at least be partially fixed with correlation to nearby moraines of known age.

Most fossil rock glaciers at lower altitudes were active during the Egesen Stadial (11,000 to 10,000 BP). Many of them cover large areas which were glacierized during the Daun Stadial as can be deduced from nearby moraines (Kerschner 1978, Maisch 1981). They indicate that a major warming period preceded the Egesen Stadial, which led to an extensive deglaciation. This warm phase is probably identical with the Allerød-Bølling Interstadial complex (13,000 to 11,000 BP; Welten 1982, Eicher 1979, Eicher et al. 1981). As the Younger Dryas cold phase lasted for about 1,000 years and as sufficient debris was available from intense frost shattering and moraines, it is assumed that these rock glaciers closely approached their lowermost position as controlled by topography and climate. In places with appropriate topography, they extend to altitudes between 1,900 and 2,000 m a.s.l., about 450-550 m below presently active rock glaciers. The available data show that there is no significiant spatial variability of the altitude of Egesen rock glacier termini in the study area. Similar altitudes can be observed in central and southwestern Switzerland. Rapid warming after 10,000 BP, as it can be inferred from numerous paleobotanical and glaciological studies (e.g. Welten 1982, Patzelt and Bortenschlager 1982) suggests that the activity of these rock glaciers came to an end at the Lateglacial/Postglacial boundary around 10,000 BP.

While there exists already a fair amount of data on the distribution of rock glaciers of Egesen age, information about rock glaciers of older age is still limited. This is mainly due to the fact that large valley glaciers were more frequent during older phases of the Alpine Lateglacial. These glaciers occupied large areas suitable for rock glacier formation and ended at altitudes that were obviously too low for the existence of permafrost. Rock glaciers of Daun age in the Tuxer Voralpen, 30 km south of Innsbruck, are 620-680 m below the present-day lower boundary of permafrost(Patzelt 1983). Push moraines of Daun age in the Karwendel to the north of Innsbruck can be observed 150-200 m below Egesen rock glaciers. Rock glaciers which can be correlated with the Senders Stadial seem to have been at similar altitudes as the Daun rock glaciers (Kerschner and Berktold 1982).

PALEOCLIMATIC INTERPRETATION

Numerous measurements show that the surface velocity of rock glaciers in the Alps rates from approximately 0.1 to 1.0 m/yr. A surface velocity of 0.3 m/yr is chosen as a reasonable average by Barsch (1977a,b). From this it is deduced that the formation of a rock glacier of considerable length (i.e. several hundred metres) demands at least several centuries (Vietoris 1972). Possible former periods of fossilization and reactivation can usually not be recognized in the field. From this it follows that fossil rock glaciers only provide a general picture of climatic changes on a time scale of several centuries.

About the same level of resolution can be attained for the inference of timberline fluctuations from lateglacial pollen diagrams, which have also been used as a source of paleoclimatic information (Kerschner 1982a). Thus, paleoclimatic models with rock glacier data as input variables should be comparable with models which use timberline fluctuations as one source of information. Both models cannot make full use of the much more detailed, but unrevealed paleoclimatic information which is present in the large number of lateglacial morainic systems.

Mean Annual Air Temperature (MAAT)

The spatial pattern of the distribution of active rock glaciers--as permafrost phenomena--reflects the pattern of annual isotherms in the study area very well (Fliri 1975, Barsch 1977a, Haeberli 1979b). The same should hold true for fossil rock glaciers which had sufficient time to develop. Hence, as a first approximation, the vertical difference between active and fossil rock glaciers of identical exposure, comparable extent and comparable morphologic setting is proposed as a measure of the lowering of the MAAT (Kerschner 1978). This vertical difference is converted into the lowering of the MAAT with the help of a temperature lapse rate of $-0.65^{\circ}C/100$ m. From the lowering of the Egesen rock glaciers (-450 to 550 m) a lowering of the MAAT in the order of -3.0 to

-3.6°C can be inferred for the period 11,000 to 10,000 BP. This is more than the lowering of summer temperature, which can be calculated from the lowering of timberline (approximately -400 m throughout the study area) as about -2.5° to -3.0°C. These results suggest an increase in seasonal contrasts of temperature between summer and winter during the Egesen Stadial. The same figures seem to apply for the late Egesen Stadial, when glaciers were already much smaller than during the maximum.

