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Equilibrium-line altitudes and rock glaciers during the Younger Dryas cooling event, Ferwall group, western Tyrol, Austria

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ABSTRACT. Three cirques in the Ferwall group, western Tyrol, Austria, which are characterized by distinct Late-glacial moraines and rock glaciers, are discussed. The morphology of the moraines and the depression of the equilibrium-line altitude suggest they were deposited during the Egesen Stadial (Younger Dryas), which can be subdivided into three substages. Rock-glacier formation was initialized during or after the Egesen II substage. They became inactive at the Pleistocene–Holocene transition. ELA values are 290–320 m lower than the Little Ice Age ELA during the Egesen I substage, 190–230 m lower during the Egesen II substage and 120–160 m lower during the Egesen III substage. The lowering of the rock-glacier belt (discontinuous permafrost) during and after the Egesen II substage is about 400 m, indicating a mean annual air-temperature depression in the order of 3 K. During the Egesen I (early Younger Dryas), the climate seems to have been rather cold and wet with precipitation similar to present-day values. During later phases (Egesen II and III), the climate remained cold and became increasingly drier. The rise of the ELA during the Egesen I–III substages seems to have been mainly caused by a decrease in precipitation.

INTRODUCTION

Late-glacial equilibrium-line altitudes (ELA) and rock-glacier altitudes are parameters which can be easily and accurately determined in wide areas of the Alps. They provide qualitative and quantitative information about the former climate in the Alpine valleys, because their distribution in space and time is predominantly controlled by climate. In this paper, an attempt is made to describe and discuss the fluctuations of the ELA and phases of rock-glacier development in the Ferwall group, western Tyrol, Austria, during the Younger Dryas cooling event.

The decay of the Alpine glaciers after the Last Glacial Maximum was interrupted by a series of several, successively smaller readvances ("stadials"). The moraine sequence is fairly consistent from valley to valley and has been extensively mapped in both the Austrian and Swiss Alps (e.g. Heuberger, 1966; Mayr and Heuberger, 1968; Kerschner, 1978b; Maisch, 1981; Müller and others, 1981; Suter, 1981; Furrer and others, 1987 and references therein; Ivy-Ochs and others, 1995, 1996).

The moraines of the Egesen Stadial are the most marked and widespread of the series. In most valleys, three distinct series of moraines can be found (Egesen I to Egesen III). In some places, moraines of a fourth, slightly smaller advance (Kromer/Kartell) can be found. They represent the last cold event prior to the many advances of Holocene order of magnitude, which characteristically reached only the Little Ice Age (LIA) extent (e.g. Patzelt and Bortenschlager, 1973; Holzhauser, 1984; Patzelt, 1995). Basal radiocarbon dates from peat bogs in the tongue areas of Egesen moraines in the Austrian Alps are in the late Younger Dryas–early Preboreal time range (Patzelt, 1972; Kerschner, 1978b; Bortenschlager, 1984). In the Val de Nendaz (southwestern Switzerland), the last phase of the Younger Dryas could be found by pollen analysis in lake deposits within the Egesen II moraine (Müller and others, 1981). Surface-exposure ages of an Egesen I moraine at Julier pass (Switzerland) show it was deposited 200–300 years after the onset of the Younger Dryas (Ivy-Ochs and others, 1996). At the same locality, the activity of rock glaciers in connection with Egesen moraines continued into the early Preboreal. The Kromer/Kartell advance might be the correlative to the early Preboreal Erdalen event in western Norway (Nesje and Dahl, 1993; Dahl and Nesje, 1996). Similar moraines in the Zugspitze Massif (southern Germany) are assumed to be of late Younger Dryas–early Preboreal age (Hirtlreiter, 1992).

