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Geological Processes during the Quaternary

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Abstract

A short comprehensive overview of the geological development of the Eastern Alps and their foreland during the Quaternary is given. From the onset of rhythmic loess accumulation at the turn from the Gauss to the Matuyama chrons these climatic conditions continue into the lower part of the Quaternary. A frequent change of humid-warm and dry-cool climate with loess and occasional gravel accumulation can be reconstructed until the end of the Matuyama chron.

Up to now, remnants of four glaciations (Günz, Mindel, Riß, Würm) within the Eastern Alps and their foreland have been known long since. More recently, evidence for a cold period between the older two was found. The four glaciations show a complete succession of terminal moraines with terraces connected to them, as a result of a major cooling and buildup of piedmont glaciers in the foreland. These are positioned in the Brunhes chron according to paleomagnetic studies. Recent detailed investigations of benthic $\delta^{18}O$ values yielded also 4 major glaciations during this 800 ka period with a very good time control. They occurred during the Isotope stages 16, 12, 6, and 2. Because of the positioning in stages 2 and 6 due to radiometric time control on the two younger ones (Würm, Riß), a position of Mindel and Günz in the stages 12 and 16, respectively, is very likely. This is also supported by the great time interval reported by the $\delta^{18}O$ record between Riß and Mindel, known as "Großes Interglazial" since the establishment of the system of the four glaciations.

The last interglacial-glacial cycle can easily be reconstructed climatologically and by sediment development. Thus, a model for climatically induced sedimentation in the longitudinal valleys as well as the mechanism for ice distribution there has evolved, explaining some individual development within the Eastern Alps. This cycle may serve as a model for the older ones, which had very similar climatic successions, in order to understand the type of some of their deposits.

A short explanation of the tectonic activity within the Eastern Alps and their surroundings, and the influence on Quaternary sediments is given.

In the recent past, overdeepened valleys became increasingly important to drinking water supply, as did landslides and slope instabilities to infrastructure needs. New data are briefly discussed.

The Course of the Quaternary

Around the boundary Neogene/Quaternary (AGUIRRE and PASINI, 1985), which is established at about 1.8 Ma BP (Fig.1), we have only little information on geological activities. At that time the drainage pattern of the Eastern Alps was developed to its present stage. Apparently after a longer time of forming red clay, loess accumulation had started at the beginning of the Upper Pliocene (FRANK et al., 1997) at the turn of the Gauss and Matuyama chrons, 2.6 Ma ago. This sedimentation obviously occurred in a similar climatic succession as in China where, loess accumulation, also above thick deposits of red clay as on the Loess Plateau, started at this time (DING et al., 1997). According to paleontological investigations (FRANK et al., 1997), this time span at the turn of Neogene to Quaternary was a moderate-warm humid climate with cool, dry periods. All facts indicate a frequently repeated change of climate, but without any reference to glacial events. Within the Eastern Alps no remnants of this early phase of the Quaternary are found, due to the high relief energy and the glaciations later on.

Therefore, sediments, mostly loess, of this phase are preserved only in the foreland along the Danube and its tributaries. In the western part, gravel relics high above the recent rivers indicate periodic gravel accumulation interrupting the slow lowering of the drainage system (Fig. 1). This accumulation of the rivers may be interpreted as climatically induced periods under braided conditions, accompanying the loess accumulation.

The loess profiles in the eastern part of the foreland show a constant change of climatic conditions before and after the Neogene/Quaternary boundary. Only during the beginning of the Quaternary is it possible that an enhancement of the climatic changes might have occurred (FINK and KUKLA, 1977), which is documented in the loess sequence at the shooting range of Krems (FINK et al., 1976).

Due to paleomagnetism, development of paleosoils and gastropods, this sequence reveals a repeated change of dry-cold (*Pupilla* fauna), warm-dry (*Striata* fauna) and warm-humid interglacial (*Chilostoma* fauna) conditions from the beginning of the Quaternary (FRANK and VAN HUSEN, 1995; FINK et al., 1976). This was interpreted as 17 interglacials after the Olduvai chron and may find equivalents in one or the other Oxygen isotope stages younger than stage 63. Beside the loess deposited under dry-cold conditions, no

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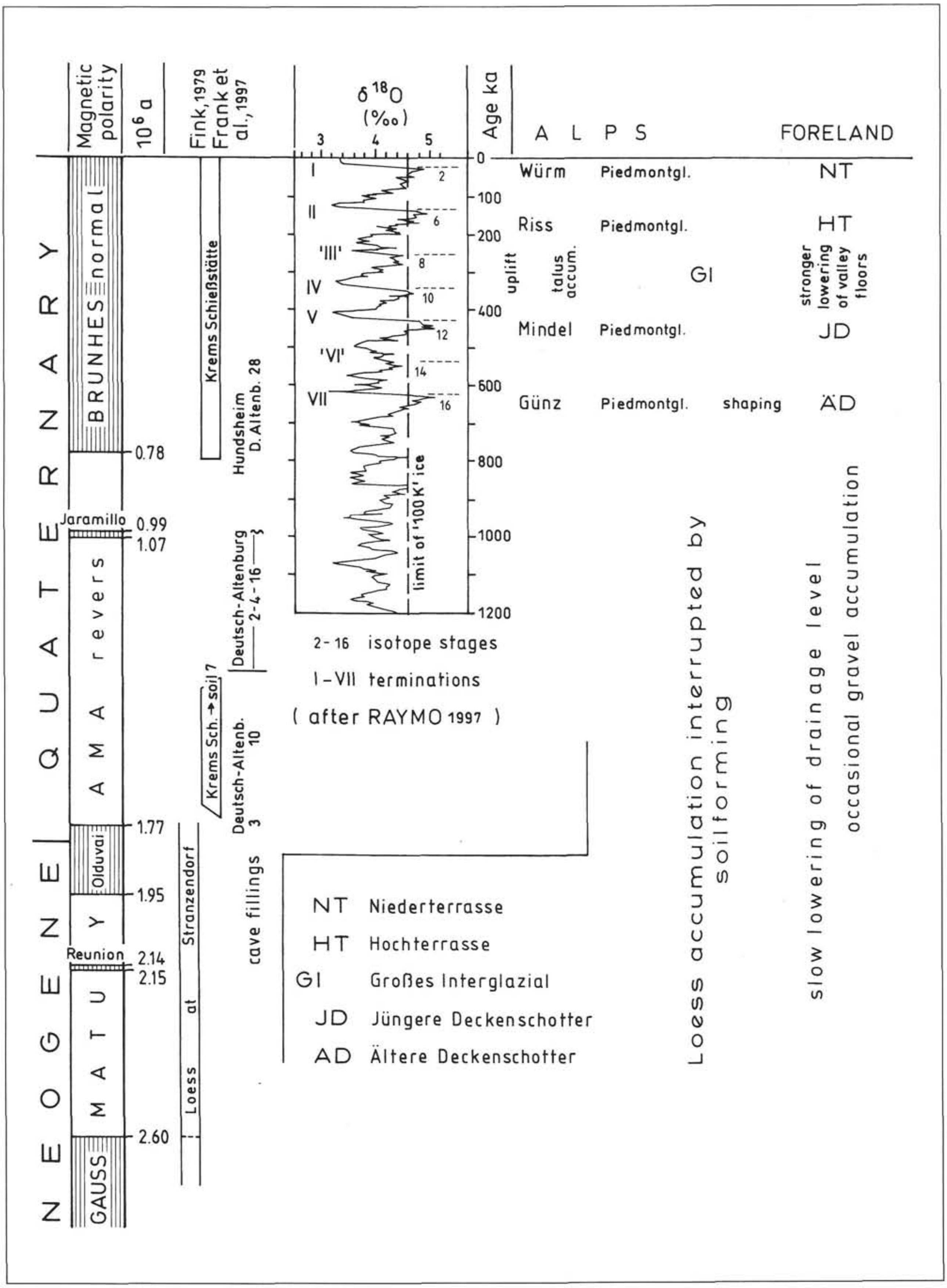


Fig. 1
Temporal position of geological activities in Austria during the Quaternary in comparison to the paleomagnetic and $\delta^{18}O$ timescale.

evidence was found for a climatic decay strong enough to generate glaciation.

The four Glaciations

Following younger interpretations of the Oxygen isotope record at about 0.9 Ma, isotope stage 24 represents a clear transition to a different regime characterized by more extreme glaciations than in the previous period (SHACKLETON, 1995). This may explain why within the Eastern Alps and their foreland in Austria no glacial deposits older than the Günz glaciation sensu PENCK and BRÜCKNER, 1909, were found.

Terminal moraines of this glaciation are connected at the Salzach, Traun and Krems rivers to terrace bodies (WEINBERGER, 1955; KOHL, 1974). These "Ältere Deckenschotter" sensu PENCK and BRÜCKNER, 1909, are part of a widespread gravel cover, between the rivers Traun and Enns, which in terms of gravel composition and age is a genetically polymict body (VAN HUSEN, 1980, 1981). It probably was formed over a longer time span of some cool periods by accumulation, reworking and lateral erosion by the rivers, incorporating older deposits apparently forming one terrace.

After this oldest recognizable glaciation in the foreland east of the Salzach river (Figs. 2 and 3), remnants of three glaciations can easily be ascertained (WEINBERGER, 1955; DEL NEGRO, 1969; KOHL, 1976; VAN HUSEN, 1977, 1996; SPERL, 1984). The knowledge with regard to extent, development by tills, terminal moraines, glaciofluvial sediments and weathering is good enough to reconstruct the ice streams and tongues of the piedmont glaciers and their temporal relation (PENCK and BRÜCKNER, 1909; SPERL, 1984).

Due to a former paleomagnetic investigation on tills the temporal position of these glaciations and their connected outwash terraces – well known as Günz/Ältere Deckenschotter, Mindel/Jüngere Deckenschotter, Riß/Hochterrasse, and Würm/Niederterrasse depicted in Fig. 1. (PENCK and BRÜCKNER, 1909) – fits into the Brunhes chron (FINK, 1979).

Detailed analysis of character and strength of Oxygen isotope stages suggest that during the Brunhes chron four major glaciations occurred on the Northern hemisphere (SHACKLETON, 1987; RAYMO, 1997). They are positioned at the Oxygen isotope stages 2, 6, 12 and 16 (RAYMO, 1997). According to radiometric dating, geological position and relation, as well as weathering the two younger glaciations are determined at Oxygen stages 2 and 6.

Due to much more developed weathering, cementation and solifluidal shaping on top of all the Mindel deposits compared to those of Riß, a longer time span has to have separated these glaciations, as was first postulated as "Großes Interglazial" by PENCK and BRÜCKNER, 1909. Thus, the position into stage 12 seems to be very likely. Therefore, the position of Günz at stage 16 can be derived from this (Fig. 1).

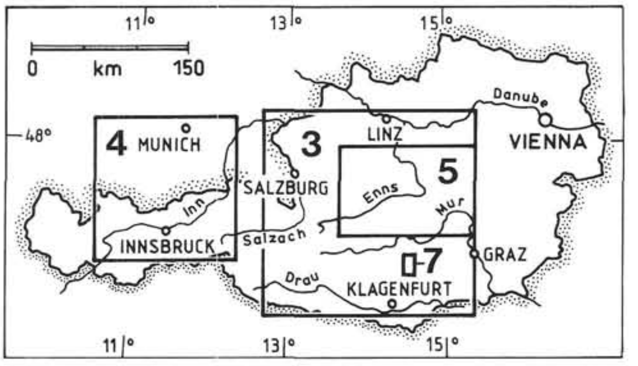


Fig. 2
The main drainage system of Austria. The Danube as the receiving water course and the longitudinal valleys. Squares mark figures 3, 4, 5, and 7.

Remnants of a cold period leading to gravel deposition in the foreland were found more recently (KOHL, 1976), fitting between depositions of Günz and Mindel. Therefore this accumulations probably occurred during isotope stage 14.