From the lowering of the Daun and Senders rock glaciers and push moraines (approximately -650 m) a lowering of the MAAT in the order of -4.0° to -4.5°C is inferred. Due to a lack of data, no direct estimates can be given for the summer temperature during these periods.

The figures for the lowering of the MAAT during the Egesen Stadial seem to be rather reliable due to the long duration of the cold phase and the large sample size. The figures calculated for the Daun Stadial and the Senders Stadial are less well supported due to the small sample size and our still insufficient knowledge of the duration of these cold phases.

Paleoprecipitation

Active rock glaciers are abundant in the rather dry valleys of the central Alps which are sheltered from the precipitation bearing air masses from the north and south. Precipitation at 2,000 m a.s.l. is in the order of 750 to 1,200 mm/yr in these areas. The equilibrium line (EL) of glaciers there is high compared with the humid northern slope, where precipitation is in the order of 1,600 to 2,000 mm/yr (Gross 1983, Kuhn 1983). Active rock glaciers are almost absent in the humid northern areas of the Alps where the EL is close to the lower boundary of permafrost, thus leaving no space for the developement of rock glaciers. The vertical distance between the termini of active rock glaciers and the equilibrium line altitude (ELA) increases markedly with decreasing precipitation. From this it follows that the MAAT at the ELA in dry areas is lower than in humid areas (Haeberli 1979b, 1982, 1983). Hence, the MAAT at the ELA can be taken as an indirect measure for the precipitation in a given area. The relationship between the MAAT at the ELA and the precipitation at 2,000 m a.s.l. in the Alps (Figure 1) can be expressed as

$$\text{Precipitation}_{2,000} = 3613.(-\text{MAAT}_E)^{-0.8679} \qquad (1)$$

from the data of Haeberli (1982). A standard altitude of 2,000 m a.s.l. is chosen for practical reasons. It is also used in other models for the determination of paleoprecipitation (Kerschner 1982a).

Equation (1) serves as the basis for the quantitative estimation of paleoprecipitation during some of the lateglacial stadials. The MAAT at the ELA is calculated from the vertical difference between the altitude of the termini of fossil rock glaciers and the ELAs of nearby glaciers of similar age. Following the lines of Haeberli (1982), it is assumed that the MAAT at the termini of rock glaciers varies between -2.0° and -4.0°C, depending on aspect and topographic setting of the respective rock glaciers.

Most of the available data come from glaciers and rock glaciers of the Egesen Stadial cold phase (11,000 to 10,000 BP). They show that at the humid northern margin of the study areas the MAAT at the ELA was not below -2.5°C, from which a precipitation in the order of 1,600 to 2,000 mm/yr can be calculated with the help of equation (1). This is about equal to the present-day precipitation in this area. In the sheltered valleys of the central Alps, the MAAT at the ELA was about -6.0° to -7.0°C indicating a precipitation in the order of 650 to 800 mm/yr, which is about 25-33% less than present-day values.

During the late stages of the Egesen Stadial, glaciers were much smaller and their EL was at higher altitutdes than during the maximum. In some areas rock glaciers developed within the area which was glacierized during the maximum advance (Müller et al. 1981, Maisch 1981, Kerschner 1982b). Estimates show that the MAAT at the ELA was of the order of -3.5°C along the northern slope but -8.0°C in the sheltered valleys, thus pointing to a reduction of precipitation by 25 and 55% respectively.

These results can be cross-checked with a stochastic glacier-climate model (Figure 1) which relates the summer temperature at the ELA and the precipitation at 2,000 m a.s.l. (Kerschner 1982a) and with a glacial-meteorological model, which relates ablation and accumulation at the EL through a system of equations defining heat and mass exchange at the glacier surface (Kuhn 1980, 1982). In these models, data on the change of the altitude of tim-