The Ferwall group is situated at the western margin of the central Alps in western Tyrol (Fig. 1). Crystalline bedrock (mainly gneisses, granites, amphibolites) favours the devel-

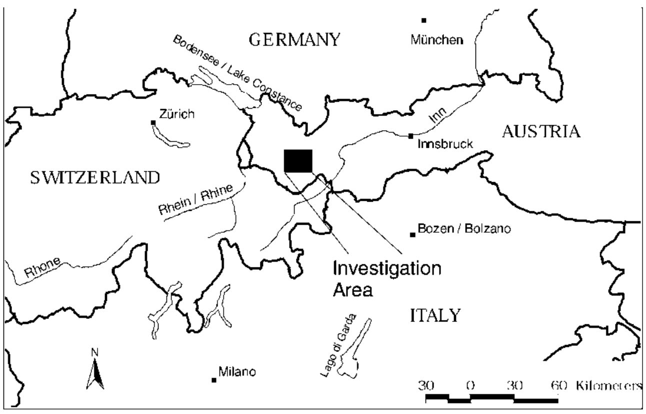

Fig. 1. Study area.

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opment and preservation of moraines and rock glaciers. Most peaks are in the range of 2500–3000 m. From a climatic point of view, the western part of the Ferwall group, which is open towards the Rhine valley, is rather humid with precipitation values around 2000 mm a^{-1}, whereas the eastern and southern part is somewhat drier (Fliri, 1975). This pattern is also reflected in the general rise of the present-day ELA from west to east (Gross, 1983). Earlier work on the glacial geomorphology of the Ferwall group includes papers by Bobek (1933), Senarclens-Grancy (1956) and Fraedrich (1979). A first paleoclimatic interpretation of Egesen moraines and associated rock glaciers in the Ferwall group was attempted by Kerschner (1978a).

METHODS

The assignment of Alpine Late-glacial glaciers to a chronostratigraphy is based on:

(a) the relative position of the moraines within a moraine complex;

(b) the morphological appearance of the moraines; and

(c) depression rates of the ELA relative to a mean LIA (1850) ELA in the catchment area of the specific Late-glacial glacier.

In areas with crystalline bedrock, Egesen moraines usually do not show any evidence of solifluction overprint, but retain their fresh and sometimes rather blocky appearance. Older moraines at similar altitudes, which were deposited by glaciers of similar size (Daun Stadial), are much less distinct and were affected by solifluction in many places (Heuberger, 1966). Therefore, it is not difficult in the field to distinguish Egesen moraines from older moraines at altitudes above 1900–2000 m a.s.l.

Comparing the Younger Dryas ELAs with those of the LIA offers three advantages. First, it is possible to determine ELAs of regions where no modern glaciers exist; second, it is possible to combine an inhomogeneously glaciated area to one decisive ELA; and third, the ELA of the LIA is an invariable quantity (Gross and others, 1977; Maisch, 1992). In the study area, the ELA of the LIA was about 100 m lower than the "present-day" (i.e. Austrian Glacier Inventory, 1969: cf. Gross, 1983) ELA.

To determine the ELA, two methods are commonly used. Where well-preserved lateral moraines can be found, the highest point of the moraine indicates the ELA of the specific glacier. But in most cases, the lack of well-preserved lateral moraines efforts the accumulation area ratio (AAR) method. The AAR in the Alps for Younger Dryas and modern glaciers is assumed to be 0.67. Both methods yield practically the same results (Gross and others, 1977).

It is evident that a distinct rock-glacier formation occurred during the Egesen Stadial (Heuberger, 1966; Kerschner 1978a, b). Kerschner (1978a) compared the beginning of the rock-glacier formation to the early Younger Dryas and correlated it with the Egesen I Stadial. One objective of this work is to test this hypothesis and to determine the time at which the rock glaciers formed.

YOUNGER DRYAS GLACIATION

During the Younger Dryas, several valley glaciers and many cirque glaciers existed in the Ferwall group. Moraines of this region were previously assigned to older stadials (Bobek, 1933; Senarclens-Grancy, 1956; Fraedrich, 1979), but recently Sailer and others (in press) have correlated these deposits to the Egesen Stadial.

