Geomorphological evolution of an alpine area and its application to geotechnical and natural hazard appraisal in the NW. Rätikon mountains and S. Walgau (Vorarlberg, Austria)

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GEOMORPHOLOGICAL EVOLUTION OF AN ALPINE AREA
AND ITS APPLICATION TO GEOTECHNICAL
AND NATURAL HAZARD APPRAISAL

In the NW. Rätikon mountains and S. Walgau
(Vorarlberg, Austria)

(including map series at 1:10,000 scale)

A.C. Seijmonsbergen
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ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam,
op gezag van de Rector Magnificus,
Prof. dr. P.W.M. de Meijer,
in het openbaar te verdedigen in de Aula der Universiteit
Oude Lutherse Kerk, ingang Singel 411, hoek Spui,
op dinsdag, 16 juni 1992 te 12.00 uur,
door
Arie Christoffel Seijmonsbergen
geboren te Amsterdam
‘An ideal geomorphological map should not only describe and explain landforms based on the morphogenesis of individual landforms but also, more importantly, the explanations should be based on the relations between various landforms affected to varying degrees by numerous processes.’ (D.A. ST.ONGE 1981: Theories, paradigms, mapping and geomorphology. In: The Canadian Geographer Vol.XXV, No.4, pp.307-315).
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1. General introduction

General aim and structure of this study

Alpine and subalpine environments are commonly characterized by complex geological, topographical and geomorphological conditions, which are reflected in a variety of climatological zones and vegetational belts in the alpine mountain chain. Pleistocene glaciations have often modified the mountain landscape; this implies that many present landforms, materials and the processes that act upon them can be related to former conditions. Because increase of pressure on the land in alpine regions, man's activity is entering areas that are (potentially) endangered by landslide hazards, flooding or avalanches. Therefore, there is a growing need for earth-scientific data that can serve as a basis for planning. In Vorarlberg the need for this type of information on a detailed scale is especially felt in forest planning circles.

Detailed geomorphological inventories can provide information of both past and present geomorphological development. To a certain extent, prediction of future developments is also possible. Geomorphological maps contain a wealth of information that is ‘not directly visible’ for a common user; therefore derived maps, largely based on the geomorphological maps and supplemented with additional information, have been prepared for planning purposes.

Based on this approach, it is the first aim of this study to reconstruct the geomorphological history of the northern Rätikon Mountains and southern Walgau and to present this history in large scale 1:10.000 maps (Chapter 2). In the second place it is shown that the geomorphological understanding crystallized in these maps, is indispensable for a thorough appraisal of geotechnical units and natural hazards (Chapter 3 and 4). The methodology used is a further development of the work of SEIJMONSBERGEN AND VAN WESTEN (1986/1988) in the Hintere Bregenzerwald area.

This thesis is supplemented with an important Annex; in Annex I, the 1:10.000 geomorphological, geotechnical and natural hazard maps, are given. Chapter 2 also serves as explanatory notes to these maps. These notes comprise detailed geomorphological descriptions of each map sheet, as well as illustrations and specific information on relevant geomorphological topics. A German text of explanatory notes will appear as a separate annexe to the map sheets. Reference is often made to Annex I to avoid elaborate descriptions. An index with reference to map sectors should bridge the distance between the written section and the maps (Annexe V).

During the fieldwork periods (summers of 1988, 1989 and 1990) access to the road to Nenzinger-Himmel and local forest roads was kindly permitted by the 'Agrargemeinschaft Nenzing' and 'Beschling'. The printing of the coloured geomorphological maps and corresponding transparent overlay maps was financially supported by the Agrargemeinschaft Nenzing, the 'Land Vorarlberg' and the Alpine Geomorphology Research Group of the University of Amsterdam (AGRG).

Geographical setting

The northern Rätikon Mountains and the southern Walgau are part of Vorarlberg, the westernmost federal state of Austria, which is 525 km west of the capital city of Vienna (Fig.1). The study area covers the drainage basin of the Gamperdona and Galina valleys, small parts of the lower sections of the Samina and Brandner valleys, and a portion of the southern flank of the Ill valley between the village Frastanz (509m) and the Planetenwald area. The geographical co-ordinates lie approximately between 47°4’ and 47°13’ latitude and 9°38’ and 9°46’ E-longitude (see Fig.2). The area that is mapped at 1:10.000 scale measures almost 150km², of which 110km² politically belongs to the southern flank of the Ill valley between the village Frastanz (509m) and the Planetenwald area.

The rivers that drain the various valleys flow towards the north and northwest into the river Ill. NW of the city of Feldkirch the Ill flows into the river Rhine that here forms the state boundary between Austria and Switzerland (Fig.2).

The traditionally inhabited areas are situated on the alluvial fans and lower slopes of the Ill-valley below an altitude of ap-proximately 1200 m. Rounded hills and gentle slopes here determine the scenery. The presence of well-preserved (ice-marginal) terraces on the southern side of the Walgau is characteristic. Since the regulation of the river Ill and many of its tributaries by the 'Ill-Kraftwerke' company and the 'Wildbachverbauung' more land on the valley floor has become available. A tendency exists to abandon the higher situated pasture sites. This shift in landuse is increased by the post war change towards industry and tourism as a source of income. The abandoned sites are gradually occupied by (natural) forests.

The landscape within the southern valleys is determined by narrow V-shaped gorges and steep cliffs in the lower sections, and broader, U-shaped upper catchments. The waterdivides in the south along the Swiss border, reach elevations of over 2800m. The Gamperdona valley is not permanently inhabited. The settlement Nenzinger Himmel (‘heaven of Nenzing’, 1367m) is located in the basin-like upper valley section. Before 1950 it served as summer pasture.
ground and health resort for the rich. Since the nineteen fifties Nenzinger Himmel can be reached by car, which is permitted only to local residents. Tourists can be driven by a private bus service to and from these extraordinarily beautiful surroundings. The major valley systems in Vorarlberg are open to the northern windward side of the Alps; therefore a strong oceanic influence determines the climatic parameters (e.g.: 60% of the time moist oceanic western winds). In the valley floor region between Feldkirch and Nenzing the mean annual precipitation is 1000mm to 1250mm (see Fig.3).

