Geomorphological Hazards in Austria

Christine Embleton-Hamann[1]

[(1)] Department of Geography and Regional Research, University of Vienna, Austria
christine.embleton-hamann@univie.ac.at

Abstract. This systematic review summarizes geomorphological hazards in Austria and synthesizes the information on causes, regional distribution, damage and mitigation measures by the Austrian government. The term 'geomorphological hazard' has been very broadly interpreted to mean any hazard to people or to their economic infrastructure caused by natural earth surface processes or, sometimes, by human induced processes that, in most cases, involve change in relief. Thus the review deals in turn with river flooding, hazards associated with mountain torrents, landslides, avalanches, soil erosion, risks posed by glaciers, by permafrost and by earth tremors.

Keywords. Austria, floods, mass movements, avalanches, permafrost, earthquakes, control measures.

1. Introduction

About 75 percent of Austria consists of mountainous terrain. It includes the greater part of the Eastern Alps, which in the west still support many glaciers. In the Pleistocene the ice cover was more or less complete, save for the highest peaks, and extended roughly as far east as the lower Enns Valley. The ice was responsible not only for glacial erosion forms, often with steep relief, but also for the widespread deposition of unconsolidated sediments. The mountains are also a zone of active tectonic uplift, with a rate of about 2 mm a year in the watershed area of the Eastern Alps. The high mountain climate promotes rapid rates of weathering and provides abundant precipitation to help in debris transport. Many factors therefore favour active geomorphological processes, whose direct effects are not only apparent in the mountains but can also reach out far into the Alpine foreland.

The intensity of the processes can sometimes reach catastrophic levels presenting a series of hazards to the population, the economy and its infrastructure. This contribution will deal in turn with the hazards of flooding, mass movements (including avalanches) and soil erosion; hazards associated with glaciers and permafrost, and finally those connected with seismic activity. The four major groups of catastrophic processes - river flooding, mountain torrents/debris flows, landslides and avalanches - are dealt with in most detail since they are potentially the most life-threatening. The remaining hazards - soil erosion, risks posed by glaciers, by permafrost and by earth tremors - are either rarely life-threatening or, in the case of glaciers, largely historical.

In terms of flooding there are fundamental differences between the lowland rivers and the rivers in mountainous areas, not only in respect of flood danger but also regarding the causes of floods, and counter-measures. In the upper reaches in mountain areas the main hazard is heavy sediment transport and deposition on valley floors. Many rivers here take the form of torrents (the so-called ‘Wildbäche’); in contrast, high-water stages in the middle and lower reaches appear as more familiar flood events. Because of these differences there are two separate authorities in the Austrian Ministry of Agriculture and Forestry, Environment and Water Management (BMLFUW) dealing respectively with rivers and torrents. Part of the damage associated with torrents is caused by debris flows. Other forms of mass movement that present serious hazards in Austria include landslides and avalanches.

The Alps has long been known as an area subject to frequent natural catastrophes. In former times when the population was relatively sparse, catastrophic events had less economic impact: people lived with them and accepted them as a part of life, at the same time avoiding endangered areas as far as possible (e.g. location of settlements). In recent decades, however, there has been rapid expansion of settlement, mainly in response to the development of tourism which nowadays has overtaken agriculture as the prime source of income.

Engineering works for hazard control are the common solution. But they are often expensive and rarely provide complete protection. There is an increasing realisation that four other approaches can be more successful and efficient, namely, integrated flood protection, the operation of strict planning controls (e.g. to prohibit building in danger zones), risk management and working with nature, rather than against it, to combat the hazard. For example, forest conservation is vital in the fight against avalanches and torrent disasters; in flood mitigation conservation and reactivation of natural run-off and retention areas are a priority. Counter-measures and control of hazards in Austria are largely in the hands of the Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW).

2. River flooding

2.1. Type and degree of flood danger

Floods on Austrian rivers occur mostly through prolonged heavy rainfall or through a combination of rainfall and snowmelt. Fig. 1 shows that the heaviest rainfall is associated with the barrier effect of the mountains. The isolines of highest daily precipitation illustrate this clearly on the northern side of the Alps. A second ‘peak’ area is located in the south of the country: here the north-south trending valleys of the Italian Alps direct Mediterranean air masses far into the mountains before they are forced to rise. A difference from torrent disasters should be noted at this point: in the case of torrents the most dangerous conditions are linked to the short and most intense rainfall events, which are not only caused by the barrier effect of the mountains but also by convective thunderstorms.

Because of the storage effect of snowcover many Austrian rivers show a seasonal regime that does not involve winter flood danger. Very occasionally damaging floods are related to ice jams. According to PRODINGER (1975) such phenomena may occur in the upper reaches of Alpine rivers every 20 years. The area of the upper Mur and its tributaries, often called the cold pole of Austria, is particularly susceptible. In severe winters the ice must be broken by explosives. Also on the Danube the winters of 1828/29 and 1932 produced ice jams.

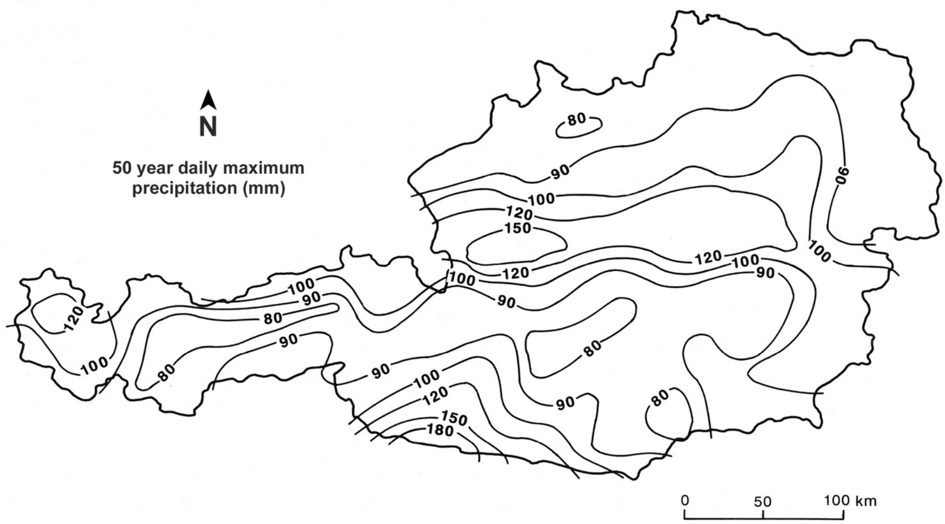

Fig. 1: 50-year daily maximum precipitation (mm). Source: Fig. 9D in SEEBACHER & SHANIN (1985).