Tectonic Activity

The lowering of the drainage system around the Alps down to the level of the "Ältere Deckenschotter" and further on seems to be a process with similar erosion rates as those along the Danube and her tributaries in time and amount (GRAUL, 1937; FISCHER, 1977; FUCHS, 1972). This

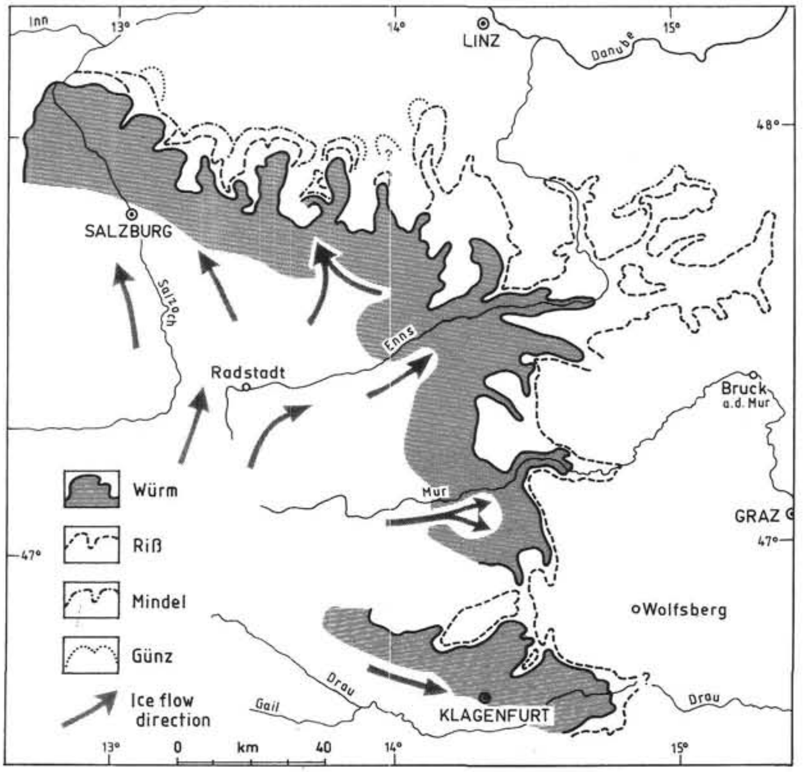


Fig. 3
The extent of the glaciers of the 4 glaciations known in Austria. Explained are only glaciers of the main valleys. Ice flow direction is rather the same during all the glaciations.

indicates no differential uplifting or other tectonic activity like faulting within the northern foreland of the Alps. A time control of these remnants of terrace systems older than the "Ältere Deckenschotter" is yet still impossible. Slight differences in the elevation of the base of the gravel bodies may rather be due to different ages of the gravel accumulation.

According to the loess sequence near Krems (FINK et al., 1976), the amount of erosion along the Danube and her tributaries was about 50 m during the Quaternary period (Fig. 1). This supposedly undisturbed development along the northern edge of the Alps ends with the entry of the Danube into the Vienna Basin. Clear evidence of tectonic activity until the Holocene is recognizable here (PLACHY, 1981). The terraces of the last two glaciations (Hochterrasse, Niederterrasse, as well as Holocene deposits), show clear evidence of the tectonic displacement there.

Thus, along major faults of the basin (KRÖLL et al., 1993) parts of the "Hochterrasse" are displaced about 10 m. Local depressions 40-60 m deep within the pre-Quaternary rocks are filled with older Quaternary gravel, beneath gravel bodies of the youngest Quaternary deposits in average 10-15 m thick. This evidence of slow tectonic activity during the youngest period of the Quaternary is in good accordance with a measurement of up to 2 mm/a of subsidence in the Vienna basin (BUNDESAMT FÜR EICH- UND VERMESSUNGSWESEN, 1991), and is the result of the ongoing activities around the formation of the present Vienna basin.

Traces of recent tectonic activities in Quaternary sediments around and within the Eastern Alps, as to be expected from Miocene and Pliocene development (e.g. PERESSON and DECKER, 1996), have not been proved yet. On the one hand, the tectonic activity may have slowed down, on the other hand the piedmont glaciers of Riß and Würm have obscured some evidence of movement of the Alpine nappes (Northern Calcareous Alps and Rhenodanubian Flysch) towards the foreland (Molasse).

Only along the valley lines of Enns and Steyr and their tributaries stretch outwash terraces of the three youngest glaciations from the Alpine area into the foreland; all glaciers had ended within the Alps. The terrace bodies of "Hochterrasse" and "Niederterrasse" are more or less continuously preserved along both rivers, showing an unbroken gradient. So the surface of the terraces, as well as their base built by pre-Quaternary rocks show a continuous profile without any remarkable stepping. This indicates an undisturbed position of the northern part of the Eastern Alps against the foreland.

In contrast to this, the base of the "Jüngere Deckenschotter" (in the foreland ca. 60 m above that of "Hoch-/Niederterrasse") shows a discontinuity of about 20 m on the north rim of the Alps in terms of a higher position within it (VAN HUSEN, 1971, 1981). The base is covered all over by the same gravel with an equally developed weathering indicating the same age. This old valley floor continues through the Northern Calcareous Alps, also with some remnants south of them in the central crystalline parts of the Alps. All the way it shows a higher gradient than the younger one and ends up at about 150 m above this (VAN HUSEN, 1968). Beside the cover with weathered gravel only glacial and glacigenic sediments from the last two glaciations were found below this old valley bottom (SPAUN, 1964) indicating the same age as the "Jüngere Deckenschotter".

This steeper gradient is probably the result of a stronger uplift of the Alps during the time span between Oxygen isotope stages 12 and 6 which is also supported by the longer duration (Fig. 1). In addition to compression this may have caused a further jerky movement of the Alpine nappes toward the foreland (VAN HUSEN, 1971, 1981).

Another indication of higher tectonic activity during the period between Mindel and Riß may be the wide-spread breccia, especially along the southern edge of the Northern Calcareous Alps. These thick packs of debris – in comparison with the Höttinger Breccie close to Innsbruck – are believed to be from this time (KLEBELSBERG, 1935; AMPFERER, 1935). They may have been caused by a specific geological situation: a ductile incompetent base (e.g. Werfen Schists) of the slopes, overlain by brittle competent rocks (limestone, dolostone), are responsible on the one hand for landslides (POISEL and EPPENSTEINER, 1988, 1989), on the other hand for a strong production of debris. This production may have been dramatically enhanced by oversteepening of the stronger uplift.

Development of Glaciers

During all glaciations the given drainage system was filled with dendritic glaciers. The filling of the longitudinal valleys (e.g. Inn, Salzach, Enns, Mur, Drau) occurred only under special circumstances (Fig. 2). Due to the relation of the longitudinal valleys to their tributaries and topography around them, these may on the one hand explain outstanding differences in glacier extent according to the catchment area. On the other hand they my clarify the reason for the rapid acceleration of ice build up during the final phase of glaciation. Two examples may explain this glacier behavior.

Inn Valley

The Inn valley is the most extended drainage system in the Eastern Alps. The source area is located south of the valley and in the Engadin, with only few exceptions in crystalline rocks. North of the Inn valley, the Northern Calcareous Alps do not have any major comparable tributary valley to the Inn, which, east of Landeck, follows the border between these two tectonic units (see Fig. 4).

The valleys within the Northern Calcareous Alps are oriented to the north (Fig. 4), forming the heads of the rivers Isar and Loisach, and other small rivers. The Inn valley is separated from them by mountain chains rising up to 2,500 m or more. Three gaps in the mountain chain are the Fernpass, Seefeld and Achensee, which are watersheds 400-600 m above the Inn Valley. During the glaciations, these valleys were filled with ice, as shown in Fig. 4.

Following the pattern of the ice streams, the boulder composition of the till might show the petrographic composition of the valley head. In the basal tills of the Inn valley crystalline components are dominant; only on the northern slope is there a considerable content of limestone boulders consistent with the local bedrock.

Up to 35% crystalline boulders (Fig. 4) can be recognized in the glacial and glacigenic material of the Isar and Loisach glaciers of the last glaciation. Investigations on these materials, carried out by DREESBACH (1983), showed a differing amount of these boulders, depending on the genesis of the material. Most of the crystalline material was fresh and unweathered save for a smalll amount of multiple reworking and enrichment in the youngest glacial and glacigenic materials. Such a large amount of unweathered crystalline rocks has to be attributed to extensive ice transport from the Inn valley to the Isar and Loisach systems across the Fernpass and the Seefeld area (PENCK and BRÜCKNER, 1909).

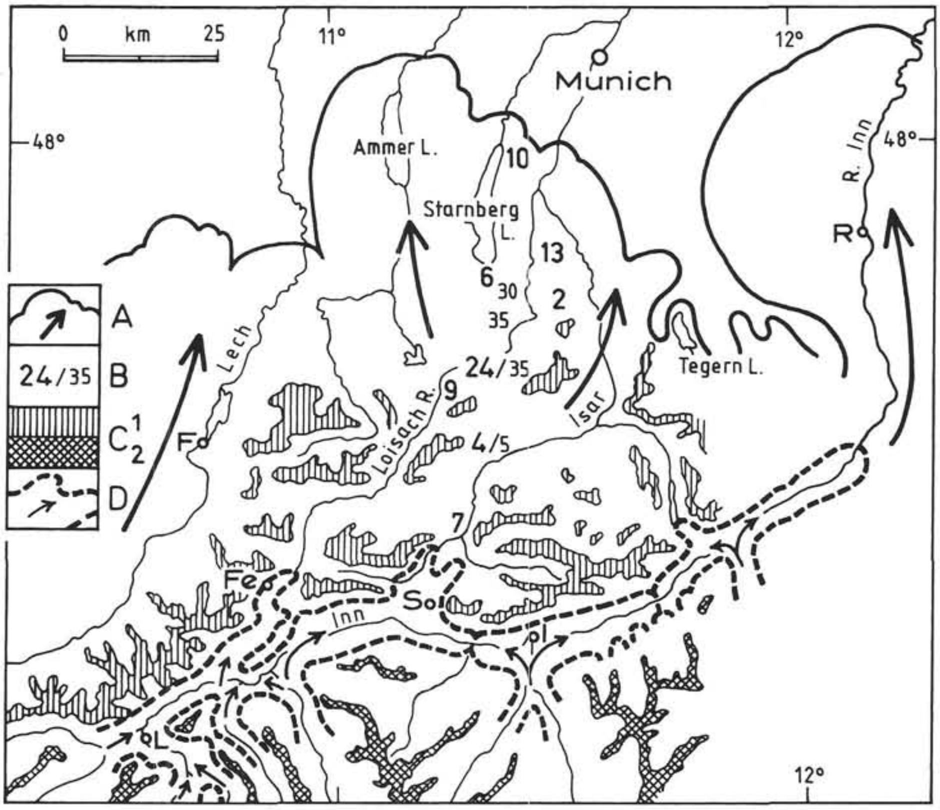


Fig. 4
Ice streams of the Inn, Lech, Isar and Loisach valleys. A: Glacier extent during the Würm Isotope stage 2. B: Percentage of crystalline boulders. Larger numbers in basal till. C: Nunataks formed of sedimentary rocks (C1) and crystalline rocks (C2). D: Probable ice extent in the Inn valley around the beginning of the final ice buildup during Oxygen Isotope stage 2. F: Füssen, Fe: Fernpass, I: Innsbruck, L: Landeck, R: Rosenheim, S: Seefeld.

During the main event of glaciation, the amount of crystalline boulders could be attributed to the gradient, because the ice filling the Inn valley was much stronger than that in the valleys to the north; its surface also reached a much higher elevation. The extraordinarily high content of crystalline boulders in the sediments in the advance phase of the ice streams argues for a stronger and much quicker ice accumulation in the Inn valley between Landeck and Innsbruck than in valleys of the Northern Calcareous Alps. Only in this way is it possible to imagine that the ice overflow from the Inn valley would be strong enough during the early phase of ice buildup to compete with the local glaciers and to affect the composition of the advance materials, in addition to enrichment by river transport.

Such an early overflow of a huge body of ice may be due to the internal ice flow within the Inn valley system. The large tributaries in the south with their extended alimentation areas at high altitudes bore huge glaciers during the final approach of the last glaciation, gradually filling up the whole Inn valley. Hence, five glaciers finally grew together around Landeck. At the same time, the ice flowing out of the Sill and Ziller valleys reached the main valley, and thus the glaciers may have blocked each other creating a conspicuous rise in the ice surface. Therefore, passing the two watersheds the ice of the Inn valley system reached the drainage systems of the Isar and Loisach (with smaller alimentation areas at lower altitudes) early enough before these valleys were filled with ice strong enough to hinder this influence.

On the other hand, blocking each other also created an ice table within the whole Inn valley at a high elevation and therefore a quick expansion of the alimentation area, and the ultimately rapid ice buildup. In this way, ice accumulated in the whole Inn valley, and the high gradient to the north persisted throughout the entire glaciation.

The volume of ice discharge over the three watersheds (crystalline material included) can be judged by the extent of the piedmont glaciers of Isar and Loisach compared with their neighbors, which are fed only by their own source areas within the Northern Calcareous Alps (Fig. 4).

Enns Valley

The Enns valley (Fig. 2) was filled with a glacier connected with the Salzach glacier in the west and the Traun glacier in the north (Fig. 5). The valley again follows the border of the crystalline zone in the south and the Northern Calcareos Alps in the north. The topography in this area is slightly different from that of the Inn valley. In the western part, the tributaries from the south have their heads in extensive areas at a higher elevation. In this part too, the Northern Calcareous Alps constitute a wall with a drainage direction mainly towards the north. Farther east, the elevation of the crystalline zone decreases over a short distance, and the topography of the Northern Calcareous Alps changes from continuous chains and plateaus to more isolated mountains in much lower surroundings.