Table 1. Little Ice Age (LIA) and Younger Dryas (Egesen)–early Preboreal (Kartell) equilibrium-line altitudes (ELA) and ELA depressions (ΔELA) in three cirques of the Ferwall group

	Kli Mardusa cirque		*Patteriol cirque**		*Vergröß cirque*	
	ELA	ΔELA	ELA	ΔELA	ELA	ΔELA
LIA (1850)	2510		2610		2700	
Kartell	2400	110	2520	90	**	**
Egesen III	2350	160	2480	130	**	**
Egesen II	2280	230	2420	190	**	**
Egesen I	2190	320	2320	290	2380	320

* ELAs refer to the Schönferwall glacier, of which Patteriol cirque was a part.

** No moraines.

As shown in Table 1, a northwest–southeast gradient of the LIA and Younger Dryas ELAs can be observed. This agrees well with modern observed ELAs. In the western part of the investigation area (Kli Mardusa cirque), the LIA ELA was at 2510 m; in the central part at 2610 m; and 2700 m in the southeast. The most extensive glaciation, showing "fresh" lateral and terminal moraines, can be correlated with the Egesen I advance with ELAs 320 m (west), 290 m (central) and 320 m (southeast) below the ELA of the LIA. These values are typical for the maximum of the Egesen Stadial (Kerschner, 1978b; Maisch, 1982). In the Kli Mardusa cirque, the AAR method and the highest point of the Egesen I moraine lead to the same ELA.

In most cirques and valleys of the Ferwall group, at least two other glacier advances can be found which are part of the Egesen sequence of the Younger Dryas glaciation. The second glacier advance, with ELA depressions of 230 m (west) and 190 m (central) is part of the Egesen II glaciation which can be correlated with the Bockten substage of the eastern Swiss Alps (Maisch, 1981). The Egesen III advance, with ELA depressions of 160 m (west) and 130 m (central), indicates the end of the Younger Dryas close to the Pleistocene–Holocene transition. A fourth major glacier advance (Kartell advance) can be observed in the investigation area with ELA depressions of 110 m (west) and 90 m (central).

RELICT ROCK GLACIERS

Numerous active and relict rock glaciers cover an extensive area of the cirques in the Ferwall group. The modern lower limit of the rock glaciers is at 2400–2500 m, depending on the aspect of the cirque. As the lower limits of relict rock glaciers are indicators for variations of the distribution of discontinuous Alpine permafrost (Haeberli, 1985; Barsch, 1996), it is important to determine the time of their formation and the duration of their activity to make conclusions about the paleoclimate.

Kerschner (1978a) postulated the beginning of this extensive rock-glacier formation to the early Younger Dryas (Egesen I) that created a cold and dry climate during this period of the Late-glacial. New investigations, based on morphological mapping in three cirques (Kli Mardusa, west;