Almost the whole of Austria belongs to the Danube system excepting only a small part of the Rhine basin. The whole country north of the main Alpine ridge drains directly to the Danube across Austrian territory. Because of this unity two-thirds of the country experience approximately simultaneous flood danger from relief rainfall on the north side of the Alps. The most important catchments south of the main Alpine divide are those of the Drau and Mur which reach the Danube far outside the Austrian frontier. The most important Danube tributaries in the north are the Inn with its feeder the Salzach, the Traun and the Enns. All these main streams possess series of power stations. River power stations without significant storage lead to an ambiguous situation with respect to flood risk. Their construction will improve local flood protection but at the same time the danger for places farther downstream is increased because of changes to the river gradient and the nature of the channel. This will increase the speed of the flood wave. If the operation of the power stations is properly interlinked, however, accurate flood warning can offset some of the disadvantages for the downstream area.

The water-level information service for shipping and flood warning was founded in Austria at the turn of the century. Forecasts are based on a network of automatic river gauging stations, which is being steadily increased in density. This information service is not only of national but of international importance. In terms of floods Austria is involved both in flood transmission to other countries downstream and in handling floods derived from upstream areas. For all cross-frontier main rivers there exist bilateral and multilateral agreements with neighbouring states. These deal with all questions of water management and impose a duty on the upstream countries to provide warnings of flood danger.

2.2. The flood disasters of the last 100 years

If one looks back on the flood events of the last century, those of 1954 and 1959 as well as 1965 and 1966 stand out. The pairing of these events is deliberate: the second catastrophe in each case came hard on the heels of the first giving insufficient time for damage repair. A detailed description of the flood disasters of the nineteenth and twentieth centuries in Austria is given in BMLF (1973).

The 1954 and 1959 floods affected the whole drainage area of the Danube north of the main Alpine divide and the Danube itself. In 1954 the flood reached its peak in July and the flood waters in the Danube lowlands were up to 7 km broad; numerous settlements were submerged. In 1959 the acute flood danger lasted from mid-April to mid-August. During this time there were altogether five flood waves, which were progressively worse, partly due to increasing saturation of the soil.

The most catastrophic flood of the last 100 years was in 1965. On the one hand the rainfall was exceptionally pro-longed and on the other hand the convergence of weather systems between March and September led to record precipitation over the whole country. Even the normally relatively dry north-eastern areas suffered levels of flooding not previously known. The worst damage occurred in the Drau basin, which was severely affected by a deep depression from the Mediterranean in September. In the East Tyrol and western Carinthia almost all valleys were devastated and wholesale re-forming of river beds occurred. The next year (1966) saw two flood events, one in August and one in November, and once again the area worst affected was the Drau basin. The two major floods of this century occurred in 2002 and 2005. The 2002 flood incurred damages at approximately 3 billion Euros, largely concentrated in the Danube basin of Upper and Lower Austria. In 2005 a lesser flood accounted for 560 million Euros in economic losses (AQUAFENCE 2007).

2.3. Flood control in Austria

Sometime in the middle of the nineteenth century came the change-over from small-scale local attempts to control flooding, to large-scale flood protection works that involved hydraulic engineering and broader economic goals. For this, government finance had to be provided, the first legislation dating from 1830. Until the new law of 1884, however, money was only granted in practice for works of national importance and all other protection projects failed because of lack of money. After this date and up to the beginning of World War II a great deal was achieved; in contrast little or nothing was done during the war.

After 1945 river regulation and maintenance stagnated completely, but this time was marked by an uninterrupted series of small and large flood events, which finally culminated in the disasters of the 1950s and 1960s. There were then desperate attempts to catch up with the backlog of essential flood protection works. The beginning of the 1970s marked a new era when engineers concentrated not only on damage repair but on longer-term river management and flood prevention. This was based on quite new principles; the construction of straightened and confined flood channels without water retention areas was to be abandoned, and flood danger was to be dealt with also at the regional planning level.

The new goals demanded an emphasis on comprehensive planning. It was necessary to make an attempt at land-use zoning and to redirect intensive land use away from areas bordering rivers to avoid the need for more and more flood protection works. Further, flood protection by means of water retention areas involves broad-scale planning: individual flood protection works can no longer be considered in isolation but must be integrated at the wider level of whole river systems. The most recent legislative guidelines were published in 1994 (BMLF 1994). Two important planning tools under these guidelines are (i) river development schemes and (ii) the preparation of hazard zone maps.

River development schemes represent the highest level of river basin planning. Besides hazards and threats they not only take into consideration the ecological situation but are also responsive to general conditions such as current use, designated use, rights and so on. They comprise three steps. The first step is establishing the basic data on hydrology, river morphology, sediment budgets, vegetation, fauna, water quality, flood hazard, already existing flood protection measures and present land use. The second step is the mission statement which has two parts. It includes a scientific assessment of the appropriate ecological and environmental goals for a particular river and the level of protection required depending upon social, cultural and economic values. For instance, areas used for agriculture and forestry are not to be specifically protected. The third step is to develop a catalogue of future planning measures and priorities.

In the preparation of hazard zone maps the following constraints apply: Within the inundation boundaries of HQ30, any building project requires permission in accordance with the

Austrian Water Law Act. Areas that due to the expected damaging effects of floods are not suitable for permanent use regarding settlement and transport purposes are defined as Red Zone (building ban zone). Those areas that are required for the run-off of floods or the retention of water combine to form the Red-Yellow Zone (water management priority zone for run-off and retention). The remaining areas up to the inundation boundaries of HQ100 are suitable only for conditional use and are shown as Yellow Zone (regulated and precautionary zone). The Blue Zone (water management demand zone) includes areas that are required for water management measures and/or as the case may be for maintaining their functions, e.g. when special management is required. In addition, residual risk areas are marked as hatched in red and yellow. They indicate in which areas flooding is possible if flood protection structures fail or if certain water levels are exceeded (up to HQ300).

2.4. Flood protection for Vienna

Flood protection for Vienna has been one of the most costly undertakings. Formerly, the braided river Danube around Vienna was up to 5 km broad and normally impassable for travellers; after 1870, however, this was totally changed by the first major river regulation works. An artificial channel was constructed, designed for a maximum discharge of 11,000 m^3/s and about 12 million m^3 of material was removed. These dimensions were unfortunately not big enough: quite soon the engineers became aware that flood protection for Vienna must be designed to cope with a flood of 14,000 m^3/s. In 1969 the second major Danube regulation works were at last started. An entirely new channel with a length of 22 km and a width of 160 m (‘New Danube’) was constructed, separated from the old channel by the so-called ‘Danube Island’, 200 m broad. The construction of this by-pass not only served for flood relief, but also helped to improve the groundwater situation and to provide a new recreation and bathing area for the citizens of Vienna.