Würm: During the last glaciation, the Enns valley was filled with a glacier extending down to the area of more isolated high mountains with local glaciers (Fig. 5). Both the local glaciers and valley glacier were in contact, but had little influence on one another in the ice discharge. To the south, the valley glacier filled the non-glaciated valley around Trieben with a 20 km long tongue. To the north, ice discharge crossed the Pyhrn Pass to the drainage system of the Steyr

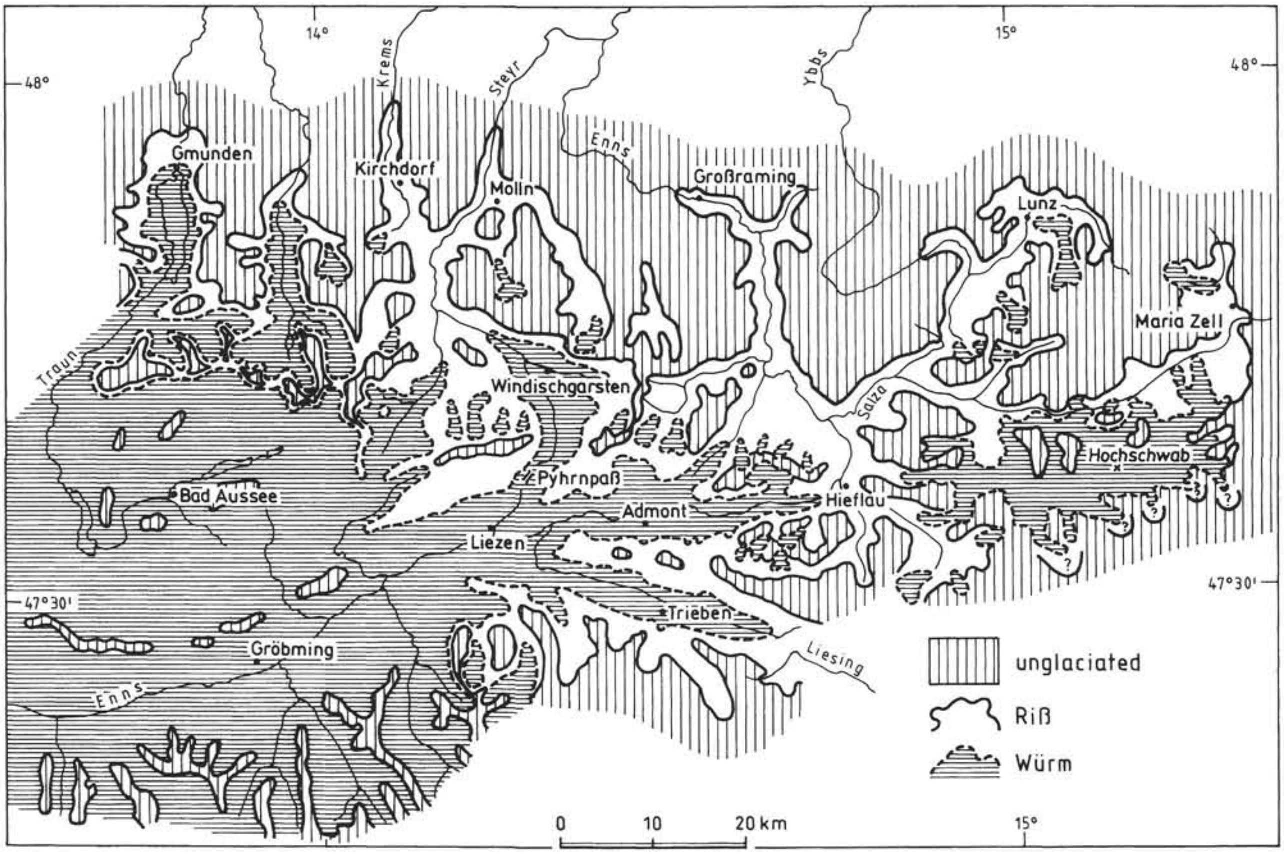


Fig. 5
Glacier extent during the Würm (Isotope stage 2) and Riss (Isotope stage 6) In the Enns valley and around it at the rivers Steyr and Ybbs.

river and filled the small basin of Windischgarsten. The content of crystalline boulders in the tills is around 2-3% here.

This relationship among other valley glaciers and local glaciers was a stable one according to the elevation of the equilibrium line of the last glaciation (Würm).

Riss: During the penultimate glaciation (Riss), the equilibrium line of the glacier system was about 100 m lower than during Würm (PENCK and BRÜCKNER, 1909). This led to more extended piedmont glaciers on the northern rim of the Alps and longer valley glaciers within the mountain body. The difference in length was about 5-6 km (Fig. 3). The situation was very different in the Enns and Salza valleys and the Steyr-Krems drainage system (Fig. 5).

In the Enns valley, the end moraines at Grossraming (VAN HUSEN, 1999) show a glacier extent of around 40 km longer than during the Würm. The tills all over the valley and in the immediate vicinity north of Hieflau contain abundant crystalline boulders indicating that the Enns valley was filled with a much larger Enns glacier and not several larger local glaciers.

Tracing the crystalline boulders from the basins of Windischgarsten down the Steyr river and into the Krems valley reveals strong ice discharge and influence of the Enns glacier in this area. Crystalline boulders constitute up to 5% of tills and glacigenic deposits around Molln and also some of the material in the Krems valley. These materials, especially phyllites, which could not have been transported by water over longer distances, were transported by ice over the Pyhrn Pass to these drainage systems and distributed over greater distances, for example down to Windischgarsten, during the last glaciation. Differences in lengths of the valley glaciers and the much greater ice discharge from the Enns valley to the northern drainage system are due to the special topography.

During the last glacial event, the Enns valley glacier and the local glaciers in higher mountains in the east reached such an extent that they came into contact but did not affect one another. This was a stable situation consistent with the equilibrium line of the event.

In respect to the lower position of the equilibrium line during the Riss glaciation, both the local glaciers and the valley glacier grew. Thus, the local glaciers were powerful enough to block the valley glacier in the very narrow portion of the valley west of Hieflau. This impediment to ice flow caused a higher ice surface in the Enns valley west of Admont. This area, an ablation area during Würm, consequently became the accumulation area. This great addition to the accumulation area affected the extent of the glacier as explained above, together with the ice of the local glaciers.

In the same way, the glaciers on the north slope of Hochschwab built up (KOLMER, 1993; FRITSCH, 1993) filling the Salza valley up to an elevation so it became part of the accumulation area. As a result an extended ice stream was formed there; this may have occurred even more quickly through the additional cooling of the glaciated Enns valley (Fig. 5).

The same feedback occurred in the basin of Windischgarsten. The stronger overflow of the ice from the Enns valley in the south caused a greater glacier tongue to develop and to extend further and further into the basin. In the same way the larger local glaciers also caused the ice surface to rise. Thus, the whole basin became an accumulation area too. The extent of the accumulation area enabled the glacier to advance down the valley, over 30 km more than during Würm. It was even powerful enough to pass the watershed to the Krems river system (town of Kirchdorf on the Krems), generating a much greater ice stream in this valley, too (KOHL, 1976).

Overdeepened Valleys

Since the beginning of research on ancient glaciers and their paleogeographic distribution overdeepened tongue basins have been known (Fig. 6). They are probably formed predominantly in the ablation area, due to higher ice velocity, increasing the debris load at the base and running water under hydrostatic pressure at the base (VAN HUSEN, 1979). They were formed during all of the glaciations because the tongue areas were developed more or less in the same position (cf. Fig. 3). Investigations mostly on groundwater resources in the longitudinal valleys continuously provide new data on the shape and depth of these basins. These investigations, carried out mostly by geophysical methods along with drillings, also gave good evidence about the filling of the basins and the position of the underlying bedrock.

Thus, on the one hand in the tongue basins of the Salzach glacier the base was cored several times at between 160-340 m, on the other hand the base in the Gail and Drau valleys was determined at 200-240 m (KAHLER, 1958). These and many boreholes in other valleys not reaching the pre-Quaternary basement show that in this part of the Austrian Alps the overdeepening may be limited to about 400 m. A similar amount of this is also indicated by some lakes (e.g. Traunsee) with near to 200 m of depth and a thick sediment fill on the bottom. A depth of ca. 200 m was also determined in the Steyrtal with ice covers only during glaciations with the most extended glaciers (Fig. 6, M) (ENICHLMAIER, pers. comm.).

Higher amounts of overdeepening are reported more to the west: in the Inn valley east of Innsbruck for example the pre-Quaternary basement probably lies at ca. 180 mabove sea level, about 400 m below the valley bottom (ARIC and STEINHAUSER, 1977). Farther to the east, seismic investigation indicated that the bedrock lies at about 500 m below sea level (1000 m below the valley bottom). This was proved by a drill hole 900 m deep passing 900 m of loose gravel, silt and clay without reaching the bedrock (WEBER et al., 1990).

This amount of erosion and overdeepening may be due to the higher linear ice and melt-water discharge along the valleys with extensive catchment areas, and is in good accordance with the values of erosion of about 600-1000 m recently reported from the longitudinal valleys of Rhein and Rhone in Switzerland (PFIFFNER et al.,1997)

An astounding feature of a local overdeepening was recently revealed in the small basin of Bad Aussee. Below a thick sequence of till and gravel from the last glaciation (VAN HUSEN, 1977), drilling excavated 980 m of gravel, silt and sand without reaching the bedrock (pers. comm. M. MAYR, Salinen Austria GmbH). The formation of this more than 1000 m deep hole in a 6-7 km wide basin may be due to a former salt body, which can be expected due to the tectonic situation and salt-bearing clay (Haselgebirge) on the edge of the basin nearby (SCHÄFFER, 1982). Beside the usual dependence of the hydrodynamic situation at the base of the glacier, this example shows in addition a dependence on the local geological situation.

The filling of these overdeepened valleys depends strongly on the relation of main rivers to their tributaries in terms of water and debris discharge and the size of the basin. Large basins with a strong main river and small tributaries were often filled with a thick layer of fine-grained bottom set interfingering with coarse delta deposits (e.g. Salzachgletscher: BRANDECKER, 1974) with a clear hydrogeological situation. The strong input of coarse gravel and sand from big tributaries creates a more inhomogeneous filling of the valley, with shifting layers of gravel, sand and silt all over the area of the basin.

Mass Movements

In the Eastern Alps and their surroundings, landslides and slope failures are a common feature, due to rapid deglaciation, as well as to the consistent climatically induced fluvial erosion. They took place during and after terminations. Certainly, those after the last glaciation were the most frequent. Beside the long known spectacular landslides (ABELE, 1974), slow deformation of valley slopes are the most common features (first recognition by AMPFERER, 1940, 1941; STINY, 1941).

After World War II, the knowledge about this deformation rose parallel with the enhanced development of infrastructure (e.g. traffic lines, power plants) in the Alps. Thus, stability of slopes and the effect on the valley bottom was of increasing interest and became a goal of investigations. This attention led to a better knowledge of regional distribution and different mechanisms of mass movements (ZISCHINSKY, 1969; POISEL and EPPENSTEINER, 1988, 1989; POISEL, 1998).

The distribution of this kind of slow slope failure greatly depends on the appearance of more or less metamorphized schists in the central zone of the Eastern Alps and also on the glacier erosion, e.g. in tongue areas (Figs. 2 and 7). Due to the mechanical properties of the rocks, a layer of 100 to 200 m along the slope is moving downslope (e.g. REITNER et al., 1993). Both temporal and local velocities are an aperiodic in a range of mm to m/year, probably depending on precipitation and water content of the loosened material. In the majority of the slopes the movement started immediately after the ice retreat and is continuing up to now. Thus unweathered basal till was overridden by rock masses in some places (ZISCHINSKY, 1967; LAUFFER et al., 1971). Investigations on sediments of the valley floors point to a discontinued movement and blockage of the drainage in the valley bottom (POSCH, 1995; VAN HUSEN, 1979).