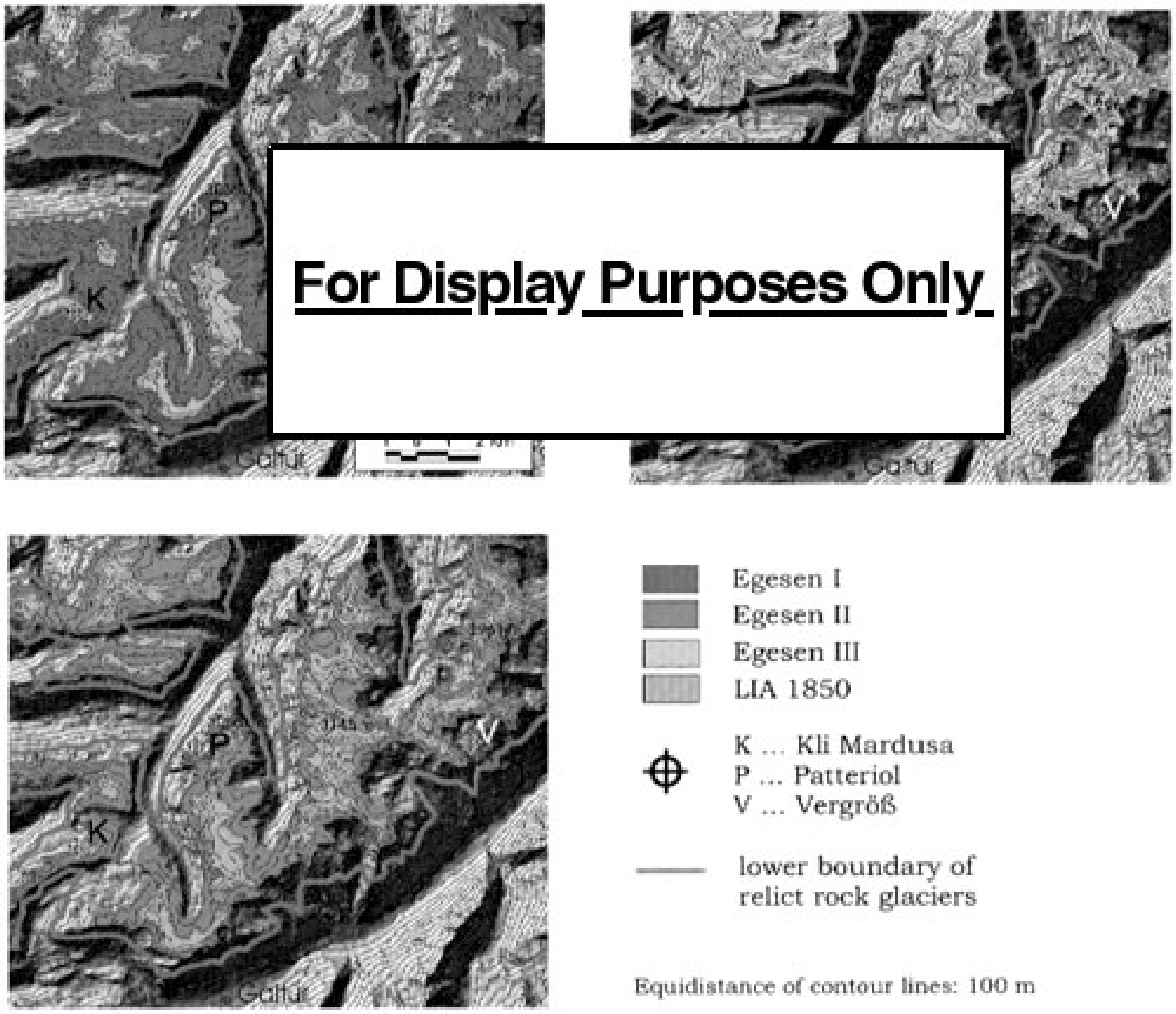

Fig. 2. Potential accumulation areas of the Egesen I–III substages and lower boundary of relict rock glaciers (lower limit of discontinuous Alpine permafrost).

Patteriol central; Vergröß, east; Fig. 2), suggest rock-glacier formation commenced at the same time as the Egesen II retreat or later. The relict rock glaciers are several hundred metres long and reach down close to the end moraines of the largest Egesen advance (Egesen I, Figs 3 and 4). They indicate a lower boundary of the rock-glacier formation at an altitude of:

a) 2000–2100 m in the northerly exposed Kli Mardusa cirque;

b) 2150 m in the westerly exposed Patteriol cirque; and

c) 2240 m in the east-southeast exposed Vergröß cirque.

In contrast to Kerschner (1978a), it can be shown that an extensive glaciation during the early Younger Dryas has occurred. Distinct lateral and terminal moraines are relicts of this glaciation and can be assigned to the Egesen I phase. Therefore, the rock glaciers must be younger than the Egesen I.

As rock glaciers can only develop in unglacierized areas, it is interesting to check them for potential rock-glacier development. Figure 2 shows the potential accumulation areas of glaciers during the Egesen I phase. It is based on the field evidence, which was extrapolated with a geographical information system (GIS)-based model, taking the variations due to aspect into account. Due to the extensive Egesen I potential accumulation areas, rock-glacier formation during the Egesen I advance seems to have been unlikely, because most of the areas above the lower limit of discontinuous permafrost were glacierized. In contrast to this, the potential accumulation areas of the Egesen II and Egesen III glaciers are very limited and enable rock-glacier development (Figs 2 and 5). Furthermore, in the western part of Kli Mardusa cirque the end moraine of the Egesen II advance is covered by a relict rock glacier, while in the central and eastern parts of the cirque, the moraine forms a continuous arc (Fig. 3). Thus, the rock glacier developed after the Egesen II advance and, at the earliest, during glacier retreat from the respective moraines. In the cirque to the west of Patteriol (3056 m), a rock glacier developed inside the Egesen I moraines. In Vergröß cirque, a large rock glacier was stopped by the Egesen I terminal moraine, which is about 20 m high (Fig. 4).