Figure 1. Location of the study area
Figure 2. Location of the various map sheet areas and important topographical information
Mounting up the southern valleys these amounts rapidly rise to reach 1500-1700 mm near the divides. Most precipitation falls in summer (37.3%), a minimum exists during the winter period (18.2%). Autumn (22.2%) and spring (22.3%) are almost even (data from the village of Thüringen, Fig.2, northern Ill-valley, altitude 573 m). In the summer period most precipitation falls during severe thunder storms. The direct response of the local surface hydrology (sudden peak discharges) can lead to severe flooding in the downstream areas. The average snow height in the valley floor region is 27 cm near Feldkirch and 39 cm near Bludenz. In the Gamperdona valley itself data are not available; however, in Brand (altitude 1037 m) the average snowcover reaches a value of 79 cm. In the Lünersee Lake region an average of 287 cm is recorded. The present snowline is located at 2650 m (KELLER 1988); therefore the small Brandner glacier can maintain itself at the local plateau of the Schesaplana in the south of the area.

Previous studies

Detailed studies that deal with all the aspects of the geomorphology and the non-lithified sediments in the area are lacking. The early workers were mainly geologists from Switzerland (TRÜMPY 1916, VERDAM 1928, SCHUMACHER 1929 and others) and they paid little attention to the occurrence of geomorphological features. Verdam as well as Schumacher explained the distribution of crystalline erratics in the tributary valleys by Late-Glacial ice-flow from the Ill glacier into the tributary valleys. Late- or Early-Glacial written with capitals refers to the last (Würmian) glacial period in this work. One of the first geomorphological descriptions is from GUNZ (1914-1927), but maps were not included. He described some geomorphological developments of the 'Inner Walgau' and its tributary valleys.

AMPFERER (1908, 1936a/b/c) made observations on the distribution and origin of conglomerates in the Gamperdona valley and described a number of mass movement phenomena. He was one of the first workers who tried to explain the distribution of sediments in the Rätikon valleys and in Montafon with a glaciological model (AMPFERER 1936a). In his "Rätikon and Montafon in der Schlussvereisung" he concludes that the end-moraines of the local glaciers belong to an independant glaciation, the so-called "Schlussvereisung".

Various (sub)recent geological maps (ALLEMANN 1953/1985, HEISSEL et al. 1965/1967) give, in general, poor expressions of the glacial and ice-marginal phenomena; this often led to serious mis-interpretations of some Late-Glacial landforms.

Recent studies (JORDI 1977, HANTKE 1980, SIMONS 1985, KELLER 1988) that cover larger areas mainly focus on the glacio-geomorphological aspects of the landforms and its sediments. JORDI (1977) recognizes several deglaciation phases related to the Ill-glacier in the terrain between the Samina and Mengbach rivers. Short descriptions of situations near Gadon, Latzwiese-Bazulwald and the Galina river-out-let are given by BERTLE et al. (1979).

HANTKE (1980) describes glacio-geomorphological phenomena in the Gamperdona valley and pays attention to the conglomerates in the lower section of the Meng river.

SIMONS (1985) published a number of maps with geomorphological data covering the outlet areas of the Samina, Meng and Alvier rivers. Valuable descriptions of (of now vanished) exposures have been made by him. De GRAAFF (in OBERHAUSER 1986) defines some deglaciation phases in the area Latz, Gampelün, Frastanz and corresponding phases on the northern valley slope near Dums.

A number of glacial-geological maps have been published by KELLER (1988) in which he attempts to subdivide the deglaciation history of the region. He made special reference to the so-called 'Weissbad' phase. A series of exposures in the Gamperdona valley have been documented by him.

Illustrations and descriptions of the geomorphological development of the Walgau and its tributary valleys are given by DE GRAAFF, RUPKE and SEIJMONSBERGEN (in: SEUFFERT (Ed.) 1989). DE GRAAFF presents a model of glacial intervention in fluvial systems that can be applied to the area (chapter 2).
Geology

In this paragraph a brief outline of the geological-tectonical setting of Vorarlberg and the fieldwork area is given. Some regional knowledge of the geology is necessary because:
- The position of the major nappe units and their geological structures is often reflected in the morphology,
- It explains a number of small and large scale geomorphological processes that occur in certain lithological zones,
- The zonation of various rocktypes that exist in Vorarlberg, allows for a detailed reconstruction of the late-Pleistocene glacier network (KRASSER 1936, HAAGSMA 1974),
- Information adopted from several existing geological maps (ALLEMANN 1985, HEISSEL et al. 1965/67), has been used in the geotechnical maps (Annexe I).

When necessary, more detailed descriptions of the various formations will be given in the coming chapters (see also Annexe IV).

The S-N trending Rhine valley is not only a state boundary, but also forms the approximate geological separation between the Western- and Eastern-Alps (LEMOINE, 1978). The Western-Alps are controlled by tectonic units of the External or Helvetic nappes. Theses nappes are composed, in general, of shallow marine sedimentary sequences with crystalline sequences at their base. In Vorarlberg the Helvetic Säntis nappe is a narrow stretch along the northern alpine boundary and disappears further to the east. The internal part (Penninic Zone) of the Western-Alps is mainly represented by low- to high-grade metamorphic rocks. In central Vorarlberg however, it is a sedimentary sequence belonging the so-called Vorarlberg Flysch.
The Eastern Alpine unit (Austro-Alpine Nappe) is subdivided into a Lower- and an Upper East Alpine unit. Within the Upper East Alpine unit a sedimentary and a crystalline part can be distinguished. The study area is located just east of the Rhine valley, were the two major geological alpine regions, the Western- and Eastern Alps, meet. Thus, in a geological sense, features of both regions occur in the fieldwork area.