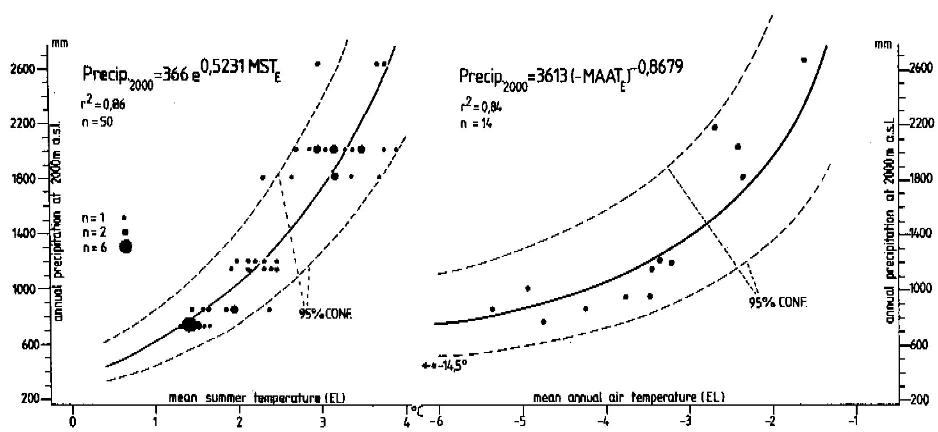

Figure 1 Relation among mean summer temperature at the equilibrium line (MST_E) and precipitation at 2,000m a.s.l. ("glacier-climate-model", Kerschner (1982a)) and relation among mean annual air temperature at the equilibrium line ($MAAT_E$) and precipitation at 2,000 m a.s.l. ("glacier-permafrost-model" after Haeberli (1982), slightly modified).

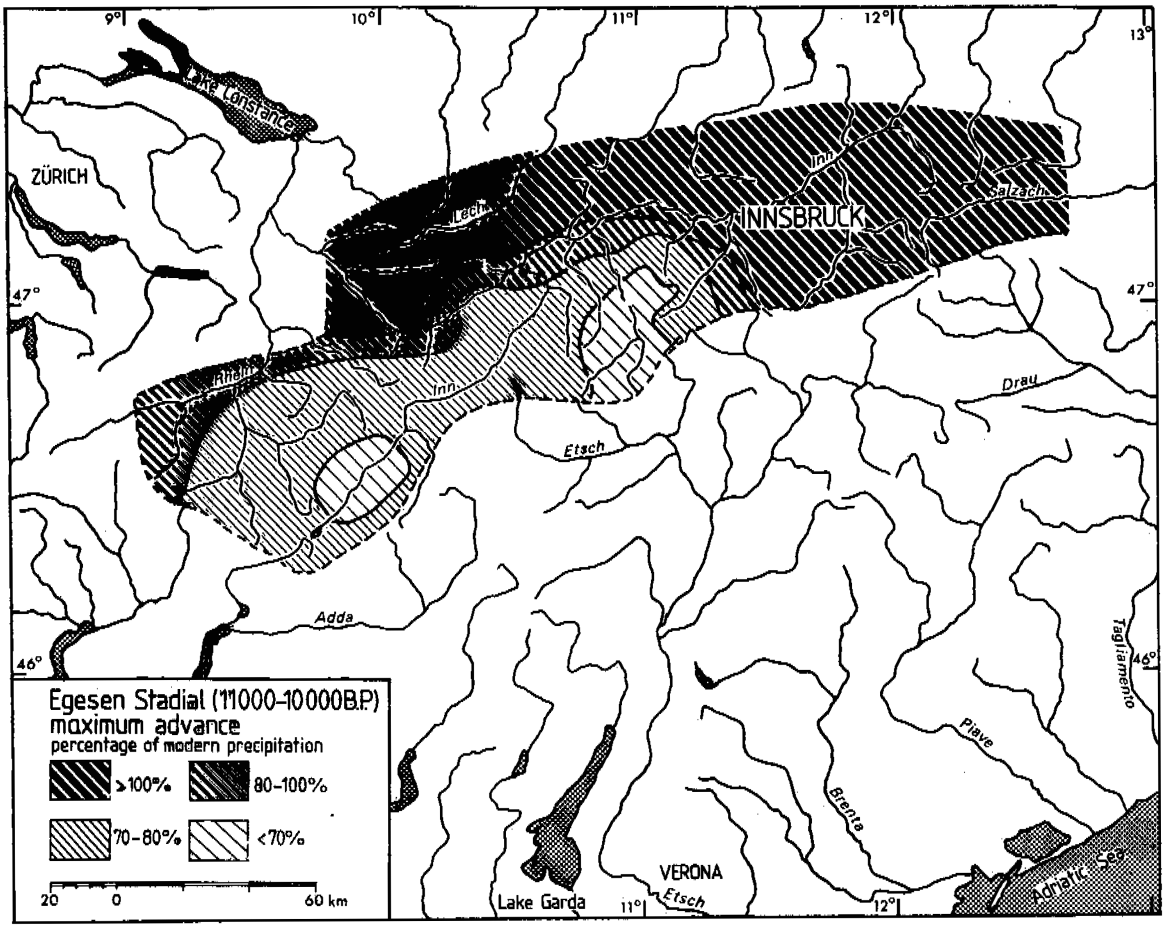

Figure 2 Distribution of precipitation in the central Alps during the Egesen maximum advance, expressed as percentage of present-day precipitation at 2,000 m a.s.l.