In the same way, large rockfalls, landslides and extended gliding masses were believed to have been released immediately or soon after deglaciation. Recent detailed investigations and radiocarbon dating revealed a very young age for huge landslide of hundreds of millions and billions of cubic

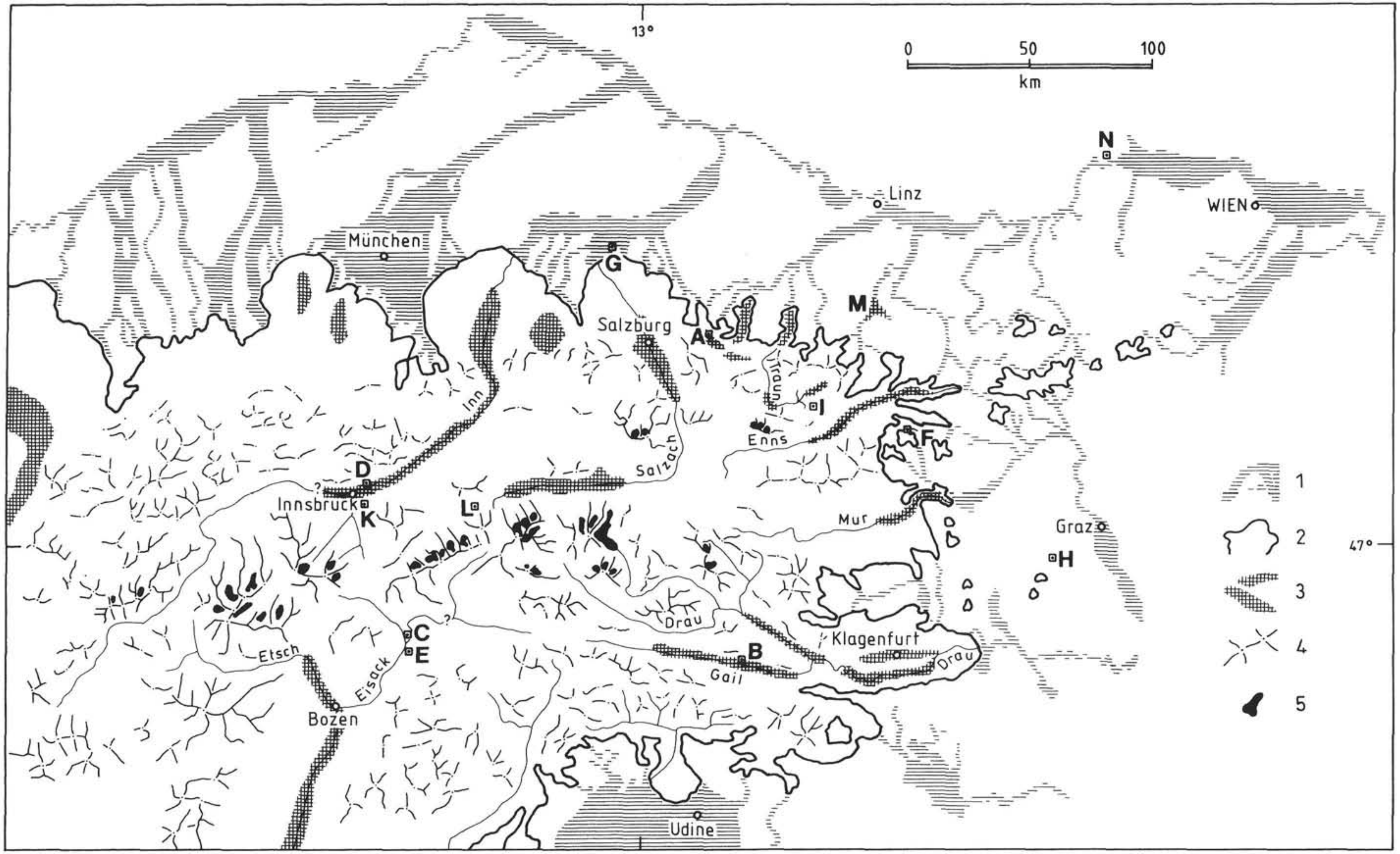


Fig. 6
Sketch map of the Eastern Alps during Würm (Isotope stage 2): 1: Terrace "Niederterrasse". 2: Maximum extent of glaciers. 3: Extended overdeepened parts of the valleys. 4: Nunataks. 5: Glacier extent of Holocene. Mentioned Localities: A: Mondsee; B: Nieselach; C: Schabs; D: Baumkirchen; E: Albeins; F: Hohentauern; G. Duttendorf; H: Neurath; I: Mitterndorf; K: Lans; L: Gerlos; M: overdeepened area at Molln.

meters in several places (e.g. Tschirgant ~2900, years BP; PATZELT, 1990; Wildalpen 5000 years BP, FRITSCH, 1993; Köfels ~9800 years BP; HEUBERGER, 1994; IVY-OCHS et al., 1998). These data are in accordance with others from Bavaria (JERZ, 1996) and Flims (VON POSCHINGER, 1997).

These results show that the instability of valley slopes caused by glacial erosion and oversteepening is not yet released. Depending on the geological situation, e.g. brittle, competent material over ductile, incompetent material (POISEL and EPPENSTEINER, 1988, 1989), or progressive failure caused by creep, as probably happened at Köfels, after a long period of preparation rock masses were ready to be triggered by some insignificant cause for a landslide.

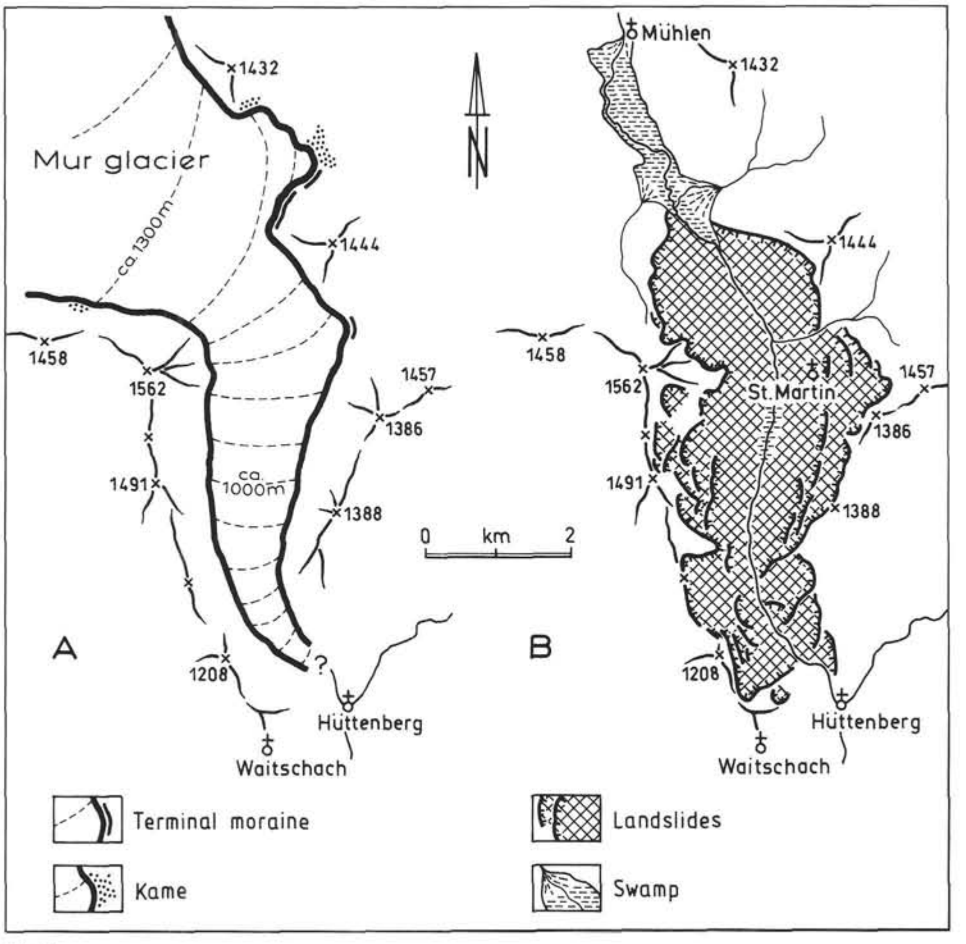


Fig. 7
Landslides as the result of strong erosion in a small tongue area of the Mur glacier. Swamps due to river blocking (POSCH, 1995). Position, see Fig. 2.

Last Interglacial – Glacial Cycle

According to $\delta^{18}O$ records all cycles within the Brunhes chron and extending into the Matuyama chron have a similar pattern. Especially the four major cycles before the terminations I, II, V and VII, following the great glaciation at the isotope stages 2, 6, 12 and 16 (RAYMO, 1997) showed – after a short warm period – a step by step cooling, with short phases of climatic amelioration down to the very short cold period of glaciations (Fig. 1).

The last cycle is easily reconizable and shows well known deposits. Therefore, it may serve as a model of other cycles in terms of climatically induced sedimentation and facies diversification in the Eastern Alps (VAN HUSEN, 1989).

Mondsee: At the northern edge of the Eastern Alps (Fig. 6, A), data gave good continuous evidence about the climatic development during termination II, the Eemian, and the first half of the Würm period (Fig. 8).

The fine-grained sediments north of the shores of the present lake Mondsee were first investigated by KLAUS (1987), and believed to be a complete sequence between the Riss and Würm glaciations. Recent investigations based on three long cores revealed a delta structure in an ancient lake with a water surface around 50 m above the recent one. Bottom set, fore set and thin top set beds of a classical Gilbert delta structure were covered by the till of the last glaciation (KRENMAYR, 1996).

The pollen content (DRESCHER-SCHNEIDER, 1996) documented the climatic development up to the beginning of the Middle Würm according to CHALINE and JERZ, 1984 (Fig. 8). At this time, about 50,000 years BP, the delta had prograded to a certain point and deposition stopped at this part of the lake.

Hence it follows, the Eemian was a warm period with temperatures averaging 2-3 °C above the current Holocene values. Valleys and foreland of the Alps were densely forested with well developed oak-mixed forest with a high content of *Abies* (fir). This phase ended with an abrupt climatic decay affecting the forest on the northern edge of the Alps and causing coarser sediments at the delta.

During the early phase of Würm, forests recovered two times, showing some elements of oak-mixed forest, with a cold stadial inbetween these periods, when the timberline was close to the water level of the lake. The cold period at the beginning of the middle part of Würm led to a timberline more or less at the level of the foreland, and was followed by a slightly warming trend, allowing a forest dominated by *Larix* (larch) and *Picea* (spruce) around the lake later. This result is in very good agreement with the profile of Samerberg, east of the Inn valley, obtained from similar sediments (GRÜGER, 1979), and the profile of Grande Pile (WOILLARD and MOOK, 1982) presented in Fig. 11.

Nieselach (Fig. 6 B) is another site with Eemian sediments (FRITZ, 1971). Above 10 m of stratified clay with sandy layers, unconformably a sequence of sandy gravel,

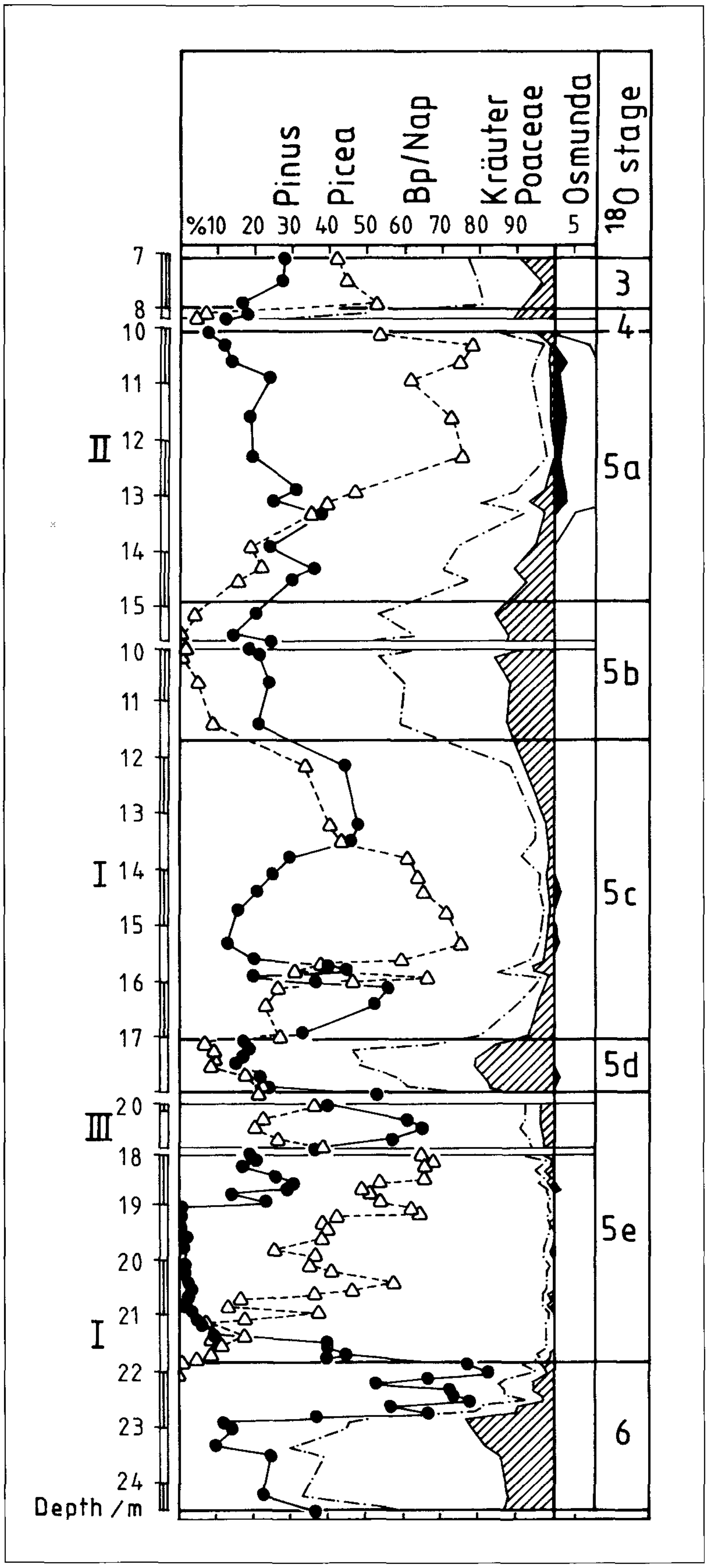


Fig. 8
Simplified pollen profile of Mondsee (A in Fig. 1) according to DRESCHER-SCHNEIDER, (1996).

sand and silt deposited by a meandering river, and clay and slate coal as fillings of former oxbows follow there. Due to the pollen content, herbaceous taxa, *Artemisia, Helianthemum,* few *Pinus* (pine) and a lack of aboreal pollen, the lowest part of the sequence seems to be a lake filling with a high sedimentation rate shortly after deglaciation. The coarser sequence with the clay and slate coal shows a very warm climate of interglacial values, with forests dominated by *Fagus* (beech), *Picea* (spruce), and *Abies* (fir), suggesting a deposition during the end of Oxygen Substage 5e (DRAXLER et al., 1996), also indicated by U/Th radiometric dating of 113,000 ± 9,000 years BP (UH 339-343) (VAN HUSEN, 1989). This would mean that at the end of the last interglacial the Gail valley bottom resembled its present appearance before cultivation and, during the whole Eemian the river level may have been at its current elevation.