Pre-quaternary geology of Vorarlberg and the fieldwork area

The southern Walgau and the northern Rätikon have been the focus of many geological workers (amongst others: TRÜMPY 1916; ARNI 1926; VERDAM 1928; AMPFERER 1934; RICHTER 1958; HEISSEL et al. 1965/1967; KOBEL 1969; ALLEMANN 1953, 1985). A review of the geology of Vorarlberg and adjacent areas was recently given by OBERHAUSER (1986). Figure 4 shows the tectonic units in the wider surroundings of Vorarlberg. From the Alpine foreland penetrating deeper into the Alps (from N to S), the following parallel WSW to ENE trending elongated structural units are successively crossed (KRASSER 1936, RICHTER 1956, OBERHAUSER 1986):
- The Molasse Zone or basin is composed of clastic Tertiary sediments derived from the uplifted mountains. The Molasse is separated from the Alps by a tectonic contact along the line Altstätten-Dornbirn-Egg,
- The neighbouring overthrusted Helvetic Säntis nappe is mainly composed of Cretaceous formations. The southern boundary roughly runs from the city of Feldkirch to the Hoher Ifen peak in the NE,
- The subordinate Liebensteiner and Feuerstätter nappes, that overlie the Helvetic, are exposed as a narrow zone to the north and south of the Helvetic nappe,
The Penninic 'Vorarlberg' Flysch covers the central part of Vorarlberg. It is subdivided into a northern and a southern Flysch zone. Relicts of Flysch formations, known as the northern Flyschzone, have been preserved as erosional outliers in some areas, e.g. near Dornbirn, on the Helvetic nappe. The northern part of the fieldwork area is underlain by the southern Vorarlberger Flysch (see Fig.5). The age of the Flysch covers the Upper Cretaceous to the Eocene. Its southern boundary runs just north of the Drei Schwestern peaks (see Fig.1), eastward to the village of Nenzing and then further ENE into the Grosses Walser valley. In general, the Flysch strata dip to the south and southeast; locally, intensive microfolding and faulting is common (RICHTER 1969, 1978). In the fieldwork area the dominant series belonging to this nappe unit are the Plankner-Brücke Formation, the Piesenkopf Formation and the competent Reiselsberger Sandstein Formation. The Penninic unit is stacked as the Falknis and Sulzfluh thrust system along the state boundaries with Liechtenstein and Switzerland (RING et al.1989). The formations here consist of massive limestones, breccia, marls (Couches Rouges) and Flysch rocks. The Flysch nappe is overthrusted from the south by the next major structural unit, the calcareous part of the Upper East-Alpine nappe (German: Kalkalpen) that covers the larger part of the study area.

The Flysch and East-Alpine nappes are separated in theory, by the Arosa-Zone, that is squeezed in between the overlying Austro-Alpine nappes and the underlying Middle Penninic nappes (RING et al.1989). The Arosa-Zone served as a decollement zone during the overthrust process and is discontinuously exposed in small belts along the Flysch-East-Alpine contact. The Arosa-Zone is considered to belong to the Penninic Zone by some authors (e.g. TOLLMANN 1976, ALLEMANN, 1985). The Arosa-Zone contains a number of imbricated slices of both Penninic and Austro-Alpine origin (RING et al. 1989). A wide scale of rock types (shales, quartzites, breccias, ophiolites and serpentinites) has been found, but complete sequences of the Arosa-Zone have not been described.

The calcareous part of the East-Alpine nappe in the Rätikon belongs to one major nappe: the Lechtal-nappe (see fig.5). Several dismembered slices or imbricated structures (in German: 'Schuppen' or 'Schollen') can be recognized within this nappe (KOBEL 1969, RICHTER 1958, ALLEMANN 1985). The central part of the study area is dominated by the large Fundl-Kopf – Alpila-Kopf slice. Parts of the underlying Arosa-Zone may have been dragged upwards and are now found at boundaries between the various slices (CZURDA & JESINGER 1982). Pinched and broken anticlinal structures are often accompanied by active diapiric intrusions of the Arosa-Zone Formations.

The most important Triassic formations of the Lechtal-nappe are Muschelkalk limestone, Partnach-Schichten, Arlberg-Schichten, Raibler Formation, Hauptdolomit Formation and Kössener Schichten. Especially the Hauptdolomit Formation is widely distributed and forms impressive massive and is typically related with huge scree cones and debris-fans.

The fact that rocks of the Raibler Formation and the Arosa Zone Formation are often mixed up is, according to KOBEL (1969), related to differential movement of the Hauptdolomit Formation on local decolle-ment zones within the Raibler Formation. This process intensified the mixing up of rocks and caused stacking of gypsum at frontal positions. A more or less continuous profile of the Raibler Formation was described near Klamperschrofen (TRÜMPY 1916, VERDAM 1928).

KOBEL (1969) mentions three main reasons that determine the characteristic tectonic relations in the western part of the Rätikon:
1) the limited thickness of the Upper East-Alpine nappe relative to its horizontal extension,
2) the presence of incompetent series of the Raibler Formation (e.g. gypsum beds) in the lower part of the Upper East-Alpine nappe,
3) the underlying basement formed by the incompetent sequence of the Arosa zone.