DISCUSSION AND CONCLUSIONS

As observed in the Alps generally, a three-phased Younger Dryas glaciation can be postulated in the Ferwall group. The prominent lateral and terminal moraines mentioned above are relicts of the Egesen sequence. The relative position, the morphological appearance and the distinct ELA depressions allow a clear separation of the moraine complexes and a correlation

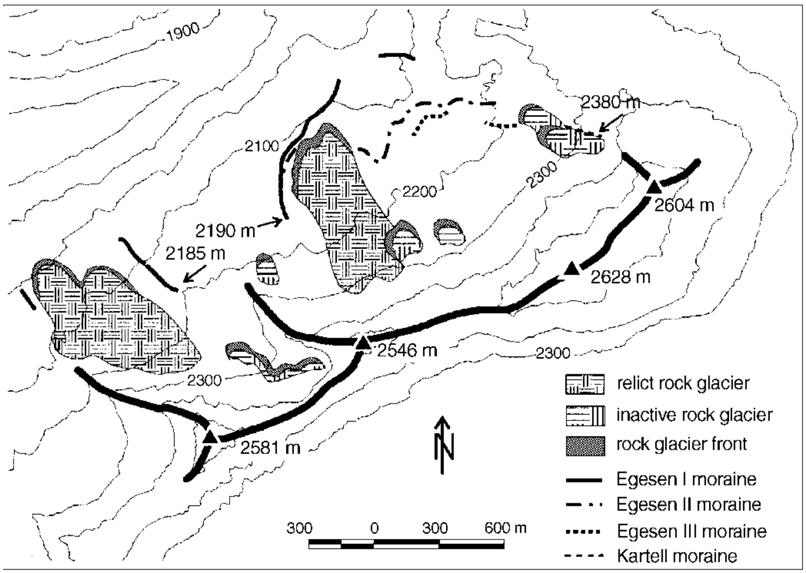

Fig. 3. Late-glacial moraines and rock glaciers in the Kli Mardusa cirque, western Ferwall group.

with the Egesen I, Egesen II and Egesen III substages, as shown in Table 1. The fourth prominent moraine complex outside the Holocene glacier maximum (LIA, 1850) is probably part of the early Preboreal. The corresponding ELAs of the Egesen sequence leads to an extensive Egesen I advance, leaving only a very limited area for rock-glacier formation. Indeed, no rock glaciers corresponding to Egesen I can be mapped in the study area. In contrast, the smaller accumulation areas of glaciers during and after the Egesen II advance allowed the extensive formation of rock glaciers (Fig. 5).

The length of the rock glaciers is 0.8–1.2 km. With an expected creep velocity 0.5–1 m a^{-1}, the development of the rock glaciers requires a period of roughly 1000 years. Thus, the rock-glacier formation began after or during the Egesen II (middle–late Younger Dryas) retreat and became inactive at the Pleistocene–Holocene transition or in the early Preboreal.

Precipitation during the early Younger Dryas seems to have been more or less the same as today in the more mari-

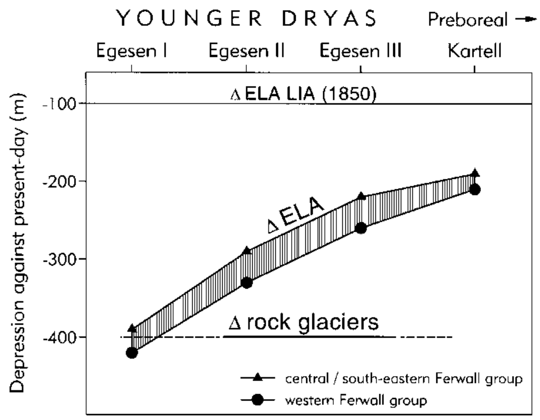

Fig. 5. Depression of the ELA and rock glaciers against "present-day" (Austrian Glacier Inventory, 1969) values in the Ferwall group during the Younger Dryas–early Preboreal. The LIA ELA was 100 m lower than "today".