berline are used as an independent variable to determine the change of summer temperature at the EL. The use of summer temperature in a glacier-climate model is physically more correct than the use of the MAAT, because summer temperature is an important factor governing ablation. The use of both models is limited to periods for which estimates of the timberline altitude can be made from palynological data. This precludes their application to stadials which preceded the Allerød-Bølling Interstadial complex (13,000 to 11,000 BP). They give similar values of paleoprecipitation during the Egesen Stadial as the permafrost-glacier model discussed in this paper. Differences do not exceed 5% on the average.

A combined application of the glacier-climate model and the permafrost-glacier model allows the plotting of a map of the change of precipitation from present-day values to the precipitation during the maximum advance of the Egesen Stadial (Figure 2) The map covers an area of approximately 250 x 100 km of the central and northern Alps in western Austria and eastern Switzerland. It shows the rapid decrease of precipitation from the northern slope towards the central valleys, which was much more pronounced during the Egesen Stadial than it is today. The transition between humid and dry areas during this period was sharp and concentrated along mountain chains with altitudes of more than 2,700 m a.s.l. to the south of the Inn valley.

Data on the Daun and Senders Stadials are still limited, so only a few remarks on the former climatic conditions can be made. These data come from valleys which were part of the humid northern area during the Egesen Stadial with 100% of the present-day precipitation. They indicate that precipitation in this area was about 25% lower during the Daun Stadial. During these Stadials, the ELA was much lower than during the Egesen Stadial (Table 1). By employing the glacial-meteorological model (Kuhn 1982) the lowering of summer temperature can be calculated. The precipitation values determined with the permafrost-glacier model are serving as input data. During the Senders Stadial, the lowering of summer temperature was in the order of -4.5°C or more. During the Daun Stadial, summer temperatures were approximately -3.5°C to -4.0°C lower than at present-day. These changes of summer temperature cannot be tested quantitatively against other information and thus must be regarded as orders of magnitude only.

The overall impression of the climate during these phases of the Alpine Lateglacial is that of a rather cold and dry mountain climate which seems to be readily comparable with the present-day climate in the high mountain regions of central Asia. It seems that the stadials started with cool and comparably moist conditions which changed to cold-dry conditions within a time span of a few centuries or less. This pattern, which was obtained from glaciological and geomorphological information, agrees favourably with the paleobotanical record of the Alpine Lateglacial. This record shows a cold and dry climate favouring a cold steppe vegetation in the upper reaches of the valleys above timberline (Welten 1972, 1982, Markgraf 1973; extensive bibliographies in Burga 1980, Küttel 1979). Results of $^{18}O/^{16}O$-investigations on lake marls in Switzerland agree also well with this pattern (Eicher 1979).

CONCLUSIONS

Fossil rock glaciers in the Alps seem to be a valuable source for paleoclimatic information. Fluctuations of the MAAT can be inferred from the difference in altitude between fossil and active rock glaciers, if data are derived from rock glaciers of identical exposure comparable extent and comparable morphologic setting. The permafrost-glacier model discussed in this paper seems to provide reliable values of the paleoprecipitation during certain cold phases of the Alpine Lateglacial. It seems to be a useful model for the determination of paleoprecipitation for periods, for which timberline data are absent but rock glacier data are available.

The use of rock glacier data in paleoclimatic considerations allows to extend quantitative paleoclimatic studies in the Alps to the northern Alps, where timberline altitude is not so much controlled by climate, but by relief and the limestone substratum. With some precautions, paleoclimatic estimates can be made for cold phases older than the Allerød-Bølling Interstadial complex (13,000 to 11,000 BP), when timberline had not yet reached its highest possible position. Thus, rock glacier studies allow to broaden the scope of quantitative paleoclimatic studies in the Alps both in space and in time.

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