The SE-part of the Austro-Alpine nappe in Vorarlberg, the Silvretta nappe, is composed for the greater part of metamorphic rocks, such as amphibolites, micaschists, para- and orthogneisses and granitic rocks. The Silvretta Mountains form a part of the upstream section of the Ill-river and served as the provenance area for the Ill-glacier. Crystalline erratic fragments can be found in the non-lithified deposits and conglomerates in the northern parts of the

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**Figure 5 (continued): legend to the geology of the fieldwork area.**

<table>
<thead>
<tr>
<th>Tektonische Einheiten</th>
<th>Penninicum</th>
<th>Quetschzone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oberostalpin Lechtal-Decke</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Drei Schwestern-Schuppe</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Heubühl-Schörnb-Schuppe</td>
<td></td>
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<tr>
<td>3</td>
<td>Augstenberg-Schuppe</td>
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<td>4</td>
<td>Gorgion-Schuppe</td>
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<tr>
<td>5</td>
<td>Fundelkopf-Alpila-Schuppe</td>
<td></td>
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<tr>
<td>6</td>
<td>Zima-Schesaplana-Schuppe</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Fresscolat-Kristallop-Schuppe</td>
<td></td>
</tr>
</tbody>
</table>

**Penninic Einheiten**

| Oberostalpin Lechtal-Decke |
|-----------------------------|-----------------------------|
| 1 | Drei Schwestern-Schuppe |
| 2 | Heubühl-Schörnb-Schuppe |
| 3 | Augstenberg-Schuppe |
| 4 | Gorgion-Schuppe |
| 5 | Fundelkopf-Alpila-Schuppe |
| 6 | Zima-Schesaplana-Schuppe |
| 7 | Fresscolat-Kristallop-Schuppe |

**Vorarlberger Flysch**

- The Flysch and East-Alpine nappes are separated in theory, by the Arosa-Zone, that is squeezed in between the overlying Austro-Alpine nappes and the underlying Middle Penninic nappes (RING et al.1989). The Arosa-Zone served as a decollement zone during the overthrust process and is discontinuously exposed in small belts along the Flysch-East-Alpine contact. The Arosa-Zone is considered to belong to the Penninic Zone by some authors (e.g. TOLLMANN 1976, ALLEMANN, 1985). The Arosa-Zone contains a number of imbricated slices of both Penninic and Austro-Alpine origin (RING et al. 1989). A wide scale of rock types (shales, quartzites, breccias, ophiolites and serpentinites) has been found, but complete sequences of the Arosa-Zone have not been described.

- The calcareous part of the East-Alpine nappe in the Rätikon belongs to one major nappe: the Lechtal-nappe (see fig.5). Several dismembered slices or imbricated structures (in German: 'Schuppen' or 'Schollen') can be recognized within this nappe (KOBEL 1969, RICHTER 1958, ALLEMANN 1985). The central part of the study area is dominated by the large Fundl-Kopf – Alpila-Kopf slice. Parts of the underlying Arosa-Zone may have been dragged upwards and are now found at boundaries between the various slices (CZURDA & JESINGER 1982). Pinched and broken anticlinal structures are often accompanied by active diapiric intrusions of the Arosa-Zone Formations.

- The most important Triassic formations of the Lechtal-nappe are Muschelkalk limestone, Partnach-Schichten, Arlberg-Schichten, Raibler Formation, Hauptdolomit Formation and Kössener Schichten. Especially the Hauptdolomit Formation is widely distributed and forms impressive massive and is typically related with huge scree cones and debris-fans.
fieldwork area and the lower sections of the Samina, Galina, Gampbach and Gamperdona valleys. These will be discussed in more detail in chapter 2.

The younger Quaternary deposits have been interpreted on the basis of a combined sedimentological and geomorphological approach. These deposits are often related to their depositional environment and can be subdivided according to their sedimentological and structural characteristics (DE JONG 1983, DE GRAAFF et al. 1987). The impact of (repeated) glaciations is clearly reflected in the wide variety of non-lithified materials, ranging from ice-dammed lake sediments (varved-like clays, deltaic sediments) to ablation deposits. The interaction of fluviolacustrine and glacial processes led to the formation of some specific deposits in the lower sections of tributary valleys of the southern Walgau (DE GRAAFF 1984, DE GRAAFF in SEUFFERT, Ed. 1989).

Periglacial deposits are represented by numerous (fossil) rock-glacier complexes. Post-glacial fluviatile and mass movement processes may have altered or covered these deposits and created their own landforms. The spatial distribution and origin of the non-lithified deposits will be dealt with in detail in the next chapter. This detailed knowledge will serve as a basis for the geotechnical and hazard zonation applications discussed in chapter 3 and 4.
2. Geomorphology

The geomorphological legend

Any geomorphological map is based on its legend. A legend should be as simple as possible for easy handling in the field and later use (see also GRAY, 1981). The legend that is used here was developed in Vorarlberg for alpine areas, at scale 1:10.000 (RUPKE & DE JONG 1983, DE GRAAFF et al.1987, based on earlier work of SIMONS 1985). A short introduction to the legend is given here; for detailed descriptions is referred to the above mentioned publications. The legend in its standard form and its step by step construction is given along with the geomorphological maps in annexe I.

Four qualities of information are incorporated:
1) Drainage (in blue),
2) Morphography/morphometry; the morphographical and morphometrical lines and symbols are combined to constitute the framework of form and relief and are not depending on genesis,
3) Non-lithified materials (the colours depend on the geomorphological environment in which they were deposited),
4) processes/genesis; a distinction is made by means of colours:
   - blue is used for hydrography and karst related forms,
   - orange is used to indicate subglacial, ice-marginal erosive and accumulative forms and related materials,
   - brown colours indicate fluvial erosive forms, slope processes and related materials,
   - olive-green is used to indicate ice-marginal fluvial and glaciofluvial landforms and related materials,
   - green for recent fluvial materials and deposits
   - black is used to indicate all numerical values as well as man-made features.

Some advantages of the use of coloured lines and symbols over a system depicting full colour bodies are:
- The possibility to map complex (polygenetical) landforms without introducing new symbols,
- To indicate time relations that exists between morphological elements. Often it is possible to infer from the map whether the activity of a certain mass movement unit is relatively younger, older or contemporaneous with other morphological elements. This proceeds mainly from the fact that boundaries of morphological elements are, in most cases, mapped in the colour of the youngest process,
- The possibility to indicate the direction in which some (former) processes act(ed). This allows, for instance, the reconstruction of former drainage or ice-flow patterns,
- The use of the material symbols within the geomorphological map enables indication of the relative thickness and of the constituent material and the intensity of the process. For instance, a scree cone determines the shape of that landform and the production of material is (or has been) relatively large, whereas the same type of scree material can give a surficial cover over a glacially scoured slope in bedrock. In that case production has been moderate and the thickness is limited.