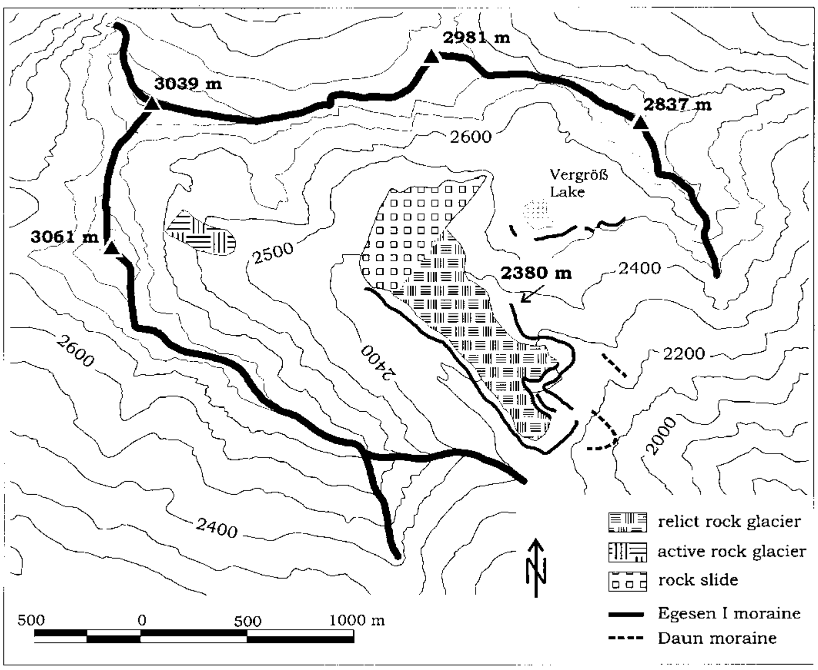

Fig. 4. Late-glacial moraines and rock glaciers in the Vergröß cirque, southeastern Ferwall group.

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time areas of the Alps (Kerschner, 1985). ELA depressions in the order of 300 m are typical (Kerschner, 1981, 1985). Because these are in the order of 290–320 m for the Egesen I moraines in the cirques investigated, we may conclude that precipitation was quite similar to present-day values in the western and southeastern parts of the Ferwall group during the early Younger Dryas. During the later phases of the Younger Dryas, precipitation in the central Alps seems to have been reduced by at least 30–40%, whereas summer temperatures remained more or less at the same level as during the early Younger Dryas (Kerschner, 1981, 1985). This should also apply to the study area.

The zone of rock-glacier development in the Ferwall group was lowered by 400 m during the later phases of the Younger Dryas. This amount is in good agreement with figures given by Lieb (1996), which are based on a much larger sample from the eastern Alps. The difference in the lower boundary between relict and active rock glaciers shows an increase in mean annual air temperature of about 3°C from the late Younger Dryas to the present. This is slightly less than suggested by Kerschner (1978a) and much less than in northwestern Europe (Isarin, 1997 and references therein; Renssen, 1997). As the late Younger Dryas ELA depressions were much smaller than the lowering of the rock glaciers, we may conclude that the later part of the Younger Dryas was comparatively cold and dry in that part of the Alps.

In conclusion, it seems likely that the early phase of the Younger Dryas was wetter than the later Younger Dryas. The short time available for glacier growth during the Egesen I substage demands high accumulation rates. The less-extensive Egesen II and Egesen III glaciers, together with a phase of distinct rock-glacier formation, leads to the inference that the later phases of the Younger Dryas were dry and cold. Therefore, as a scenario, the climate during the Younger Dryas in the western part of the eastern Alps changed from more "maritime" conditions to drier and perhaps only slightly warmer conditions.