3. Mountain torrents and debris flows

3.1. Characteristics and types of mountain torrent

In the Austrian forest law of 1975 a mountain torrent (‘Wildbach’, literally a wild stream) was defined as a permanent or ephemeral stream, liable to flash floods which pick up dangerously large loads from either the drainage basin or the stream bed; and which then transport and deposit the debris within or outside its bed, or in another stream. In order that a stream should be treated by the BMLFUW as a ‘torrent’, it must be officially recognized as such. Interpretation of the definition given above, however, varies according to the responsible official; therefore there is a range of phenomena that are classified officially as torrents. But in general, the following characteristics may be observed:

- Strong gradient: in high Alpine regions up to 20%, elsewhere in the Alpine region over 12% (according to AULITZKY 1984, Fig.4).
- Relatively small catchment and correspondingly short stream length: the mean length is between 4 and 6km (according to AULITZKY 1986).
- High discharge peaks, since intense rainfall events cover the whole catchment and discharge rises quickly in the short steep courses. Between such events base flow is often negligible: exceptions to this are the torrents in front of glaciers or in karst regions.
- Dangerously high loads of debris and other material (e.g. timber). In 1931, STINY distinguished between 'old' and 'new' debris. Under old debris was included the loose material of glacial or fluvial Pleistocene and sub-recent formations. New debris comprised newly produced weathered material, particularly plentiful in areas of less resistant rocks such as schist, rocks strongly disintegrated by tectonics and in the limestone Alps with their huge active talus slopes. Because of continuous removal, the new debris does not usually present such a danger as the old debris masses with their large stores. An exception to this is the situation where new debris builds up at the foot of large deep-seated mass movements (described in more detail in the section on mass movements, e.g. near Putschall in the Central Alps). As regards other material transported by the torrents, timber presents a particular danger, because of its ability to block the stream in narrow sections, followed by the catastrophic break-through of water and debris.
- Most torrents end in debris cones or debris fans. The steeper debris cones are formed through transport of coarser debris; the gentler slopes of debris fans are associated with finer material. Exceptionally these features are lacking where a torrent debouches into a river capable of removing the debris or where debris can be adequately deposited within the lower part of the torrent channel.

The greater the amount of debris stored in the drainage basin, the greater the danger from the torrent. In extreme cases debris flows develop, which are characteristic of the most dangerous type of torrent. In a debris flow the solid material is distributed throughout the cross-sectional area of the flow, which turns into a water-mud-gravel mixture, no longer obeying the laws of hydraulics. High speeds can be reached, the total weight of debris transported can be immense and the flow can rise high up in the channel. All these characteristics can cause great destruction. Beside this most dangerous type of torrent (Type 1), three other types are distinguished by AULITZKY (1986) according to relative debris content: (Type 2) torrents with high debris content but obeying the laws of hydraulics, (Type 3) torrents with some debris content and (Type 4) torrents without significant debris.

3.2. Torrent distribution and torrent zones in Austria

As three-quarters of Austria is mountainous, torrent catchments cover a large area: in 2003 there were altogether 10.651 torrents registered as such (BMLFUW, 2005). Fig. 2 shows the regional distribution of torrent hazards in Austria. The source for this is the map of torrent zones published by KRONFELLNER-KRAUS (1989), which has been gradually built up over the years. The zone boundaries were drawn according to the debris loads involved in about 2,000 torrent disasters from catchments up to 80 km^2 in size. The map agrees well with the results of Aulitzky who approached the problem from another standpoint: his map of torrent distribution and hazard in Austria (AULITZKY, 1986) is based on the different torrent types in individual districts. In Table 1, based on a comparison of the two maps, the proportions of different torrent types have been calculated for each zone.

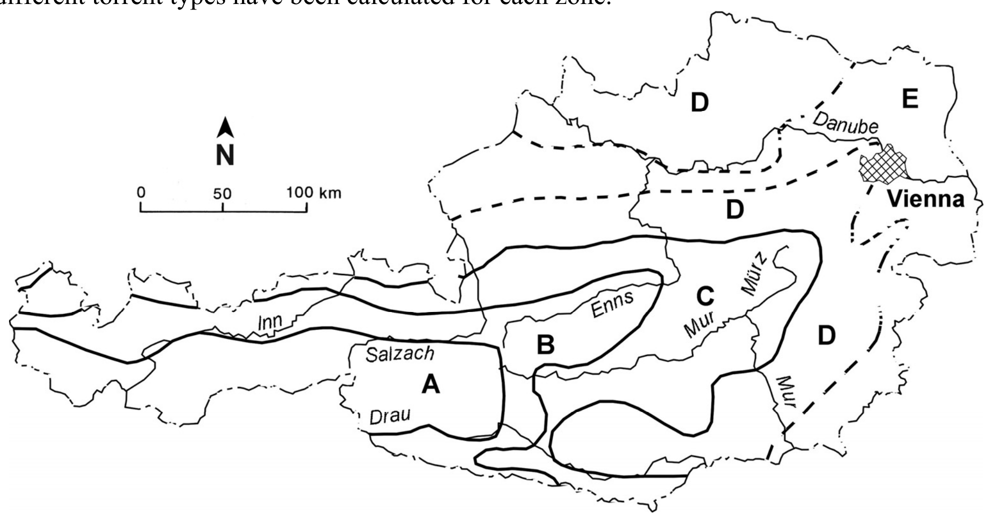

Fig. 2. Torrent zones in Austria. Source: Kronfellner-Kraus (1989). For explanation, see Table 1

Table 1: Torrent zones and types in Austria

Zone	**Observed maximum debris loads (G. KRONFELLNER-KRAUS, pers. comm.)**	**Percentage of torrent types (for explanation see text) based on AULITZKY (1986)**		
		Types 1+2	**Type 3**	**Type 4**
A	> 100,000m^3, exceptionally < 1 000 000m^3	81	19	-
B	100,000 – 200,000m^3	64	35	1
C	< 60,000m^3	33	55	12
D	< 20,000m^3	10	68	22
E	Loess gullies up to several thousand m^3; other torrents up to several hundred m^3	-	65	35

Large and dangerous 'old' debris stores are characteristic of zone A, which corresponds to the highest relief of the main Alpine watershed. This is the reason why types 1 and 2 dominate zone A (81%). Old debris stores can also be present in zone B, but are usually smaller and not so common. While zone A is clearly marked by the presence of old debris stores, the triggering factors for torrent disasters in zones B and C are more complex. They comprise mountain ridges mainly of schist and limestone where 'new' weathered debris is actively forming. Moreover both zones lie in high precipitation areas (see Fig.1). In limestone and dolomite areas, the developing flood wave can be mitigated by underground drainage systems, but not in the case of schist. The immediate causes for torrent disasters in zones B and C can therefore vary regionally, but altogether - compared with zone A - there is less danger from individual torrents because of smaller debris stores, but at the same time there are greater numbers of torrents. In the Pre-Alpine region and in areas beyond the Alps there is an abrupt decrease in the debris danger and torrent density (zones D and E). Zone E has no problems apart from those associated with loess gullies. The latter are often caused by unsuitable agricultural practices and are mostly quite recent.

3.3. Torrent damage

Since 1972 torrent disasters and torrent damage have been documented in a detailed and standardized way. ANDRECS (1996) published the data for the 22 years of 1972-1993. In this period 39 people were killed by torrents or debris flows, 12 of them during a single event, namely the debris flow disaster of 1975 in Ramingstein (Salzburg). 4630 buildings were destroyed or damaged and 6170 ha of productive land devastated. More recent data show a reduction in the number of buildings affected by the torrent hazard: In the 11 year period of 1994-2004 only 1502 buildings were destroyed or damaged. On the other hand the total for the area of devastated land has substantially increased and is 5794 ha (OBERNDORFER *et al.* 2007). Overall during the last three decades the annual number of damaging events was between 100 and 150.