The mapping procedure

Geomorphological mapping at 1:10.000 scale in mountainous terrain with a legend based on lines and other symbols is a time consuming affair. The smallest (to scale) mapping unit is approximately 0.25 cm². However, depending on the accessibility, complexity and weather conditions a total area of 0.75 to 1km² per day can be surveyed. On the other hand, since each discontinuous boundary in the landscape is documented, translation of the geomorphological map into a derived map with continuous boundaries is a relatively rapid procedure.

Three stages in the preparation of the geomorphological maps can be distinguished:
- Pre-field stage; in this phase the use of aerial photographs is indispensable. An index with numbers of the panchromatic and false-colour infrared photographs is listed in annexe II. From the aerial photographs an interpretation was made of selected subareas. The availability and combination of 1:18.000 panchromatic (1951) and 1:10.000 scale false-colour infrared photographs (1984) proved very useful, especially in complex mass movement areas.
- Field stage; during the field stage a 1:10.000 contourline basemap (contourline interval 20 m) is used on which the geomorphology is drawn using a black pencil. An ultimate decision on boundaries, proceses/genesis and materials is taken, as much as possible, in the field. Very helpful, especially for locational problems, were the 1:5.000 scale orthophotomaps with contourline overprint. In the field stage the aerial photographs are regularly consulted. Three approaches were used in the field:
  1) Geomorphological traverses; along selected sections the geomorphology was intensively documented. Next, the adjacent slopes and surrounding area could be surveyed with less intensive visits and more support from the aerial photos-graphs,
  2) Areal morphological mapping; it is experienced that, even with good quality air-photo's, some (mainly forested) areas can only be approached in the field. A pre-field air-photo interpretation of the complex Eckskopf-Neuwald area for instance (map sheet Gampberg, sector E/F4-5), proved unsatisfactory; there was hardly a link with the actual field situation,
3) Mapping 'at distance' using aerial photographs. Inaccessible terrain is viewed from a distance in the field. If possible terrain sketches are made. The final drawing is based on both field observations and aerial photographs. In the course of the research the knowledge gained in the field enables one to extract more information from the aerial photographs and increase the quality of the work.

Essential in the mapping procedure is the recognition and indication of non-lithified materials. If this is consequently done, little difficulties will arise when geotechnical units have to be delineated. Criteria that are used here to distinguish groups of sediments are (partly after DE GRAAFF et al. 1987): process/genesis at the highest level, depositional environment and/or textural differences on a lower level. These important criteria are of benefit when constructing the geotechnical map. In figure 7 a general key is shown that was used in the field during the mapping procedure to define the type of sediments that occur in the southern Walgau and the northern Rätikon mountains.

<table>
<thead>
<tr>
<th>ENVIRONMENT</th>
<th>MAIN SEDIMENTOLOGICAL AND STRUCTURAL CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Alluvial, mainly fluvial</td>
<td></td>
</tr>
<tr>
<td>1. valley floor deposits</td>
<td></td>
</tr>
<tr>
<td>2. alluvial fan dep. incl.</td>
<td></td>
</tr>
<tr>
<td>3. streambed deposits</td>
<td></td>
</tr>
<tr>
<td>II. Slope environment incl.</td>
<td></td>
</tr>
<tr>
<td>1. solifluxion deposits</td>
<td></td>
</tr>
<tr>
<td>2. debris-flow / mudflow deposits</td>
<td></td>
</tr>
<tr>
<td>3. scree deposits</td>
<td></td>
</tr>
<tr>
<td>4. rockfall deposits</td>
<td></td>
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<tr>
<td>5. protalus rampart deposits</td>
<td></td>
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<tr>
<td>6. dolomitic breccia</td>
<td></td>
</tr>
<tr>
<td>III. Glacial environment</td>
<td></td>
</tr>
<tr>
<td>A. ice-marginal</td>
<td></td>
</tr>
<tr>
<td>B. subglacial</td>
<td></td>
</tr>
<tr>
<td>1. glacioluvial deposits</td>
<td></td>
</tr>
<tr>
<td>2. lacustrine deposits</td>
<td></td>
</tr>
<tr>
<td>3. lacustrine lake bottom</td>
<td></td>
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<tr>
<td>4. ablation deposits</td>
<td></td>
</tr>
<tr>
<td>C. older deposits</td>
<td></td>
</tr>
<tr>
<td>D. Periglacial environment</td>
<td></td>
</tr>
<tr>
<td>1. rock-glacier deposits (fossil)</td>
<td></td>
</tr>
<tr>
<td>V. Other</td>
<td></td>
</tr>
<tr>
<td>1. peat or bog</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7** General key used in the field during the mapping of the geomorphology

An interesting issue is the widespread occurrence of complex valley fill deposits and conglomerates in vertical sections that can hardly be depicted in mapform; the lower fluvial sections of tributary valley systems (Galina-, Gamp- and Gamperdona-valley, see also DE GRAAFF in SEUFFERT, Ed. 1989). The ratio between the map- and terrain
The geomorphological map

The map itself as a database is a tool for storing, arranging, transmitting and analysing geomorphological data. The occurrence of a single element in the terrain is often insufficient to explain its genesis and material composition. Especially in (formerly) glaciated mountainous terrain, where a wide variety of landforms exists, the relation between various landforms and their development in time is a clue for the classification of the landscape. Therefore, 'white spots' on a map should be avoided.

Most large scale geomorphological maps from the last 15 yrs. that deal with high alpine environments use a set of coloured line and point symbols in their legend (e.g. KIENHOLZ 1977, BARSCH et al. 1983, PANNIZA 1983, NICOD 1987, PELLEGRINI 1985). An example of a black & white geomorphological map in the French Alps is the map of SALOMÉ & BEUKENKAMP (1988).

To a certain extent a geomorphological map is descriptive. However, it cannot be avoided that personal views and use of current geomorphological models enter the mapping procedure. The resulting map is therefore a combination of independant observations, e.g. morphometrical measurements as well as interpretative elements, often concerning the morphogenesis of a certain landform.