At *Schabs* (Fig. 6 C), north of Brixen, between the rivers Eisack and Rienz, a thick sequence of gravel covered by till forms a terrace (CASTIGLIONI, 1964). At an elevation of 780-790 m, 160 m above the valley bottom, gravel with interbedded layers of stratified clay was exposed then. Pollen analysis of an unoxidised layers of this clay shows cold, dry climatic conditions, as indicated by assemblages dominated by herbs and *Pinus*. The very low pollen concentrations seem to be due to a high sedimentation rate rather than to sparse vegetation (FLIRI, 1973, 1978). *Juniperus* (juniper) wood from this stratum was dated (FLIRI, 1978) using ^{14}C enrichment at 64,400 ± 1000 years BP (Gr. N7754). These data demonstrate that actively aggrading sedimentation and an open vegetation cover characterized the Schabs site (about 160 m above the present-day valley bottom) during this cool phase at the beginning of the Middle Würm.

At the village of *Albeins* (Fig. 6 E), 4 km south-west of Brixen, a *Larix* (larch) fragment was found in a thick sequence of sand and gravel at an elevation of about 800 m, 200 m above the modern valley bottom (FLIRI, 1989). This *Larix* fragment has been ^{14}C dated at 24,000 ± 210 years BP (Hv-15443).

At *Baumkirchen* (Fig. 6 D), 12 km east of Innsbruck, the "Inntalterrasse", an approximately 300 m high hilly terrace along the Inn valley near Baumkirchen, contains a thick sequence of stratified clay and gravel, topped by basal till. This well-known exposure has been frequently investigated (FLIRI, 1973; FLIRI et al., 1970).

The sequence of laminated silty clay more than 100 m thick was produced by persistent, uniform sedimentation in a shallow lake of consistent water depth, as indicated by trace fossils produced by fish on the bedding planes (FLIRI et al., 1970). Palynological analysis indicates that a shrub tundra surrounded the lake, suggesting a very cold climate during the deposition of the laminated clay. The sedimentation rate was high but variable, averaging 5 cm per year, as measured through an 86 cm high pack containing 17 distinct palynological horizons (BORTENSCHLAGER and BORTENSCHLAGER, 1978).

At elevations between 655 and 681 m, more than 100 m above the modern valley bottom, woody fragments of *Pinus*, *Alnus*, and *Hippophaë* (buckthorn) yielded ^{14}C data between 31,600 ± 1,300 years BP (VRI-199) and 26,800 ± 1,300 years BP (VRI-161) (FLIRI, 1973). Above this level, more than 100 m of stratified clay, sandy silt, sand, and coarse gravel was deposited, indicating enhanced, proximal sedimentation. The stratified sequence is covered with till of the last glaciation.

At *Duttendorf* (Fig. 6 G), on the bank of the Salzach river opposite Burghausen, generally cemented coarse gravel covered with weathered soil and solifluidal material is overlain by loess topped with loose gravel (TRAUB and JERZ, 1975). The cemented gravels interfinger with the nearby Riss terminal moraine. The thin layer (up to 4 m thick) of loose gravel on top corresponds to the uppermost part of the Würm outwash along the Salzach valley (TRAUB and JERZ, 1975). A gastropod fauna from the loess deposits, dominated by *Arianta arbustorum, Trichia, Puppita,* and *Succinea*, indicates a cold climate with non-arboreal vegetation. A ^{14}C date of 21,650 ± 250 years BP (HV 6354) from *Arianta* shells shows that sedimentation on the outwash plain in front of the Würm glacier ceased at about 21,000 years BP.

At *Neurath* (Fig. 6 H) along the Stainz Bach, gravel and sand accumulation formed a terrace, which has been dissected by the modern stream (DRAXLER and VAN HUSEN, 1991). Along one of the small tributaries, a gyttja horizon is interbedded within a sequence of silt and sandy clay layers. The pollen record indicates non-arboreal vegetation, dominated by *Helianthemum*, Chenopodiaceae, *Selaginella*, and many Cyperaceae, suggesting a cold dry continental climate. The gyttja horizon was ^{14}C dated twice, yielding results of 19,720 ± 390 years BP (VRI-718) and 21,270 ± 230 years BP (UZ 2469, ETH 4572). These dates mark the end of sedimentation under periglacial conditions in the area of transition to the eastern foreland of the Alps.

Sedimentation Pattern

All of these exposures allow the investigation of the mode of sedimentation under given climatic conditions through relatively short time spans. These and other undated locations make it possible to reconstruct the pattern of sedimentation on the valley bottoms (VAN HUSEN, 1983a).

Thus, large volumes of sediments and a high sedimentation rate characterize cool periodes. Under these conditions, higher slopes were covered only with grass. This, and enhanced congelifraction, produced high debris input by torrential flow and mudflow to the creeks and streams, causing rapidly prograding alluvial cones to develop on the valley bottoms (Fig. 9A). Consequentely, the main valleys were blocked and the ice stream gradients became unbalanced. Between the cones, frequently or constantly flooded areas with fine-grained sediments were formed and stratified clay, sand and silt were deposited, such as in Baumkirchen and Schabs (Fig. 6). This activity was confined mainly within the central part of the valley lines where the surrounding mountains were high. The rate of sedimentation depended on the growth of the cones and therefore directly on the debris input induced by climatic deterioration. The elevation of sedimentary deposits throughout the valley line, compared with sedimentation during the modern interglacial, also depends on the duration of climatic decay.

During warmer periods, vegetation on the slopes was more developed and thus slowed the debris input. As a consequence, the main river developed a constant gradient where erosion and sediment transport were in balance with dynamics of the talus cones (Fig. 9B). Extensive flood plains with meanders and oxbow lakes formed. Under these climatic conditions, similar to those of today before regulations, plant detritus infilled oxbow lakes and eventually formed organic beds (e.g. Nieselach).

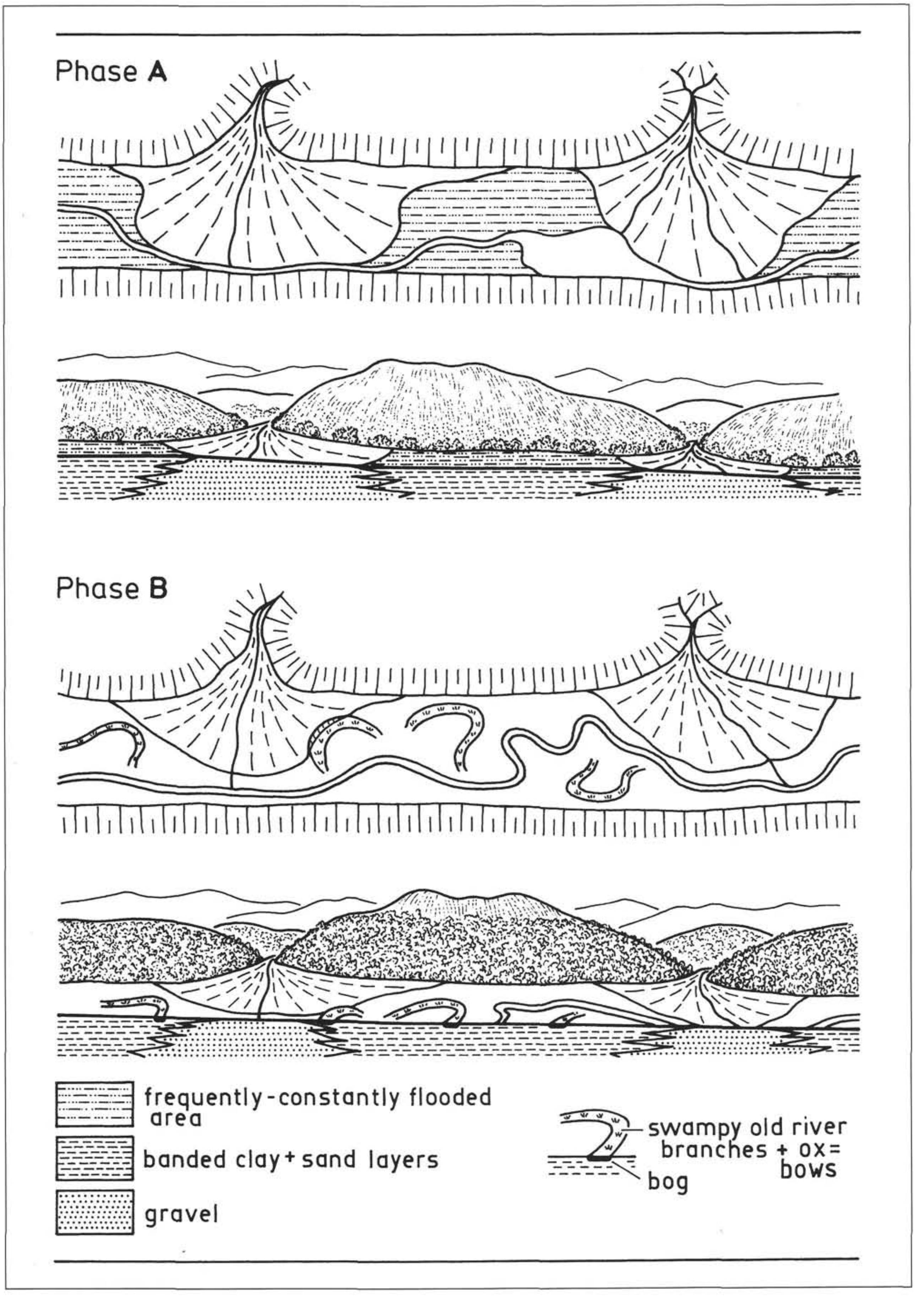
During warm periods, talus cones should have been truncated and eroded by the main river to develop a balanced runoff pattern into the foreland, as it is today (Fig. 9A). This process may depend much more on the duration of climatic change (amelioration) than on the previous sediment accumulation (Fig. 11). Evidence, however, is not sufficient to document whether this process was active during the warmer periods at the beginning of the Würm following the deposition of thick sediment sequences, or if equilibrium was only attained at the elevations reached at particular times at each site (e.g. Schabs).

During the final climatic decay (Fig. 10) the valleys were filled with coarse gravels, "Vorstoßschotter" at many places to high elevations, as a result of progressive overloading of the main river with debris (VAN HUSEN, 1983a, b). The "Vorstoßschotter" extend laterally into the terraces in the foreland, which accumulated at the same time as the thick gravel bodies along the rivers. In both the non-glaciated areas (Neurath), where deposition was induced by periglacial activity (congelifraction), and in the zones of outwash (Duttendorf), accumulation finished at approximately at the time when mountain glaciation reached its greatest extent, and climatic deterioration was at a climax.

Chronology

The chronological succession as given by radiometric dating of the sites described above, and their climatic records, correlates with the well-dated profile of Grande Pile (WOILLARD and MOOK, 1982) and can be compared with Mondsee (DRESCHER-SCHNEIDER, 1996) as shown in Fig. 11. This succession can also be readily correlated with the sequences of Samerberg (GRÜGER, 1979). This results in a good overview of the geologic development from the beginning of Würm until the climax of glaciation during oxygen isotope stage 2.