3.4. Torrent control and torrent research in Austria

Since 1884 the state has taken responsibility for torrent control, following the terrible torrent disasters south of the main Alpine divide in 1882. The responsible department of the BMLFUW is the same as that for avalanche control. Their work falls under several headings, of which the most important are: (i) engineering construction, (ii) afforestation of high areas and forest conservation measures, (iii) hazard zone mapping for regional planning, (iv) research and (v) science communication and promotion of public hazard awareness.

In spite of all the efforts of the torrent and avalanche control service, the total number of disasters in recent times shows no decline, for which the basic causes are twofold: with the opening-up of the Alps for tourism came a huge expansion of the settlement areas which often occurred in potentially hazardous areas and which can only be protected at considerable cost. The second problem concerns the state of the forest. Since interception of intense precipitation by the forest plays a vital role in the size of the corresponding flood wave its relevance to torrent control is clear. In avalanche control the forest has a decisive function in preventing dangerous levels of snow accumulation; therefore the problems of forest conservation and re-establishment will be dealt with in the section on avalanches.

Since 1975 the torrent and avalanche control service has used hazard zone maps to prevent the unrestricted spread of settlement. The maps provide a basis for district planning and show the following features: (i) torrent drainage basins and avalanche source areas; (ii) danger zones, the degree of danger being indicated on two levels as red and yellow zones, where the critical threshold for the red zone is a disaster return period of 150 years; (iii) areas where control measures are foreseen; (iv) areas where the possibility of other natural disasters such as mass movements is high. The map also marks natural or artificial features, e.g. dams, which have a protective effect and must be conserved. 80% of the Alpine area (zones A, B, C and minor parts of D in Fig.2) and 63% of the non-Alpine area of Austria (zones E and the major part of D in Fig.2) were mapped by 2005. The 100% coverage of all Austrian torrent catchments with hazard zone maps is planned for 2010 (BMLFUW 2005).

Research on processes in torrent and avalanche catchments and on improved mitigation measures is carried out in close cooperation with the University of Natural Resources and Applied Life Sciences, Vienna, the Research and Training Centre for Forests, Natural Hazards and Landscape, the Geological Survey of Austria, the University of Innsbruck and Joanneum Research. Special mention should also be made of an international research body founded in Austria, following the disastrous flood events of 1965 and 1966 in Carinthia. A working party was set up which eventually developed into the Society for the Study of Preventive Flood Control. This holds an Interpraevent Symposium every four years which reports on the latest developments in disaster control and mitigation, especially in the fields of flooding, debris flows, landslides and avalanches.

4. Mass movements

In the previous section, debris flows were considered as an important special type of mass movement. This section will deal with all the other forms of mass movement involving rock and loose material, in which soil moisture and groundwater can play a vital role but in which water is not acting as a transporting agent. When such mass movements occur in a torrent drainage basin, they are recorded by the torrent control authority and are taken into account in their hazard zone plans and in their disaster statistics. They are, however, documented more comprehensively and in greater detail by the Geological Survey. Until recently it has been estimated that the total number of both old and present-day landslides in Austria amounts to at least 100,000 (G. SCHÄFFER, pers. comm.).

4.1. Regional distribution of landslides

Fig. 3 shows the distribution of the most massive of all the mass movements, namely the 'Bergstürze' (i.e. huge rockfalls and rock slides from steep mountain sides). They are by their nature confined to the Alps, and are more or less historic and prehistoric, rather than contemporary, phenomena. The Bergsturz at Sandling which occurred on 12th September 1920 (marked by S on Fig. 3) and in which 6-8 million m^3 of rock were moved provides an exception. As Fig. 3 shows - and as Abele (1974) notes - the total number of Bergstürze in the crystalline central Alps is less than in the northern and southern calcareous Alps. In general terms, this may be ascribed to the fact that the sedimentary areas are characterised by a broad-scale pattern of joints, fractures and bedding planes which allow very large slabs of rock to become detached and to slide, whereas in the metamorphic areas, the schists, gneisses and gneissose rocks tend to be less stable and to break away in smaller rock and debris falls. In terms of volume, the Bergstürze of Köfels, the Fern Pass and the Dobratsch (marked by their initial letters on Fig. 3) are among the ten biggest occurrences in the whole of the Alps. The Bergsturz of Köfels (exact date uncertain, but ca. 8700 BP - *cf.* KUBIK *et al.* 1998) stands out in particular, since all the remaining largest examples belong to the Limestone Alps. In the case of the Dobratsch, a huge area consisting of 24 km^2 of collapsed debris spreads out from its foot and represents the combined output of several Bergstürze. One of these, dating from 1348, is an example where an earthquake tremor is known to have provided the trigger mechanism (see section 9).

Fig. 3 also shows the main geological zones in Austria. Some formations are more susceptible to life-threatening or damaging mass movement than others. In the following paragraphs the relative importance of geology - or more precisely, lithology - as a factor will be examined. In making some lithological generalisations, it must not be overlooked that locally it is not the rock formation but tectonics that is decisive. Apart from the existence of many old disturbances and related weak zones, the Alps mark a very mobile plate boundary of the Earth's crust where present-day movements are readily detectable. The uplift of the Eastern Alps in the watershed zone is of the order of millimetres per year, while lateral displacements in the northern calcareous Alps can even reach centimetres per year. The result is a loosening of the rocks along the zones of faulting and disturbance. In a number of specifically investigated areas of the Austrian Alps the relationship between tectonics and major mass movements has been proved.