The morphological map displays the present situation; in this form it can be used to unravel and reconstruct the sequence of events that took place in the past. To a certain extent, future developments can be fore-casted.

Glacial history and its relation to the distribution of materials

The region of the Walgau is characterized not only by its terrace landscape, especially between Nenzing and Feldkirch, but also by the occurrence of valley fill deposits, often with a complex genesis. These deposits and their spatial distribution can be explained by the development and decay of the glaciers, their ice-flow patterns through time and the impact this exercised on the local geomorphological conditions.

The Ill-valley has its upper catchment in Montafon, the highest area in the southeast of Vorarlberg, and is underlain by crystalline basement (fig 4.). The occurrence of crystalline erratics distributed in the lower sections of the tributary valleys of the Walgau, that are underlain by sediment series themselves, (HEISSEL et al.1967) is used as proof that these valleys were penetrated by the Ill-glacier (VERDAM 1928, SCHUMACHER 1929, ALLEMANN 1953/1985, HEISSEL et al. 1967, JORDI 1977, KELLER 1988, DE GRAAFF 1984, DE GRAAF in: SEUFFERT Ed.1989).

Detailed studies on the preserved sediment relicts prove that penetration not only took place during an early-glacial phase, but also occurred in a late-glacial phase. In the Galina and Gamperdona- valleys sedimentological and morphological evidence that supports this model is preserved and was surveyed. The results of regional investigations in Vorarlberg by DE GRAAFF (in: SEUFFERT Ed.1989), particularly in the Walgau, led to the development of a model of glacial intervention in fluvial systems. The most important elements of this model are summarized below:

- Trunk glaciers (Ill- and Rhine glacier) develop first from the highest divides and block and partly occupy the ice-free lower V-shaped sections of tributary valleys,
- These valley sections get filled with sediments of glacial, glacio-lacustrine and fluvio-deltaic origin (early-glacial accumulation phase)
- During the Pleniglacial Phase these sediments are subglacially stored; a later developed (lower source area) and fully grown tributary glacier becomes dynamically adjusted to the surface heights of the trunk glacier controlling the outlet of tributary ice (consolidation phase),
- During the late-glacial phase (temperature increase) the tributary glacier melts back rapidly and ice from the trunk glacier flowed again into the tributary valley. Late-glacial and post-glacial redistribution of sediments takes place (erosion phase).

With small modifications this model can be applied, especially to the areas covered by mapsheets Gampberg and Fundl-Kopf and is thus used in the recognition and distribution of sediments on the geotechnical maps.

Since the older deposits and complex valley fill deposits could not be represented on the geomorphological map, they will be dealt with in the next section.
Photo 1. Upstream view from the Büderhöhe outlook into the Gamperdona valley; in this stretch the gorge has been fully developed in conglomerates. The Mengbach has incised on the contact of Older (left) and Younger (right) Conglomerates, that reflect two major phases of fill, separated by an important erosion phase.

Photo 2. Vertical wall exposing valley fill deposits in the gorge of the Mengbach, seen from the Büderhöhe outlook (map sheet Gampberg, H3-4), showing deltaic sequences in the "Younger Conglomerate". Fore-set beds can easily be recognized, whereas the grass-covered conglomerate rims often correspond to the subhorizontal top-set beds.
Relations between various processes of fill by local and remote glaciers

The most striking valley fill deposits in the lower valley section of the Gamperdona and Gampbach valleys are immense series of conglomerates that now build the flanks of the steep gorge of the Mengbach. These deposits have traditionally been interpreted as interglacial or interstadial deposits (AMPFERER 1908, 1936; HEISSEL et al. 1967; JORDI 1977; ALLEMANNN 1985). In places, the dimensions of the valley fill reach more than 150m, e.g. near the confluence of the Gamphbach and Mengbach (map sheet Gampberg, sector D/E4 and photo 2). It can be observed at many places that the already existing fluvial gorges of the Meng- and Gampbach became filled with these sediments. AMPFERER (1908) and WEHRLI (1928) explained the occurrence of similar looking deposits, the 'Bürser Conglomerate' near the mouth of the Brandner valley, by tectonic movements. Sedimentological structures, geomorphological setting and petrographical composition clearly indicate a relation to glacial blocking of the tributary valleys as will be discussed below. The present courses of the Meng- and Gampbach are still cutting into these conglomerates at several locations, proving the limited degree of postglacial rejuvenation (see also DE GRAAFF in: SEUFFERT Ed. 1989). Similar relationships within older deposits were found in the gorge of the Galina valley. It appeared that at least two generations of conglomerates occur; DE GRAAFF (pers. comm.) proposed the term 'Older' and 'Younger' Conglomerate for these deposits. An important contact can be observed along the road Nenzing-Nenzinger Himmel.

Contact of the older conglomerate (O.C.) and younger conglomerate (Y.C)

The exposure is located along the Gamperdonaweg 120 m S. of the road tunnel at approx. 855 m altitude (map sheet Gampberg, sector G3). The situation is schematically represented in figure 8. The contact zone is several tens of metres high. It is evidence of an important erosional phase after the deposition and cementation of the older conglomerate. De GRAAFF (Ed. 1989) suggests an interstadial or interglacial phase for this erosional phase. The general appearance of and differences between the older (O.C) and younger (Y.C.) conglomerates within the Gamperdona valley can be summarized as follows:
- The older conglomerate exists of (sandy) gravels and is predominantly subhorizontally layered,
- The younger conglomerate is composed of sediments that were deposited in various depositional environments. They are built largely of glacio-lacustrine sequences: deltaic fore- and topsetbedding as well as bottomset-deposits. These may alternate with fluvial valley fill deposits. Ice-contact deformation structures and even dead-ice structures may be present in (former) contact zones,
- The composition of the O.C. is dominated by local fragments,
- In both the O.C. and the Y.C. the individual local fragments are for the greater part subrounded to subangular. The erratic fragments that are predominantly found within the basal lacustrine layers are, without exception, angular to very angular,
- The cementation by CaCO₃ in the O.C. is, in general, stronger than in the Y.C.; therefore it appears as massive exposures, compared to the younger conglomerates. Within the latter non-cemented layers (lacustrine silts, clays and sands and washed gravels) can be present. They can cause serious slope instability problems,
- Sorting of particles within layers is far better in the Y.C.,
- The permeability of the Y.C. is, in general, less than of the older conglomerate.