Starting from the "interglacial level", the elevation of valley bottoms may have changed drastically. Some of the non-dated and inadequately investigated gravel deposits, including fine-grained and organic material along the longitudinal valleys, may mark this change (Figs. 10, 11). The elevation of valley bottoms north and south of the main crest of the Alps during the final climatic decay and glacier


Phase A
Phase B
frequently - constantly flooded area
banded clay + sand layers
gravel
swampy old river branches + ox= bows
bog

← Fig. 9
Model showing different depositional environments in the early Würm. Phase A: rapidly prograding alluvial cones block main valley and cause deposition of fine-grained flood material in intercone areas. Phase B: reduced sediment input from tributary valleys allows through fluvial drainage on extensive alluvial floodplains (after VAN HUSEN, 1983a).

advance is also temporarily marked at Albeins and Baumkirchen, respectively. The dating of both sites indicates that the glaciers of the tributary valleys reached the main longitudinal valleys at about 25-24,000 years BP.

The rate at which further ice build-up occurred is unknown, because of the total lack of chronological data. Only in two places, Duttendorf and Neurath, in the Eastern Alps do radiocarbon dates constrain the climax of climatic deterioration and the maximum extent of glaciers and periglacial activity as well as strong congelifraction and periglacial downwash.

Around the Eastern Alps, detailed mapping of terminal moraines and outwash terraces (e.g. Traun, Enns, Mur, Drau) has shown that most glaciers behaved in a similar way. First of all, the greatest extent of the glacier tongues is marked by small moraine ridges connected with outwash fans. After this, the glacier fronts retreated some hundreds of meters and formed distinctive, high and wide end moraines, also connected to outwash which continues morphologically into the downstream terraces. These outwash fans, and their transition into downstream terraces, have a lower gradient than the older ones. Within 1-2 km, they are on the same level, forming the Niederterrasse which continues downstream, and also along the Danube river to Vienna (VAN HUSEN, 1987), also corresponding with those of the non-glaciated tributary valleys.

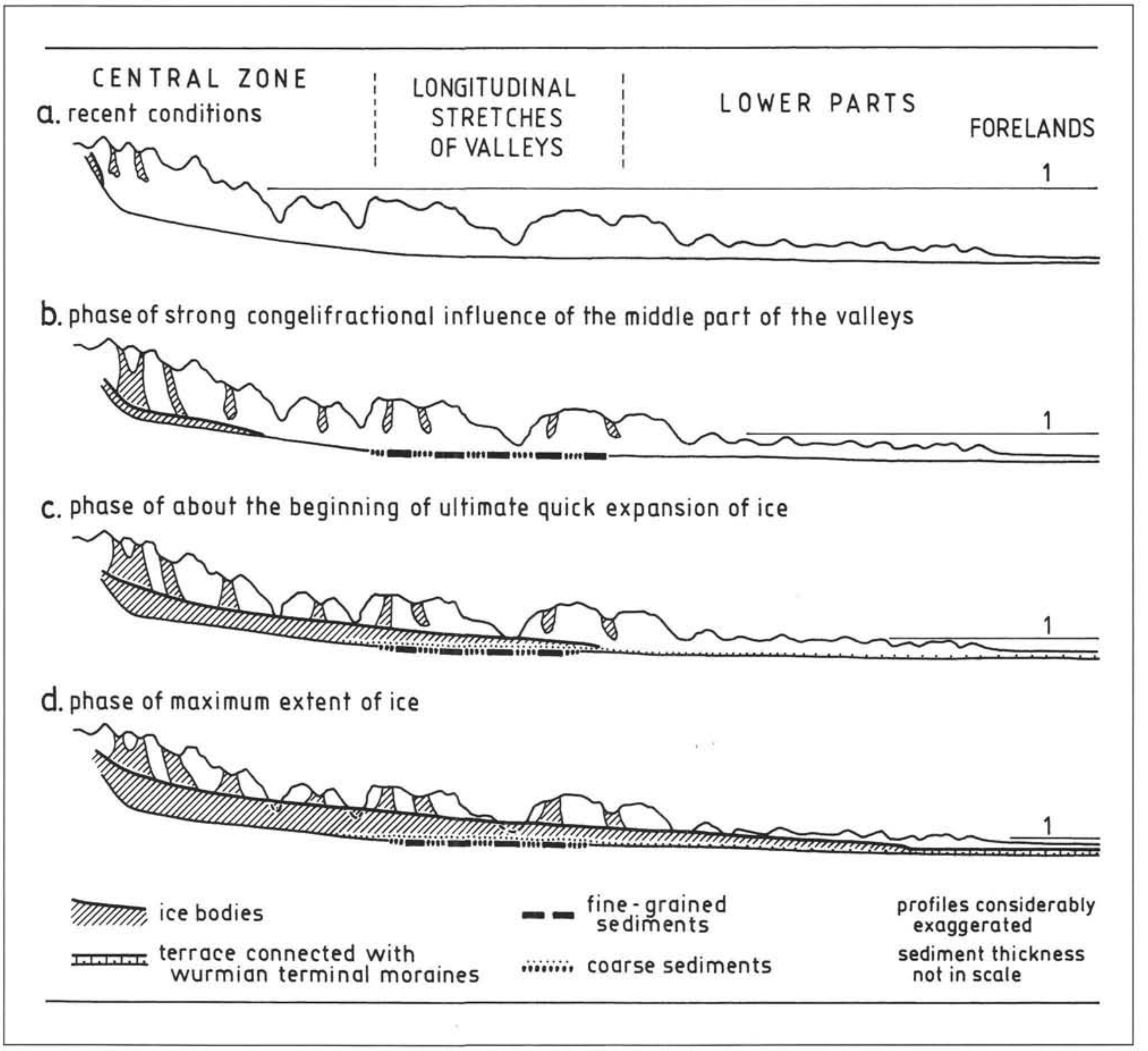


Fig. 10
Sketched profiles of gradual development of climatic decay, indicated by estimated lower limit (1) of strong congelifraction. It shows that only a little lowering of this limit and the equilibrium line (c to d) is necessary to cause a very rapid and great expansion of the valley glaciers during the final phase of the Würm (see Fig. 11). This works in either way.

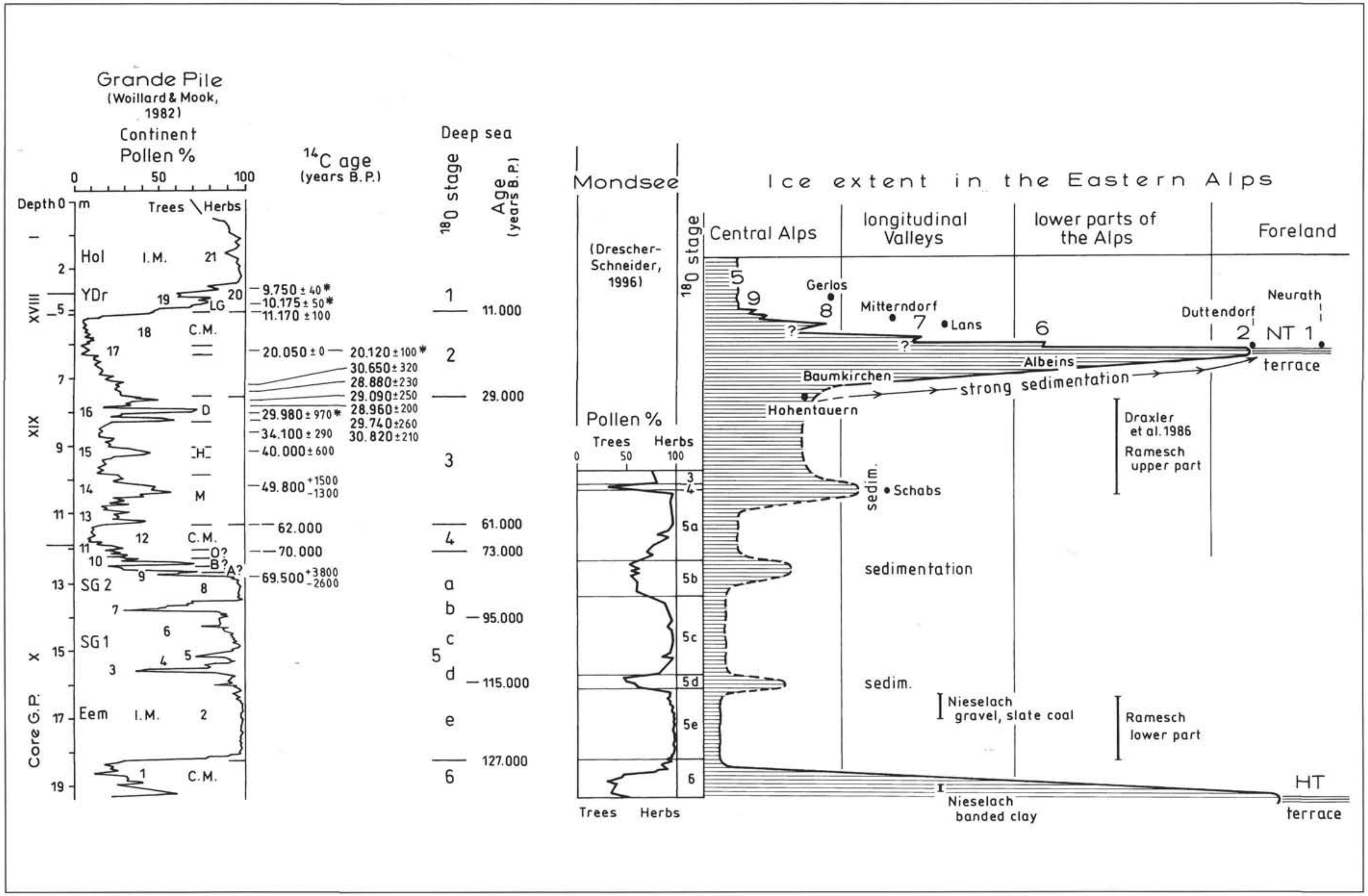


Fig. 11
Temporal development of the ice extent in the Eastern Alps, according to the sites described, and the sedimentation model (see Figs. 9, 10) compared to the pollen profiles from Mondsee and Grande Pile.

No evidence of weathering was found between the sediments of these different terminal moraines, or in the outwash gravels. This suggests that very little time elapsed between these two stages, the "Maximalstand" and the "Hochstand" (VAN HUSEN, 1977). It is not known how long the glaciers were in place to form the 20-40 m high moraines of the "Hochstand", as no datable material has yet been found.

The first retreat from these terminal moraines was some hundreds of meters to kilometers, depending on the size of the glacier. This generally led to a concentration of water runoff into only one or two outlets, and a first small incision into the outwash fan and terrace. This stage is characterized by small morainic ridges and kettle holes, indicating continuing permafrost conditions to preserve such large blocks of ice below the sediments during the whole timespan from the first greatest ice extent to this early retreat phase (VAN HUSEN, 1977). The kettle holes finally formed after the downmelting of the glacier tongue, when a single deeply-incised outlet formed from the overdeepened glacier basin.

The duration of the maximum extent of glaciation and climatic deterioration during the LGM (Last Glacial Maximum) can only be tentatively estimated. After the final ice advance around 21 ka BP, the glacier front may have remained in these three positions for about 4000 years, according to data from the phases of deglaciation that followed.

Phase of Ice Decay

Following the LGM, retreat and downmelting of glacier tongues began in the foreland, as well as in the valleys. In all of the valleys in the Eastern Alps, no sequences of end moraines or equivalent evidence of former ice margins can be traced in the great valleys of the Inn, Salzach, Drau, Mur, Enns and Traun rivers. In these areas, only kames and ice marginal terraces formed in temporary lakes have been identified. These ice-contact sediments, developed especially around the overdeepened parts of the valleys (Fig. 11), indicate an unbroken downmelting without glacier stillstands or readvances. With respect to the distribution and internal structure of the sediments which formed in temporary lakes, the downmelting occurred rapidly. The duration of this deglaciation can only be roughly estimated, but comparing it to the current retreat of glaciers in Glacier Bay, Alaska (GOLDTHWAIT, 1986), where the glaciers are of similar length and volume as those formerly in the Eastern Alps, some hundreds to a thousand years may have been all that was necessary for the loss of about 50% of the glacier lengths in the Eastern Alps. Ice-lakes first formed at the margins of the glaciers, and then extended over the entire area of the overdeepened basins. This probably resulted in glacier calving, which would have enhanced the rate of ice recession. In this way most parts of the glacially overdeepened areas became free of ice very quickly, as the glaciers lost about 50-60% of their length and probably of their volume too. At the same time these parts of the main ice streams of the Alps became stagnant glaciers, due to a slight rise of the equilibrium line (Fig. 10).