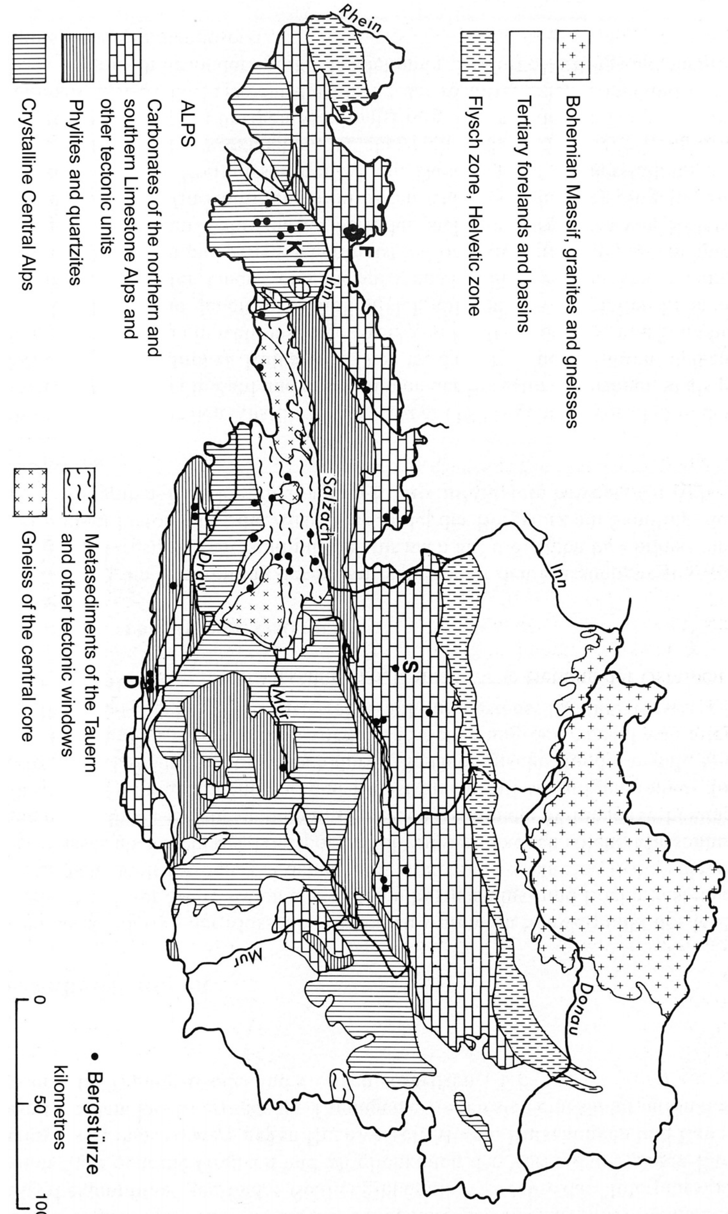

Fig.3. Geological sketch-map of Austria (after VETTERS *1980 and* TOLLMANN *1986) and the distribution of 'Bergstürze' (after* MONTANDON *1930 and* ABELE *1974). Locations of the Bergstürze in Köfels (K), Fern Pass (F), Dobratsch (D) and Sandling (S) are indicated.*

The factors of rock type and relief fundamentally determine the susceptibility to mass movement and allow the following broad regions to be distinguished:

(i) The Bohemian Massif: In contrast to all other areas of Austria, this rates as a relatively problem-free zone. Built of resistant rock types (mainly granite and gneiss), and with a relief dominated by extensive plateaus, low height differences and gentle gradients, the majority of slopes are stable.

(ii) The Tertiary Foreland and Basins: The Tertiary sediments contain layers of sand, silt, clay and marl, which can be very susceptible to mass movement when the soil moisture content is high. Problems of slope failure occur especially during road construction and are frequent in the hilly areas such as eastern Styria. In December 1985 a 150-metre section of the newly opened Südautobahn (south motorway) collapsed by as much as 15 m.

(iii) The Flysch and Helvetic zones: The sandstones and shales of this pre-alpine zone are very liable to failure and mass movements, especially sliding, are therefore frequent. They are extensive in places, endangering settlements and important traffic links or supply networks. It is especially expensive to repair and maintain the huge water mains that carry water from the Limestone Alps across the flysch zone to supply Vienna.

(iv) The Limestone Alps: The potential for danger arises essentially in the intercalated layers within the hard limestone or dolomite; these consist of unstable rocks, especially clay, shale, salt beds and gypsum. Within the calcareous zone, these comprise a quarter of the total outcrop. Although the number of mass movements is less than in the flysch zone, the scale of their activity and their dimensions are in general greater. An area of about 30 km^2 west and south of Sandling (location already mentioned in connection with Bergstürze, for location see Fig. 3) is particularly liable to movement. The drainage basin of the Stambach provides an example from this area, in which the mass movements have been described in detail by SCHÄFFER (1983). The limestone walls around the source region of the Stambach are unstable because of the underlying beds of clay and marl, the numerous joints in the limestone, and probably also because of neotectonic disturbances. In the years 1978 to 1981, three rockfalls - each of which amounted to between 30,000 and 60,000 m^3 - broke away, falling onto older, probably Lateglacial landslide debris, consisting of clay, marl and salt-bearing layers from the Limestone Alps. Loading of these by the rockfalls set them in motion, moving slowly downslope towards the valley, the movement continuing for one or two months on each occasion. In addition, a debris flow broke out of the loose material at the cliff foot. Substantial areas of forest were destroyed, along with a section of the Stambach valley road.

(v) The Phyllite and Quartzite zone: The areas included in Fig. 3 under this designation belong to different tectonic units, but their rock formations are bound together by a common characteristic - extreme susceptibility to landsliding. Because of its lower proportion of quartzite, the so-called greywacke zone is especially prone to problems. Lying between the Central Alps and the northern Limestone Alps, it runs eastwards from the source regions of the Salzach. As well as numerous small landslides, there are also some large deep-seated mass movements, an example of which will be described below.

(vi) The Central Alps: This zone is dominated by metamorphic rock types, though at the same time there is great diversity in detail, ranging from massive rock to strongly foliated and cleaved formations. Correspondingly, there is great variety in types of mass movement. The area of metasediments in the Tauern window is recognised as a particularly unstable one, since its position in the Alpine nappe structure has exposed it to exceptional tectonic stresses. These, together with the other important factors of steep slopes, high precipitation totals, and rapid infiltration through the broken rock, combine to promote extensive mass movement. Only the gneiss of the central core is relatively immune. The huge mass movement 'Gradenbach' near Putschall in Carinthia is located in the phyllite series on the southern border of the metasedimentary Tauern window with the crystalline rocks of the Central Alps. It involves the whole valley side, 1100 m high, with gradients of 25-27°, over a distance of about a kilometre. At the top is a scar 40 m high where the break-away begins, while towards the foot the slope bulges out in convex fashion. Observations have shown that both creep and sliding are involved, and that the movements tend to be spasmodic and jerky, but averaging 50-60 cm/year in the upper part and 20-30 cm/year near the toe (MOSER & GLUMAC 1982). The mass movement threatens the village of Putschall below and some farms have had to be abandoned. Even worse than this direct hazard, however, is the possibility of an added risk of a torrent catastrophe. The moving valley side delivers completely broken debris to the river course at its foot; the debris is then washed out during floods. In the flood catastrophes of 1965 and 1966, part of Putschall had to be abandoned after being buried under debris up to 12 m thick. Engineering measures to control such a torrent are tremendously expensive since the construction works have also to be able to resist the strong sideways pressure from the moving hillslope.

4.2. Recording of mass movements in Austria

Under the leadership of G. SCHÄFFER, a project with the title 'Documentation of geological-geotechnical risk factors' was started in 1979 by the Geological Survey of Austria. As well as the collation of many other data (e.g. relating to karstification, fluvial erosion, etc.), this work also embraced study of the distribution of all types of mass movement in Austria. Relevant, and often difficult to obtain, reports and scientific papers were collected, and the positions of individual landslides were identified on maps. Finally each map sheet was checked through field mapping and the inventory completed.