A striking feature along the contact of the O.C. and the Y.C. is the occurrence of downward curving layers; this is especially clear in the silty/clayey bottom-set beds. This downward curving, which is the result of post-depositional consolidation of the fine-grained sequences within the Y.C., amounts to 2.5-3m. over a horizontal distance of 2m. If the assumption is made that these lacustrine deposits can be compressed to 70 % of their original volume, then at least 10 m of consolidated sediments underlie this sequence. The following interpretation is given:
- There was a gradual fill with mainly fluviatile deposits in the already existing lower valley section of the Mengbach; this was caused by a gradual raise of the erosion base near the valley outlet due to a blockage of the advancing Ill-glacier in the Ill-valley,
- Cementation of the valley fill took place by CaCO₃; this could have started already during the deposition. This process can be observed in recent deposits in the Gampbach valley,
- Renewed incision of the Mengbach in the O.C. (more than 100 m) took place after melting-down of the blocking Ill-glacier system near the mouth and created a gorge that for a large part developed in conglomerates,
- A second important phase of blocking by the Ill-glacier, this time more rapidly, led again to blockage of the gorge of the Mengbach. Well preserved lake-bottom deposits at different levels (between 700 and 1150 m in Gamperdona-valley) reflect different lake levels; the highest lake levels are recorded valley-inwards, because of the subsequent penetration of the Ill-glacier from N. to S. into Gamperdona-valley.
- The reconstructed 1000m lake level, based on the occurrence of of the younger conglomerate, has been entered in figure 9,
- Cementation with CaCO₃ of especially the coarse-grained top- and foresetbeds and fluvial deposits, took place during and also after deposition. In some places it seems that the topset-beds are less strongly cemented than the foreset-beds,
Photo 3 A/B. Contact of the Younger and Older Conglomerate (see text)

Figure 8: The Vertical contact of the older and younger conglomerate (road Stellfeder-Nenziger Himmel (map sheet Gampberg, G3).
A new major phase of incision of the Mengbach into the Y.C. took place and has not reached the original depth of the fluvial valley yet. It is observed at several places, e.g. near the confluence of the Mengbach and the Gampbach, that these rivers are still eroding into the conglomerates. The depth of the incision in the Y.C. is in the order of 150 m near the confluence of the Mengbach and the Gampbach. Therefore it is unlikely that this incision is caused merely by post-Würmian erosion. This is supported by abundant contacts of the O.C. and the Y.C. with younger (Würmian) till deposits of the Ill-glacier. Different types of deposits from the youngest phase of fill such as deltaic deposits, fluvial deposits and subglacial till, can overly the conglomerates. These younger deposits are non-, or partly cemented, so they can, in most cases, be separated from older deposits, although non-cemented layers can occur in the Y.C.

Photo 4 and explanatory diagram: Contact of the older conglomerate with the former valley slope developed in Flysch rocks (Planckner-Brücke Formation) along the road Stellfeder-Nenzinger Himmel.
Figure 9. The former extent of the 1000 m lake level, as reconstructed from exposures in the younger conglomerate in the lower section of the Gamperdona-valley. The approximate position of the Ill-glacier has been indicated.

At several places subglacial till overlies the Y.C. and the O.C. This illustrates that the conglomerates were formed in an early glacial or interstadial period. The minimum age of the Y.C. is therefore Early Würmian. The conglomerates near the village of Bürs that seem to be deposited as a raised alluvial fan (DE GRAAFF & RUPKE, personal commun.), is underlain by a fresh looking lodgement till (AMPFERER 1908) and is therefore older than Würm maximum.

The reason why subglacial till has not been found below the O.C. or the Y.C. is the difference morphological positions in which they were deposited. The Gamperdona conglomerates are confined to a fluvial valley section that was (most likely) never occupied by a glacier before deposition of the valley fill deposits took place. The climatic implications are complex to unravel; it seems likely that the the O.C. was deposited during a relatively longer period of penetration of the trunk glacier into the Gamperdona valley compared to the Y.C. Whether this can be coupled to the speed of climatic change is questionable, because other factors, e.g. the availability of sediment, are also involved.

Sediments along the 'Hocheck'-road

The advancing Ill-glacier was responsible for the building of the present conglomerates. Its advance can also be 'read' from other non-conglomerate exposures. These deposits are either characterized by overlying subglacial till or by strong compaction of the fine-grained sequences. This pre-consolidation, which is caused by the weight of the overlying ice-masses, can be used in the field to determine whether these deposits have been overridden by ice (VAN GELDER et al.1990). A section along the so-called 'Hocheck'-road illustrates the changes in depositional environment and petrographical composition. The geomorphological situation and the position of the exposures described below are outlined in figure 10.

The 'Hocheck'-road is a small forest-road taking off from the road Nenzing-Stellfeder at approximately 700m. The road is constructed along this contourline into a NW direction for 250m, and then sharply bends to the SW over a distance of 300m and eventually to the S. The latter trajectory follows the topographical knick between the actual gorge of the Mengbach and the less steep glacially determined valley slopes for 350m (map sheet Gampberg, sectors E/F1-2). Starting from the southern end, exposure 11F is located 125 m before the dead end. Exposure 11F at approximately 720m elevation (Fig.11) shows a sequence of fine-grained sediments at least 2.5m thick. A tendency of coarsening upward exists. These lacustrine sediments exist of alternating fine sandy, silty and clay-rich laminae. The degree of compaction of, especially the clayey sequences suggests that a certain postdepositional load (ice- and/or sediment body) compressed the sediments. They are low energetic lake bottom deposits overlain by layered gravels (ø<10 cm). The petrographical composition is in favour of a local sediment source, in this case a former course of the Mengbach river at this 700 m level. Within these gravels deformation structures can be seen; they bend downwards into the underlying fine-grained sediments. This is probably caused by post sedimentary processes. In this case tensional forces that developed after the (renewed) incision of the Mengbach in this valley fill deposit led to the development of fissure systems within the fine-grained deposits.