Knowledge about further stages in recession is mainly based on the investigation of two valley systems. One is the Traun valley, where in a relatively short valley the complete sequence of retreat and readvances from the LGM to the beginning of the Holocene was investigated by mapping, sediment analysis, palynology and radiocarbon dating (DRAXLER, 1977; VAN HUSEN, 1977) A second is the Inn valley, where all the type localities of these events are situated (MAYR and HEUBERGER, 1968), and where intensive investigations were recently undertaken by S. BORTENSCHLAGER and G. PATZELT. The good accordance of the sequence in both areas, in terms of sediment and vegetation development and radicarbon dating, allows the use of classical terms for easier understanding. The following paragraphs describe key sites providing some evidence about deglaciation of the Eastern Alps.

The Bühl Phase

The first sign of a halt in the downmelting of the glaciers is marked around the basin of Bad Ischl. Extensive kame deposits partly covered by a thin layer of till are connected to small morainic ridges here, and this assemblage suggests a stillstand of the glacier margin with minor oscillations (VAN HUSEN, 1977). This phase is comparable to the Bühl Stage of PENCK and BRÜCKNER (1909), as shown by the more detailed investigation of the type locality by MAYR and HEUBERGER (1968). The lithology of pebbles and boulders in the till suggests that a dendritic ice stream in the main valley was connected to glaciers in all of the tributary valleys at this time. Large kame terraces also exist in other valleys, such as the Drau, but they have not been mapped and studied in detail. Nevertheless, their general extent suggests they were associated with ice streams comparable to those typical of the Bühl Phase (Figs. 11, 12).

The Steinach Phase

The phase of glaciation that followed the Bühl was characterized by a minor readvance of the much smaller glaciers, again linked with kame terraces and inactive ice masses (Fig. 12). Thus, the glacier tongue in the Traun valley near Bad Goisern advanced over lacustrine and fluvial sediments deposited high above the valley bottom, apparently formed when drainage in the valley to the north was still blocked by stagnant ice masses (VAN HUSEN, 1977). A similar situation was described for the Steinach Stage (introduced by SENARCLENS-GRANCY, 1958) by MAYR and HEUBERGER (1968) in the Sill valley south of Innsbruck. Here also, a thick sequence of gravels deposited in contact with stagnant ice masses was covered by the till of a glacier readvance. Thus, after the Bühl Phase, the main valleys had become free of active ice and the glaciers were back in the tributary valleys. The time interval between the two phases could not have been very long, since large inactive ice masses lingered in the valleys, despite climatic amelioration and large lakes of meltwater (Figs. 11, 14).

The Gschnitz Phase

The next phase in the sequence of deglaciation is marked by well developed blocky end moraines. In the Traun valley these are present around Bad Goisern and in all of the other source areas of the Würmian ice stream. The morainic ridges are connected to outwash gravels almost everywhere. In the Traun valley, north of Bad Goisern and around Bad Aussee, these deposits can be recognized as terraces ex-

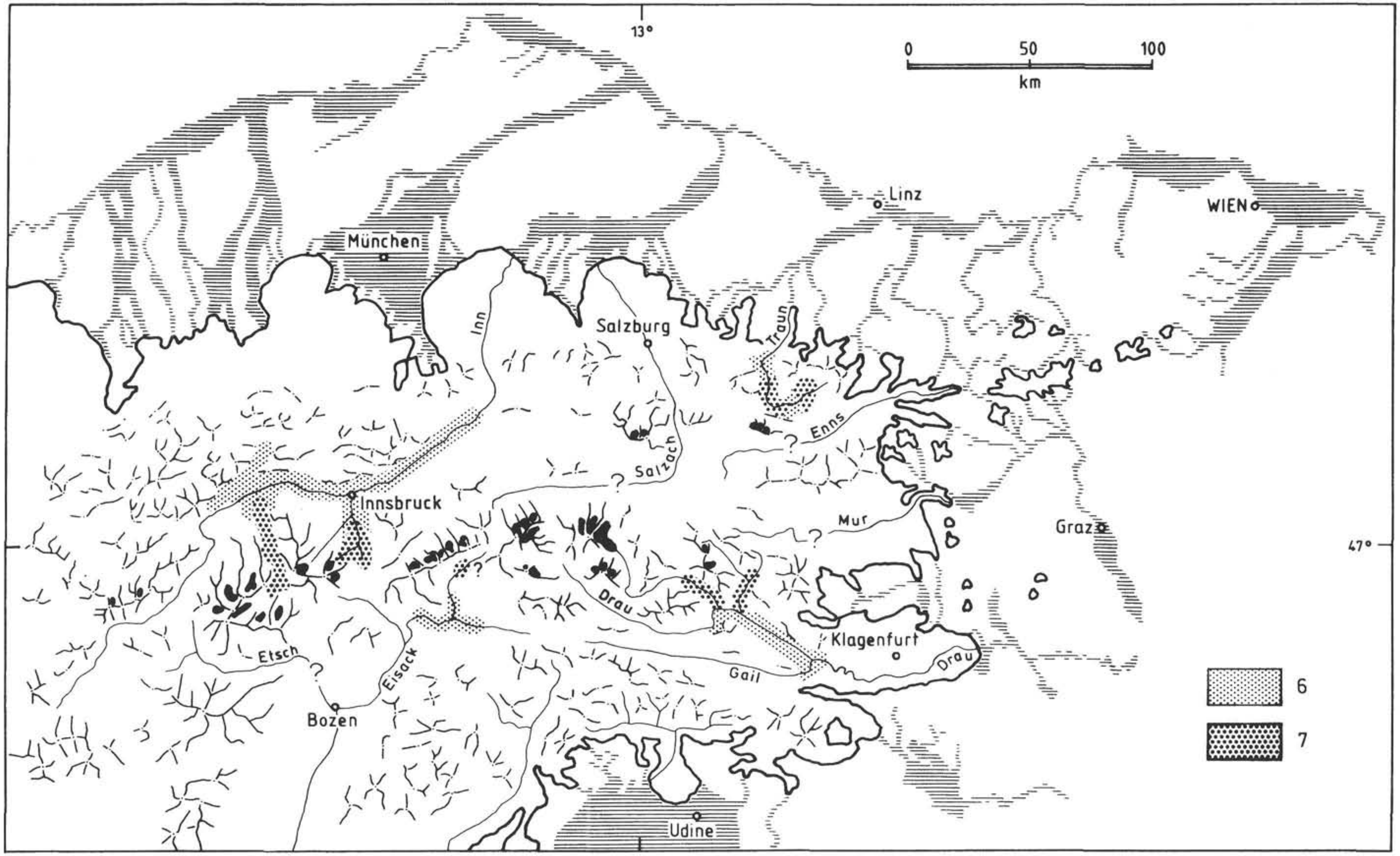


Fig. 12
Sketch map of the Eastern Alps during the Bühl (6) and Steinach (7) Stages (see also Fig. 11).

tending about 10 km downstream. This indicates that the valleys were free of inactive ice masses, permitting free drainage along the valley bottoms (VAN HUSEN, 1977). This suggests a comparatively long period of time and probably climatic amelioration between the Gschnitz and Steinach Phases, and considerable recession (Fig. 11). The Gschnitz moraines are relatively unmodified by slope activity, suggesting that little or no solifluidal shaping has occurred since their deposition. The moraines of the Steinach Phase, in contrast, were smoothed by solifluction activity during the following (Gschnitz) glacial stage. The Gschnitz moraine Phase is also well developed at Trins, south of Innsbruck (MAYR and HEUBERGER, 1968), and similar distinctive moraines can be recognized in many of the large tributary valleys draining from higher parts of the central Eastern Alps, as well as in the high cirques to the north and south (Fig. 13). This means that the glacial event was regionally extensive, reflecting a uniform lowering of the equilibrium line (ELA) by about 600 m in comparison to that of the Little Ice Age (GROSS et al., 1978).

Chronology

The ages of these glacial phases have been determined from palynological studies of bogs in the Traun valley (DRAXLER, 1977, 1987). During the early phase, after the main LGM deglaciation, some depressions were slowly filled with banded clay. The pollen record of this time is dominated by *Artemisia, Helianthemum, Ephedra, Hippophaë* and *Juniperus,* in addition to *Pinus;* the *Juniperus* becomes important towards the end of the sequence. This vegetation assemblage, especially the high content of *Artemisia*, is typical of the pioneer phase under dry cold conditions (DRAXLER, 1987). The same feature of this early phase is also described from the western part of the Eastern Alps (BORTENSCHLAGER, 1984). This phase terminates with the rapid increase of *Pinus* pollen to values of 70-80%. This interval is well dated in the Traun area to around 12,300 ^{14}C years BP. For example, the following are reported in VAN HUSEN (1977): Moos Alm: alt. 730 m, 12,520 ± 180 years BP: VRI-431; Ödensee: alt. 770 m, 12,220 ± 180 years BP: VRI-433; Plakner: alt. 550 m, 12,410 ± 190 years BP: VRI-430; Ramsau: alt. 515 m, 11,970 ± 200 years BP: VRI-432; Rödschitz: alt. 790 m, 12,440 ± 420 years BP: VRI-485. Dates for the equivalent interval from Tyrol, reported by BORTENSCHLAGER (1984), include: Lanser See: alt. 840 m, 13,230 ± 190 years BP: HV-5269, and Gerlos: alt. 1590 m, 12,155 ± 210 years BP: HV-5284.

The difference of some 100 years between sites may be due to the different rates of soil-forming processes on limestone and crystalline bedrock, as well as to plant migration. However, the dates suggest that this event occurred during, or at the end of the Bölling 1b chronozone (Fig. 14). In the Traun valley, bogs documenting this event lie outside and inside end moraines of the Gschnitz Phase. Thus, this glacial advance occurred no later than the cold dry interval associated with the Oldest Dryas.

The chronology can be determined more exactly in the pollen profile from Rödschitz in front of the Gschnitz moraines, in which the cooling event is marked by a strong increase in *Artemisia* at 6.40 m depth. Radiocarbon dates from gyttja in 5.40 m depth (12,420 ± 440 years BP: VRI-485) and organic detritus (pieces of shrub and herbs) at 7.20-7.00 m depth, yielding an age of 15,400 ± 470 years BP: VRI-484, suggest that the Gschnitz cold Phase could have occurred around 14 ka BP, assuming an approximately constant rate of sedimentation in the lake. A similar estimate was made by PATZELT (1975).

The periglacial modification of end moraines of the earlier Steinach advance, and the lack of such reshaping on the Gschnitz moraines, agrees well with an Oldest Dryas age for the Gschnitz event, immediately preceding the climatic improvement at Termination I. After the Bölling interstade, there is no evidence for permafrost conditions on the floors of the main valleys in the Eastern Alps.

According to the Rödschitz site (basal date of ca. 15,400 ^{14}C years BP), the event may have occurred at around 16 ka BP (Fig. 14). Thus, the earlier Bühl Phase possibly culminated shortly before this date. During the warmer conditions of the Bölling chron, the valley bottoms became ice-free. Only high parts of the limestone plateaus of the Northern Calcareous Alps and valleys at higher elevations in the Central Alps remained covered with ice.

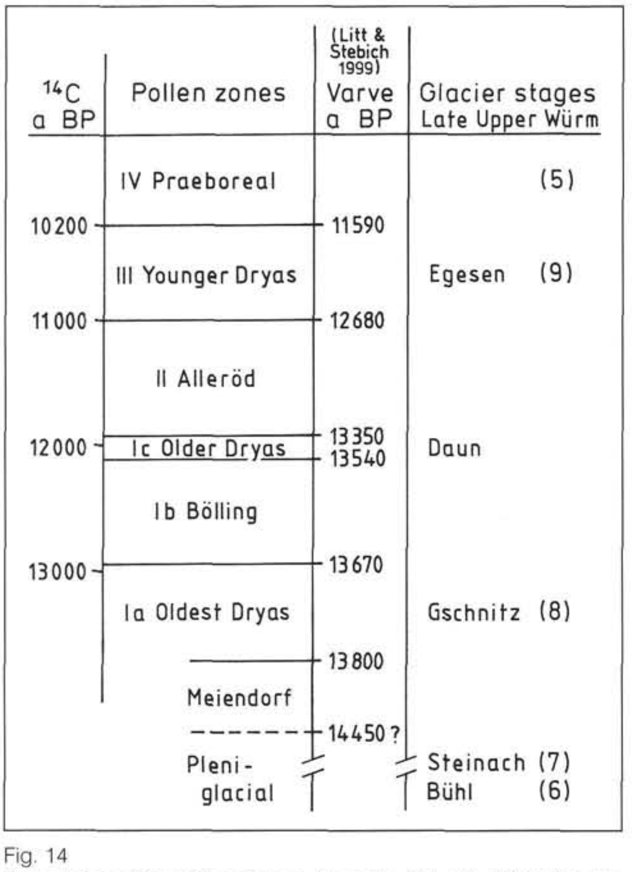


Fig. 14
Temporal position of the phases (see also Fig. 11) during the late Upper Würm (Termination I). For the numbers see also Figs.: 11, 12, 13).