5. Avalanches

5.1. Causes of avalanches and avalanche types

Avalanches stem basically from lack of cohesion between the snow crystals or too little adhesion between the snow cover and the ground surface beneath, combined with stress changes in the snow cover.

The most important process leading to loss of cohesion is change in the crystal and snow structure during and after snow accumulation. These diagenetic changes vary according to the temperature and moisture content of the soil, snow and air as well as the effects of wind. They can lead to a diminution or an increase in grain size or the formation of crusts. Therefore during the process of snow diagenesis the avalanche danger is high and continuing heavy snowfall will prolong and aggravate the hazard level. Longer term conditions after completion of snow diagenesis depend on its outcome. In the case of grain size diminution the snow cover will have settled, showing denser packing and improved cohesion between snow crystals. On the other hand, diagenetic increase of grain size or crust- formation causes both immediate and long-term instability of the snow cover. Increase of grain size leads to the so called 'Schwimmschnee', in which any cohesion between individual snow crystals is completely lacking. The term crust refers to a hardened snow surface, which develops either through freeze-thaw or wind pressure. When buried, both Schwimmschnee layers and crusts present extremely dangerous sliding surfaces for avalanches.

Next to diagenetic changes, sudden rises in temperature or rainfall can reduce snow resistance. In this case the snow crystals become enveloped by a water film. Finally strong stresses in the snow cover increase avalanche danger. They can be triggered by precipitation, temperature and wind, but they can also be triggered by the sudden addition of the weight of skiers. To summarise, the most dangerous situations are created by heavy snowfalls, sudden temperature increases and strong winds, which cause snow drifting, formation of crusted surfaces and increased stresses. These facts are also brought out in avalanche statistics (LUZIAN 2002).

There are various classifications of avalanche types, but only one emphasises the form of the break: powder-snow avalanches break away from a point, broadening downwards, whereas snow slab-avalanches break away along a line, below which the whole slab is set into motion. Snow-slab avalanches are usually the cause of the greatest damage and unfortunately are also the more frequent. In the twenty-year observation period from winter 1974/75 to winter

1993/94 79% of the avalanches were classified, from which 70% were snow-slab avalanches and 30% were of powder snow (LUZIAN 2000, 2002).

5.2. Distribution of avalanche danger in Austria

According to the Avalanche and Torrent Control Service there are 4843 avalanche tracks in permanently settled areas (BMLFUW 2005). Most of them endanger only traffic routes. Most of the valleys originating near the main Alpine divide have only one exit and if this is threatened by avalanches the whole valley can be cut off for several days. The areas of greatest danger comprise the high Alpine areas, where the steepness of the slopes favours the breaking-away of avalanches and the high altitude leads to considerable snow accumulation. Within the Alps three regions with highest avalanche hazard may be identified. These are from west to east: the Arlberg region, the inner valleys of the western Tyrol, and somewhat less distinctly the inner valleys of Eastern Tyrol. In these areas heavy snowfalls are particularly frequent owing to the blocking effect of the Alpine divide on weather fronts. Since the most frequent weather situations in winter involve air masses coming from the north-west, the Arlberg region and west Tyrol are at higher risk than the southern Alpine slopes of East Tyrol.

5.3. Avalanche catastrophes in Austria

Since 1950 avalanches in Austria have claimed the lives of more than 1600 people, which is on average approximately 30 fatalities per year (HÖLLER 2007). A high percentage of this death toll is associated with off-piste and backcountry skiing. The worst winter on record was that of 1953/54 when 143 people lost their lives; damage was especially great in Vorarlberg, where 300 houses and other buildings were destroyed. There has been no subsequent event of such magnitude. According to LUZIAN (2002) avalanche accidents causing death in the 26 winters of the period 1967/68 to 1992/93 are distributed as follows: 65% were involved in ski-touring in high Alpine areas, 20% inhabitants or visitors of settled areas, 7% service personnel (rescue, avalanche warning and army officials) and 8% skiers on open pistes.

A tragic exception from this distribution is the winter of 1998/99. On February 23, 1999, an avalanche hit the small village of Galtür, Tyrol, and destroyed six houses that were situated outside the red and yellow hazard zones. In the course of the event 31 people were killed. One day later a second avalanche further down the valley caused another seven fatalities. A model of the disastrous avalanche of Galtür based on the damage and the snow height of the release area points towards a recurrence interval of more than 150 years. Thus the event exceeded the design event used in hazard zone mapping and falls under the residual risk category (Stötter *et al.* 2002).

5.4. Avalanche control in Austria

The annual funds for avalanche control measures in Austria are in the order of 16.8 Mio. € (BMLFUW 2005). Because of the huge expansion of areas of settlement which now need protection, the problems of increasing costs and labour needs are similar to those of the torrent control.

5.4.1. Long-term avalanche control

Alpine farmers in the seventeenth and eighteenth centuries had already established simple avalanche protection structures: some of them are still effective today. In the last century the building of railways and military roads led to further measures to protect these new communication links. After 1884 the government took on the task of avalanche control. The work of this branch of the BMLFUW has already been described in the section on Torrent Control in Austria (section 3).

A particularly difficult task in avalanche control today concerns the afforestation and preservation of protective forest in high areas where the area to be dealt with is continually expanding and new problems are constantly arising. Forest characterized by trees with varied heights, ages and a dense growth helps to lift the wind off the ground, to distribute the snow more equally, to prevent the formation of zones of tension in the snow cover, and to compact the snow around the tree trunks. This ideal forest structure has become seriously depleted over the centuries, requires much effort to be restored and is continually threatened by increasing man-made disturbance in recent times.

The areas which have to be afforested because of avalanche danger are increasing in size. On the one hand there is the rapid expansion of wintersports activity which until recently was extending ever farther into avalanche-prone areas above the tree line; on the other hand, land has been going out of farming for economic reasons. In many cases clearance areas in the mountain forest dating from the Middle Ages no longer have the necessary intensive care lavished on them to prevent avalanche formation. Frequently today, tall grass has taken over, which provides a potential sliding surface for the snow. In these areas the traditional land use must either be restored or the areas re-afforested.

5.4.2. Temporary mitigation of the avalanche danger

Measures here include warning, closure of ski pistes and roads, evacuation and artificial triggering of avalanches. Two bodies have responsibility here: the Avalanche Warning

Service and the locally-based Avalanche Commissions. The Avalanche Warning Service has existed since 1975 in all provinces in Austria with the exceptions of Lower Austria, Vienna and Burgenland. Relying on weather and snow observations from representative meteorological stations, daily avalanche bulletins are distributed through the media of radio, press and telephone recordings. The avalanche bulletin reviews the overall hazard situation and provides important data for the local avalanche commissions in assessing the level of danger. The local commissions then decide which roads and ski pistes should be closed, which buildings evacuated, or whether artificial avalanche triggering should be employed to reduce the danger.