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REFERENCES

Barsch, D. 1996. *Rockglaciers: indicators for the present and former geoecology in high mountain environments.* Berlin, etc., Springer-Verlag. (Springer Series in Physical Environment 16.)

Bobek, H. 1933. Die Deutung der Schottervorkommen im Ferwall- und Schönferwalltal. *Verh. Geol. Bundesanst.* (Wien), 1933, 51–59.

Bortenschlager, S. 1984. Beiträge zur Vegetationsgeschichte Tirols I. Inneres Ötztal und unteres Inntal. *Berichte des Naturwissenschaftlich-Medizinischen Vereins in Innsbruck* 71, 19–56.

Dahl, S.O. and A. Nesje. 1996. A new approach to calculating Holocene winter precipitation by combining glacier equilibrium-line altitudes and pine-tree limits: a case study from Hardangerjökulen, central southern Norway. *Holocene*, **6**(4), 381–398.

Fliri, F. 1975. *Das Klima der Alpen im Raume von Tirol. Vol. 1.* Innsbruck–München, Universitätsverlag Wagner. (Monographien zur Landeskunde Tirols.)

Fraedrich, R. 1979. Spät- und postglaziale Gletscherschwankungen in der Ferwallgruppe (Tirol/Vorarlberg). *Düsseldorfer Geographische Schriften* 12.

Furrer, G., C. Burga, M. Gamper, H. Holzhauser and M. Maisch. 1987. Zur Gletscher-, Vegetations- und Klimageschichte der Schweiz seit der Späteiszeit. *Geogr. Helv.*, **42**(2), 61–91.

Gross, G. 1983. Die Schneegrenze und die Altschneelinie in den österreichischen Alpen. *Innsbrucker Geographische Studien* 8, 59–83.

Gross, G., H. Kerschner and G. Patzelt. 1977. Methodische Untersuchungen über die Schneegrenze in alpinen Gletschergebieten. *Z. Gletscherkd. Glazialgeol.*, **12**(2), 1976, 223–251.

Haeberli, W. 1985. Creep of mountain permafrost: internal structure and flow of Alpine rock glaciers. *Eidg. Tech. Hochschule, Zürich. Versuchsanst. Wasserbau, Hydrol. Glaziol. Mitt.* 77.

Heuberger, H. 1966. Gletschergeschichtliche Untersuchungen in den Zentralalpen zwischen Sellrain- und Ötztal. *Wiss. Alpenvereinsh.* 20.

Hirtlreiter, G. 1992. Spät- und postglaziale Gletscherschwankungen im Wettersteingebirge und seiner Umgebung. (Ph.D. thesis, Universität München.)

Holzhauser, H.P. 1984. *Zur Geschichte der Aletschgletscher und des Fieschergletschers.* Zürich, Universität Zürich. Geographisches Institut. (Physische Geogr. 13.)

Isarin, R. 1997. *The climate in north-western Europe during the Younger Dryas. A comparison of multi-proxy climate reconstructions with simulation experiments.* Utrecht, Elinkwijk (Proefschrift Amsterdam, VU).

Ivy-Ochs, S., Ch. Schlüchter, P. Kubik and J. Beer. 1995. Das Alter der Egesenmoräne am Julierpass. Oberflächenalterbestimmungen in Graubünden (Schweiz) mit den kosmogenen Radionukliden ^{10}Be und ^{26}Al. *Geowissenschaften*, **13**(8–9), 313–315.

Ivy-Ochs, S., Ch. Schlüchter, P.W. Kubik, H.-A. Synal, J. Beer and H. Kerschner. 1996. The exposure age of an Egesen moraine at Julier Pass, Switzerland, measured with the cosmogenic radionuclides ^{10}Be, ^{26}Al and ^{36}Cl. *Eclogae Geol. Helv.*, **89**(3), 1049–1063.

Kerschner, H. 1978a. Paleoclimatic inferences from Late Würm rock glaciers, eastern central Alps, western Tyrol, Austria. *Arct. Alp. Res.*, **10**(3), 635–644.