The Daun Phase

During the following cold and short-lived Older Dryas chron, enhanced ice accumulation stimulated small glaciers on the higher limestone plateaus, like the Dachstein Plateau. These small ice masses formed blocky end moraines with boulders the size of houses. This glacier advance is believed to have occurred during the Older Dryas

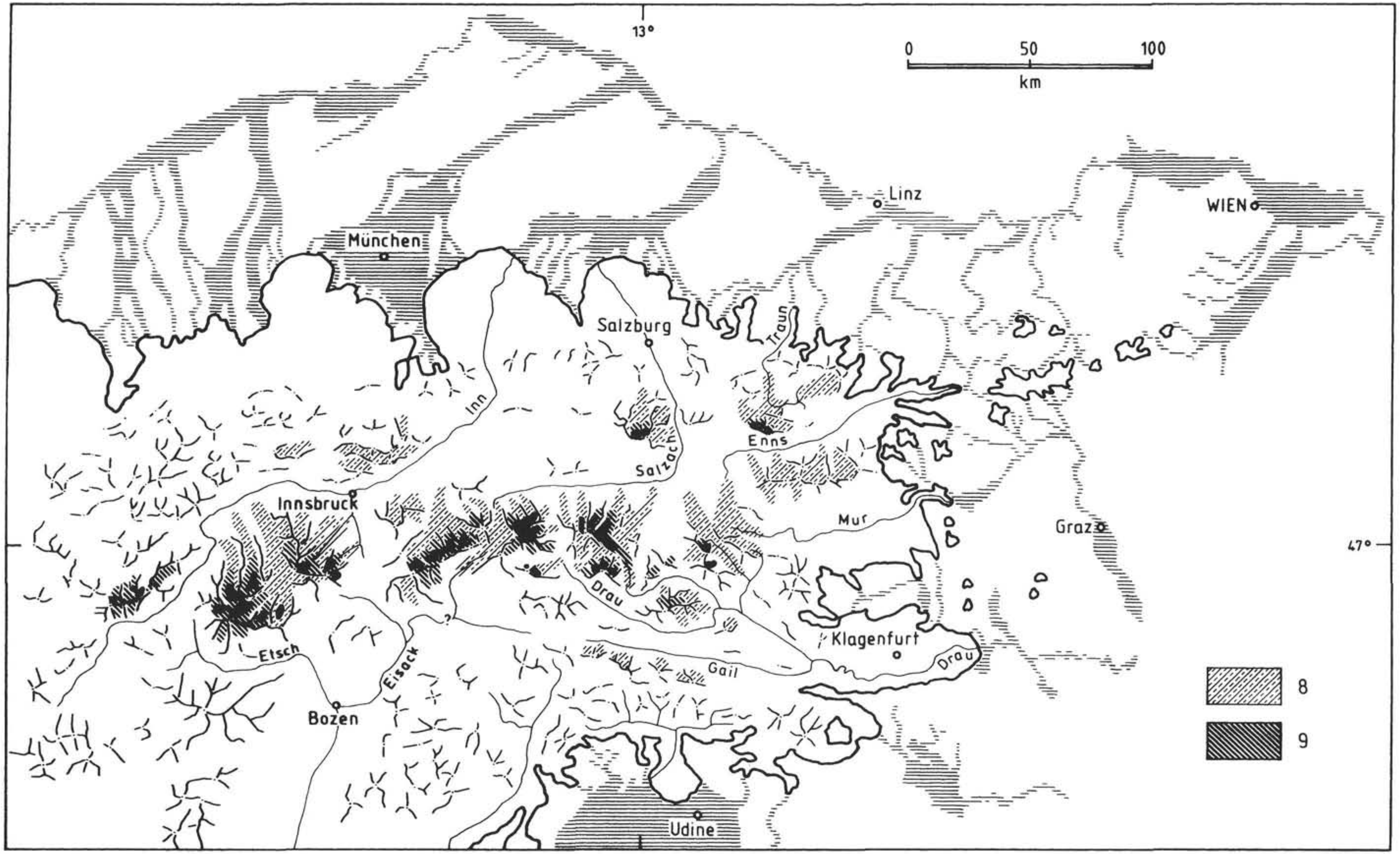


Fig. 13
Sketch map of the Eastern Alps during the Gschnitz (8) and Egesen (9) Stages (see also Fig. 11).

chron. Yet, in general, this and the following (Egesen) event are not well-marked on the comparatively low terrain of the limestone plateaus. By contrast, in the higher part of the Eastern Alps, moraines of Older and Younger Dryas ages are well developed. The older event shows a lowering of the ELA by more than 300 m, compared to the A.D. 1850 (Little Ice Age) snowline (GROSS et al., 1978).

The Egesen Phase

This event is marked by well developed end moraines, which, according to palynological records and radiocarbon dating (PATZELT and BORTENSCHLAGER, 1978) and exposure dating (IVY-OCHS et al., 1996), are believed to have formed at the time of the Younger Dryas stade of NW Europe. The ELA lowered by about 300 m (GROSS et al., 1978), but due to precipitation differences across the mountains, this value varied from 280 m in the drier continental part, to 400 m in the more oceanic northern ranges (KERSCHNER, 1980). Generally, the Younger Dryas was characterized by drier, more continental conditions (around 70% of modern precipitation), with a lowering of the mean annual temperature of 2.5-4 °C, the higher value affecting the drier central parts of the Alps. Many rock glaciers became active under such cold and dry conditions (KERSCHNER 1980). This distinct climatic decay was probably triggered by a massive influx of fresh water from the Laurentide ice sheet (Lake Agassiz) to the North Atlantic and its influence on the Golf Stream (BROECKER and DENTON, 1990; TELLER and KEHEW, 1994; ANDERSON, 1997).

After this event, with the onset of the Holocene, the glaciers receded behind their recent limits and fluctuated only within the range of these and the extents developed during the Little Ice Age.

Holocene

After the Egesen Phase with the onset of climatic amelioration, glaciers tongues shrank approximately behind their present size. Thus, pieces of trees *(Pinus cembra)* were found in front of the Pasterze. These were dated to 9,100-8,000 years BP, showing that at this time 200-300-year old trees were growing on the valley floor (SLUPETZKY, 1990). Due to this fact, the present glaciated valley bottom must have been ice-free long enough to create a soil allowing trees to grow well in it. Since then, glaciers are often fluctuating between (more or less) the extent of the 1850 – stadium at the maximum and smaller lengths than today (Fig. 15). This was the result of 30 years of continuous investigation on glacier dynamics and climatic development during the Holocene, carried out by S. BORTENSCHLAGER and G. PATZELT.

These investigations, including extensive mapping of the surroundings of many recent glaciers, pollen analysis of bogs, and radiocarbon dating, showed a frequent climatic oscillation during the Holocene (Fig. 15). Therefore, the equilibrium line, as well as the timberline, fluctuated around 200 to 250 m during the whole period.

According to this, summer temperatures oscillated more or less about 1.5 °C (BORTENSCHLAGER, 1984), with a climax in the first half of Holocene (Fig. 15). This climatic development, along with the geologic dynamics, influenced the uppermost part of the Alps and the valleys in higher elevation very intensely in different ways, e.g. by mudstreams and short-lived lakes (PATZELT, 1994b).

This geologic activity was not only limited to the uppermost parts of the Alps. As we have seen in the Würm period, valley bottoms during the Holocene were also affected by

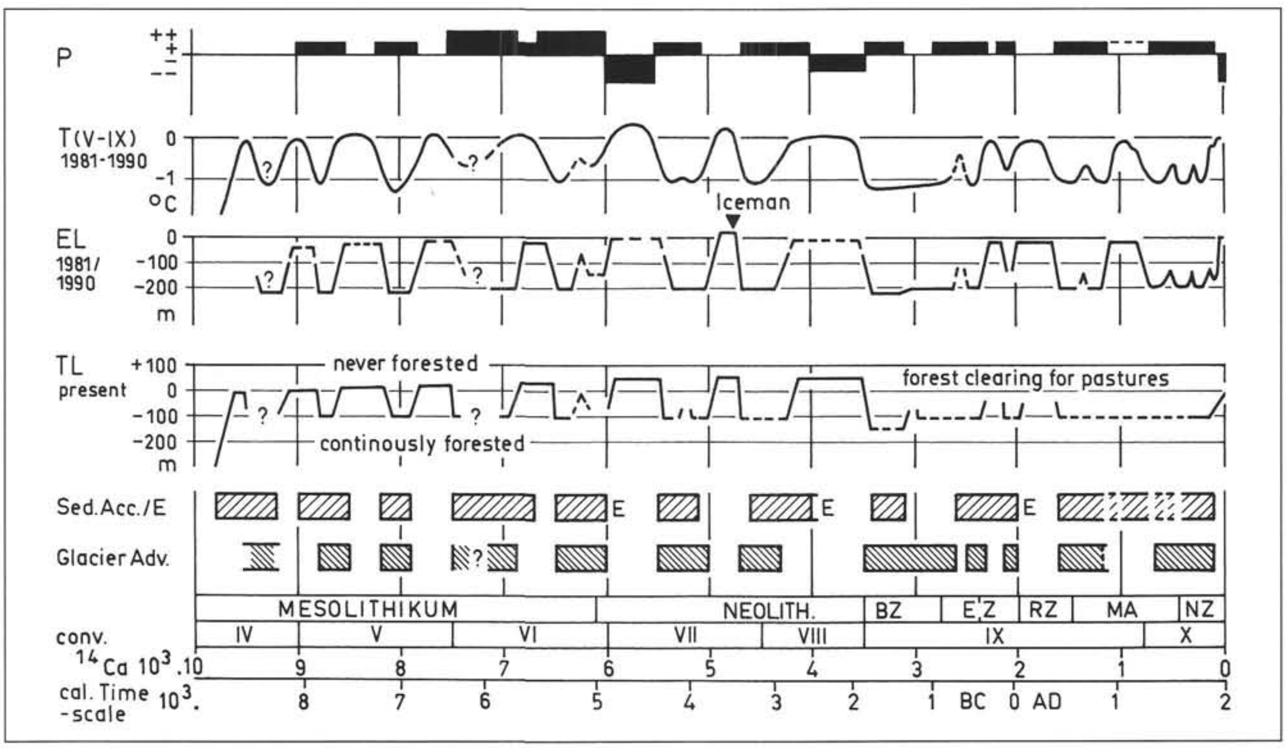


Fig. 15
Development during the Holocene according to Patzelt, 1995. P: precipitation, T: temperature, EL: equilibrium line, FL: timberline, Sed.Acc./E: sedimentation and erosion phases in the Inn valley compared to the glacier advances.

the activity of the tributaries (PATZELT, 1994a). During glacier advances and lowering of the timberline higher mudflow activity enhanced the sediment load of creeks and rivers down to the tributaries of the main longitudinal valley, e.g. Inn valley (Fig. 15). Accumulation periods interrupted by erosion phases were determined Here at the cones in a range of 10 m, also blocking the main valley. This activity determined in detail in the Inn valley (PATZELT, 1994a), could also be proved in a few locations in other valleys and is the same activity as during the Würm, but on a much larger scale (see above).

Another climatic influence on the river system of the Eastern Alps during the Holocene is unknown as yet. Only along the Danube intensive sediment transport and reworking took place, due to climatic development and sediment discharge.

The "Niederterrasse" was accumulated during the maximum period of extent of glaciers along the tributaries, as well as the Danube river. These terrace bodies can be traced almost continuously from the terminal moraines of the tributaries to the Danube and along its banks. Probably immediately with the retreat of the glaciers from their terminal moraines, the dissection of the terraces began due to the unloaded water discharge after passing the lake-filled tongue basin and decreasing input of congelifraction debris parallel to climatic amelioration. The eroded material of all of these river terraces was transported toward the Danube as the final receiving water course of the Alpine drainage system (Fig. 6). Thus, the Danube was heavily loaded with gravel and sand at the late glacial phase of the Würm and beginning of the Holocene. The Danube, therefore, was not able to cut into its bed and had to transport the debris. For a long time the river flowed at the elevation of the former glacial terrace. The river system changed from braided to meandering. In this way,the gravel body was often reworked, internal sediment structures changed and the drift blocks concentrated at the base (EPPENSTEINER et al., 1973). Here also logs from oak, elm, willow were deposited. Remnants of the glacial terrace with ice wedges and loess cover can be recognized at the same elevation as Holocene, according to radiometric data showing results between 9,000-10,000 years BP west of Vienna (PIFFL, 1971) and up to approximately 6,000-8,500 years BP (FINK, 1977) east of it.

After this period, the Danube started dissecting its gravel filling and forming lower terraces. Radiocarbon data also obtained from logs showed ages of 4,000 years BP around Linz (KOHL, 1978), Tullner Feld (PIFFL, 1971), and Marchfeld (FINK, 1977). All these logs were once the main source for establishing tree ring chronology (BECKER, 1982, 1993).

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