6. Soil erosion

The forms of soil erosion due to natural causes in the mountains and of gully erosion in general are monitored and controlled in Austria alongside those of torrents and debris flows. This section is concerned only with sheet erosion caused by unsuitable land-use practices in agricultural areas. Because of the extent of forest and uncultivable land, the area under agriculture amounts to less than 50% of the total surface of Austria, or 3.47 Mio. ha (as of 1995). This area has, however, in recent decades become increasingly affected by soil erosion as a result of the intensification of agriculture. Mechanization giving rise to larger and larger fields frequently ploughed downslope, replacement of soil protecting plants such as clover and lucerne by crops such as maize which afford little protection, and a change-over from grassland to arable on slopes, are among the main causes.

7. Glacier hazards

There are two main types of potential glacier hazard: collapses and falls from glacier tongues (also known as ice avalanches), often associated with periods of glacier advance, and hazards related to glacier meltwater, such as the bursting of ice-dammed lakes. There are few historical records of the first category (e.g. the ice avalanches from the glacier Nördliches Bockkarkees; SLUPETZKY 2002), probably because glacier falls never appear to have threatened permanent settlements, but there are many records of the second category. There appear to have been two periods in recent historical time when meltwater catastrophes were particularly frequent and damaging; towards the end of the seventeenth century and during the nineteenth century (approximately 1830-1890 with a maximum in the 1860s). Some of these catastrophes were owing to the bursting of supraglacial lakes or of marginal lakes dammed at the junction of glaciers. The two best-known cases are, however, related to the blocking of valleys by glacier tongues advancing into them; the resulting temporary lakes were the Rofener ice lake and the Gurgler ice lake in the Ötztaler Alps (for more details see the field guide in this volume). Since the beginning of the nineteenth century, glaciers have on the whole been retreating, and consequently hazards on the former scale have not recurred. There is however increasing evidence that associated with the retreat of glaciers new proglacial lakes are being formed (SLUPETZKY & WIESENEGGER 2005). These are sites of potential rapid lake draining hazards. Monitoring of glacier hazards falls within the purview of the Torrent and Avalanche Control Service.

8. Permafrost

Prior to 1980, the possible existence of permafrost in the Alps was not usually recognised. On the one hand there were hardly any scientific publications on this topic except for studies on rock glaciers in western Austria. On the other hand there were a number of technical engineering problems caused through permafrost that proved costly to overcome. The problems have occurred in connection with the construction of high-altitude weather stations, military radar installations and winter sports facilities. The latter include installations such as pylons for ski-lifts, access roads and tunnels, and large buildings (restaurants, etc.). Because the foundations of some of these encountered permafrost, there had been continuing difficulties which in some cases involved reconstruction.

In the meantime the situation has changed. While the engineering problems have long been solved a different type of hazard has emerged through climate warming and possible permafrost degradation. This could cause destabilisation of slopes and rock walls, thereby increasing the volume of easily to be mobilised debris and enhancing the debris flow and rock fall activity. Today there are many research projects and scientific publications dealing with permafrost in the Austrian Alps (see for example the contributions in this volume). The University of Graz and the Graz University of Technology for instance have set up a project called ALPCHANGE (Climate change in Southern Austrian Alpine Regions) and there are also research groups at Innsbruck and Salzburg dealing with permafrost research.

Fig. 4 shows the overall distribution of discontinuous permafrost in Austria. Patches of permafrost too small to be drawn in detail are marked by dots. The map was originally compiled by G.K. LIEB for the first edition of the national report on natural hazards (Fig. 1.9 in EMBLETON-HAMANN 1997). For the eastern and southern part of the Austrian Alps LIEB used his own data-base (subsequently published in LIEB 1996 and 1998); for the western part of the Central Alps data were kindly provided by H. KERSCHNER (University of Innsbruck). In the area of the main Alpine ridge, the distribution was based on the lower limit of intact rock glaciers. On the north-facing slopes of the Hohe Tauern (Salzburg) the lower limit of intact rock glaciers lies at about 2400 m, on the south–facing slopes at about 2500 m. From here it rises to 100-200 m higher levels farther west in the Tyrol. In contrast to the Central Alps the Northern and Southern Limestone Alps have very few rock glaciers and here other evidence indicative of discontinuous permafrost, sometimes indirect, had to be sought, such as basal winter snow temperatures, near-zero temperatures of spring water in summer, and seismic refraction surveys. LIEB'S and SCHOPPER'S (1991) temperature measurements in the Dachstein area for instance suggest that the lower limit of discontinuous permafrost in the northern Limestone Alps lies at 2300 m.

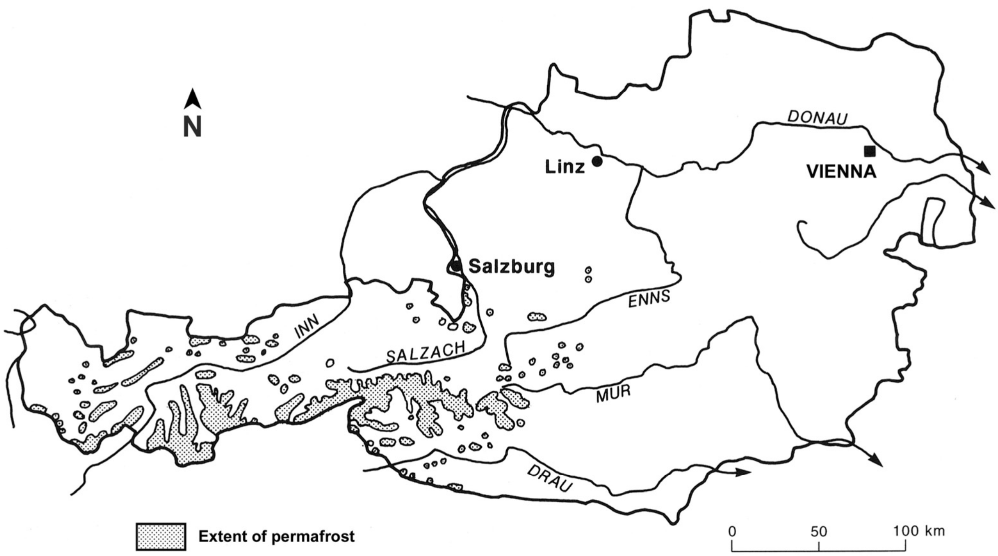

Fig.4. The distribution of discontinuous permafrost in Austria. Map compiled by G.K.LIEB

In the meantime there were also attempts to model the distribution of discontinuous permafrost in Austria, for instance with the program PERMAKART, originally developed in Switzerland (KELLER 1992; see e.g. EBOHON & SCHROTT, this volume or KELLERER-PIRKLBAUER 2005). Modelling at the nation wide level, however, so far has not improved the approximation given in Fig. 4.

9. Seismic activity

Austria is not to be regarded as in any sense a typical earthquake country; nevertheless it has experienced exceptional earthquakes of magnitudes similar to that of the Friuli event (6^{th} May

1976) with a Richter magnitude of 6.5. The earthquake activity is predominantly linked to alpine tectonics. Seismic activity in Austria has been monitored by the Earthquake Service of the Zentralanstalt für Meteorologie und Geodynamik since 1904. The broad picture of seismic activity in Austria has been studied especially by J. Drimmel, and the following account is based primarily on his work (see particularly Drimmel in Fink 1986 and Drimmel 1980).