Kerschner, H. 1978b. Untersuchungen zum Daun- und Egesenstadium in Nordtirol und Graubünden (methodische Überlegungen). *Geogr. Jahresber. Österr.*, **36**, 1975–1976, 26–49.

Kerschner, H. 1981. Outlines of the climate during the Egesen Advance (Younger Dryas, 11 000–10 000 BP) in the central Alps of the western Tyrol, Austria. *Z. Gletscherkd. Glazialgeol.*, **16**(2), 1980, 229–240.

Kerschner, H. 1985. Quantitative palaeoclimatic inferences from Late Glacial snowline, timberline and rock glacier data, Tyrolean Alps, Austria. *Z. Gletscherkd. Glazialgeol.*, **21**, 363–369.

Lieb, G. 1996. Permafrost und Blockgletscher in den östlichen österreichischen Alpen. *In* Lieb, G.K., *ed. Beiträge zur Permafrostforschung in Österreich.* Graz, Karl-Franzens Universität. Institut für Geographie, 9–124. (Arbeiten 33.)

Maisch, M. 1981. *Glazialmorphologische und gletschergeschichtliche Untersuchungen im Gebiet zwischen Landwasser- und Albulatal (Kt. Graubünden. Schweiz).* Zürich, Universität Zürich. Geographisches Institut. (Physische Geographie 3.)

Maisch, M. 1982. Zur Gletscher- und Klimageschichte des alpinen Spätglazials. *Geogr. Helv.*, **37**(2), 93–104.

Maisch, M. 1992. *Die Gletscher Graubündens: Rekonstruktionen und Auswertung der Gletscher und deren Veränderungen seit dem Hochstand von 1850 in Gebiet der östlichen Schweizer Alpen (Bündnerland und angrenzende Regionen).* Zürich, Universität Zürich. Geographisches Institut.

Mayr, F. and H. Heuberger. 1968. Type areas of Lateglacial and Postglacial deposits in Tyrol, Eastern Alps. *In* Richmond, G. M., *ed. Glaciations of the Alps.* Boulder, CO, University of Colorado. INQUA International Congress, 143–165. (Series in Earth Sciences 7.)

Müller, H.-N., H. Kerschner and M. Küttel. 1981. Gletscher- und vegetationsgeschichtliche Untersuchungen im Val de Nendaz (Wallis) — ein Beitrag zur alpinen Spätglazialchronologie. *Z. Gletscherkd. Glazialgeol.*, **16**(1), 1980, 61–84.

Nesje, A. and S. O. Dahl. 1993. Late Glacial and Holocene glacier fluctuations and climate variations in western Norway: a review. *Quat. Sci. Rev.*, **12**(2), 255–261.

Patzelt, G. 1972. Die spätglazialen Studien und postglazialen Schwankungen von Ostalpengletschern. *Ber. Dtsch. Bot. Ges.* 85, 47–57.

Patzelt, G. 1995. 5th day: August 15; Stops 14–18. 12. Alpine traverse, Max Maisch. *In* Schirmer, W., *ed. Quaternary field trips in central Europe. Vol. 2.* München, Pfeil, 672–675.

Patzelt, G. and S. Bortenschlager. 1973. Die postglazialen Gletscher- und Klimaschwankungen in der Venedigergruppe (Hohe Tauern, Ostalpen). *Z. Geomorphol.*, Supplementband 16, 25–72.

Renssen, H. 1997. *The climate during the Younger Dryas stadial.* Utrecht, KNAG. (Nederlandse Geografische Studies 217.)

Sailer, R., H. Kerschner and A. Heller. In press. Three dimensional reconstruction of Younger Dryas glaciers. *Glacial Geol. Geomorphol.*

Senarclens-Grancy, W. von. 1956. Zum Spätglazial der mittleren Ferwall-Gruppe. *Carinthia II. Mitteilungen der Naturwissenschaftlichen Vereins für Kärnten*, **20**, 149–157.

Suter, J. 1981. *Gletschergeschichte des Oberengadins: Untersuchungen von Gletscherschwankungen in der Err–Julier-Gruppe.* Zürich, Universität Zürich. Geographisches Institut. (Physische Geographie 2.)