All Austrian earthquake foci are located in the upper crust, mostly in the depth range 7-12 km, exceptionally down to 20 km. A striking characteristic of the stronger earth-quakes in the eastern Alps is the form of the felt-area, which approximates to an elongated ellipse in which the long axis lies across the alpine trend and the earthquake epicentre corresponds to the southern focus of the ellipse. This means that the seismic waves are preferentially propagated towards the north and north-west and are frequently felt unusually far north in Bohemia and central Germany. The phenomenon was already known in the last century and led to the term 'Transversalbeben' (literally, 'transverse earthquake'), commonly used for eastern alpine earthquakes; a completely satisfactory explanation of this is still lacking.

Drimmel (in Fink, 1986) has prepared a map of areas liable to earthquakes in Austria (Fig. 5). It is based on historical and instrumental data for the period 1201-1982, and shows maximum epicentral intensities calculated on the Medvedev-Sponheuer-Kárnik = MSK scale (a detailed version of the modified Mercalli-Sieberg scale). Damage to houses in good conditions starts at about VI MSK; the distribution of earthquakes with such epicentral intensities forms the basis of Fig. 5. For historical earthquakes, where the only information available concerns the area over which the disturbance was felt and the centre of maximum disturbance, it is possible to estimate the seismic energy and derive the Richter magnitude, and also to suggest the depth of focus. The epicentres of recorded earthquakes with the highest seismic energy (exceeding Richter M = 5) are marked on the map, as are corres-ponding intensity values.

On average, Austria has to expect an earthquake of epicentral intensity VIII or more every 46.3 years; earthquakes of epicentral intensity ≥ VII occur every 8.5 years, and ≥ VI every 1.6 years. The three most dangerous earthquake localities are, in order, Villach, Murau and Neulengbach (Fig.5) with maximum epicentral intensities of IX-X and M = 6-6.5. The most extensive Austrian earthquake area is related to the Mur-Mürz tectonic disturbance and the so-called 'Thermenlinie' (hot spring line) of the Vienna basin. It forms a zone 30±5km broad and 250km long, starting from Murau and stretching towards Vienna. 50% of all strong earthquakes occur in this zone. For example, there were major earthquakes at Murau in the Mur valley and Kindberg in the Mürz valley, and the strongest earthquake of the last century (M = 5.3) occurred 55 km south of Vienna in the Vienna basin.

Another quarter of all earthquakes are located in Tyrol, the strongest around Innsbruck and Hall where the Wipptal disturbance meets the Inn valley tectonic line. Whereas the tremors associated with the Mur-Mürz and Vienna basin zones originate from foci at 8-12 km depth (up to 18 km at Semmering), those of the Innsbruck-Hall region tend to be slightly shallower (8-10 km). There were also some very shallow tremors related to ground subsidence in the Hall salt-mining area.

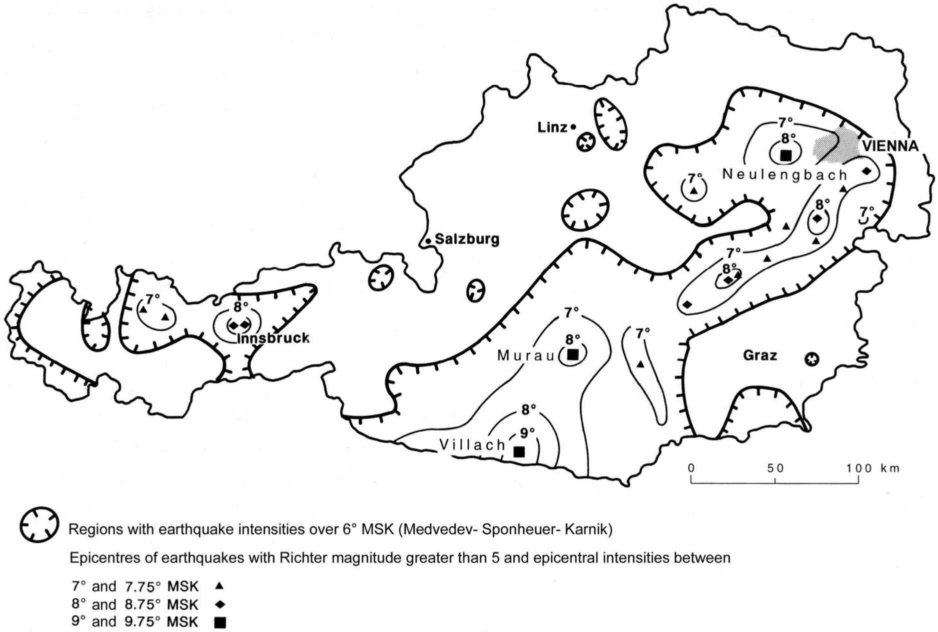

Fig.5. Areas liable to earthquakes in Austria, derived from maximum epicentral intensities of events between 1201 and 1982. Source: Fig.3.2 in FINK 1986

The most potentially dangerous earthquake zone in Austria is connected with the Peri-Adriatic lineament, on which the so far most damaging earthquake of central Europe occurred. This was the event of 25 January 1348 near Villach (Fig.5), with an epicentral intensity of X and M=6.5, similar to the Friuli event of 1976. Villach itself was partly destroyed by the tremors, and completely devastated by the consequential fires. The most sensational after-effect, however, was the huge landslide from the south slope of the Dobratsch. Together with the bursting of a lake formed behind the debris, it destroyed 17 villages, 3 castles and 9 churches. The year 1690 saw another event of almost equal magnitude, and another strong tremor hit the area in 1855.

A fourth slightly more dispersed group of earthquake foci extends along the northern border of the Alps, including Neulengbach (see Fig. 5); west-south-west from here lies Scheibbs (the epicentre is marked on the map by the symbol for epicentres with intensities of VII-VIII) and, farther on, Molln (south of Linz). There is debate over exactly where the tectonic line responsible is located. The three foci occur in the crystalline basement underneath the alpine

nappes on deep-seated disturbances which cannot be traced on the surface. DRIMMEL (1980) postulated that all three foci are associated with one and the same east-north-east to west-south-west trending lineament. TOLLMANN (1986) on the other hand connects the Neulengbach epicentre with the similar trending disturbance of the Mailberger fault system.
It should be mentioned that this scientific controversy generated considerable attention, because it became linked to the public discussion about Austria's first and (so far) last nuclear power station, for which a site north of Neulengbach had been chosen. In the end a plebiscite prevented the opening of the plant. For all that, scientists have never denied the seismic activity of the area, which lies in the impact zone of a dangerous 'Transversalbeben' epicentre. The stumbling block to this project had been created much earlier by the planning board, which completely overlooked the possibility of an earthquake hazard when making the first decisions. The hazard, though, is obvious, even if the actual alignment of the fault responsible is unknown.

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