In exposure 11E a fifteen metres wide and four metres high series of thinly laminated silts and clays in the lower section and dominantly fine to medium coarse sands in the upper part is exposed (coarsening upward). The complete sequence, especially the silty fractions, is characterized by a high degree of compaction. They are lacustrine deposits that can be regarded as the lateral equivalent of those in Fig. 11F. Deformation in these sediments has led to a network of minor wedge-like faults.

In exposure 11D a partly-cemented gravel deposit was found below the lateral equivalent of the lacustrine deposits of 11E. This may be part of the younger conglomerate. The overlying fine-grained lacustrine deposit is faintly layered and developed here as a sandy/silty coarsening upward sequence.
A structureless deposit with uncertain contacts is interpreted as a slope deposit. Small silt and clay lenses, a few mm wide and some cm long are present; the matrix is irregularly brownly weathered. Crystalline erratic cobbles were found, and are probably derived from upslope areas.

Figure 10. The geomorphological situation (at scale 1:10,000) in the vicinity of Stellfeder (map sheet Gampberg, F/G1-2-3) and the location of the exposures as shown in figures 11 and 12.

Exposure 11C shows the erosive contact in compacted lacustrine deposits and overlying gravels. These cross-bedded subrounded to rounded (sandy) gravels contain substantial amounts of crystalline erratics. This general description also applies to the exposures 11B and 11A. In 11B two diamicitic layers of 20-30 cm thick with a sandy/silty matrix are enclosed between subhorizontally bedded gravel deposits; these were interpreted as debris flows. In exposure A the sequence can be continued with several erosional surfaces within the fluvioglacial gravel deposits. On top a dense subglacial till covers the section. Samples 81/83 and 82 were taken from the fluvioglacial gravels and subglacial till respectively. The petrographical composition strongly suggests a remote provenance area and depositional direction from the Ill valley (see Annexe IIIB for petrographical composition).

Based on horizontal and vertical relationships the following succession of environmental changes can explain the sequence as exposed along the 'Hocheckweg':

A glacier in the Ill-valley blocked the outlet of the Mengbach to a level of approx. 700 m. A narrow ice-dammed proglacial shallow lake came into existence within the gorge-like downstream section of the Mengbach. Gradually the Mengbach dumped its sediments in this lake. The fine-grained sediments in exposures 11F, 11E, 11D and 11C reflect the lake-bottom sediments that correspond to this situation. Corresponding coarse grained sediments of the Mengbach (either deltaic and fluviatile) were deposited 1km to the south, which was the approximate contemporary upstream lake extension. The (sandy) gravels of local origin in exposure 11F could correspond with a fluviatile fase developed during a (temporarily) lower lake level. It is uncertain if this is caused by a temporary lowered ice-surface or that possible subglacial drainage of the lake was involved. The absence of erratic (Ill-derived) material in this position supports the idea to place these gravels in an early glacial sequence.

In a further development, the influence of the penetrating Ill-glacier became more pronounced. Fluvio-glacial or fluvio-lacustrine materials were deposited in an ice-marginal proglacial position and characterize this period. The occurrence of debris flow deposits that could be generated from a nearby ice front also suggest an advancing system. The coverage by a dense subglacial till indicates that the Ill-glacier was responsible for the deposition and overriding of the fluvio-glacial and lacustrine sediments at this location.

The gravel pit of Stellfeder is located just above these exposures at approximately 740 m (map sheet Gampberg, sector D2). Gravels and sands have accumulated in ice-marginal fan-terraces of Late-Glacial origin. Equivalent deposits have been preserved on the western side of the Gamperdona valley outlet near Bazulwald and surroundings (see map sheet Gurtis, sector F5).

Since absolute dating of the described sequence is still lacking, its position might indicate an age older than Würm-maximum.
Sediments along the 'Haseltuala'-road

All the deposits that are interpreted as older than Würm maximum are, morphologically seen, situated in erosional and denudational landscapes. Detailed reconstruction on former positions of the glacier during these periods is therefore difficult. KELLER (1988, Bd. I, pp. 115, Bd. II, pp. 192-195) tried to use a series of exposures along a forest road at approx. 885m. for the reconstruction of Late-Glacial ice-marginal deposits of the oscillating Gamperdona glacier. However, the bulk of the exposures along this road are interpreted here as older than Würm maximum. The road is located in the NE part of geomorphological map sheet Gampberg (sector E2-3) near the confluence of the Gamperdona- and Ill-valleys (see Fig. 10). At approx. 885m the road takes off from the Nenzingerbergweg and can be followed for 660m to the south.

Figure 11. Exposures along the 'Hocheck' forest-road, illustrating early-glacial penetration of the Ill-glacier into the Gamperdona-valley. The location of the individual exposures has been indicated in figure 10.
The road is constructed on the eastern valley slope of the lower section of the Gamperdona valley, approximately 400 m S of the confluence with the Ill-valley. The morphology is determined here by (former) erosive and denudative processes in unconsolidated deposits. This led to the development of typical wide and relatively shallow niches within the unconsolidated deposits. Comparable development into similar forms can be found near the Galina and Samina valley outlet, where extensive deposits are also available.

The numbers used in the descriptions below refer to the locations in figure 10. Forty metres S. of the road junction a first exposure (1) in the roadcut exposes a dense, compact subglacial till. The individual (scratched) subrounded fragments are embedded in a silty matrix. The petrographical composition is dominated by light- and dark-coloured limestone fragments; the amount of erratics originating from the Ill-glacier is relatively low, but present throughout the sequence.

Site 2 is located in a small local stream and exposes a ten metre thick sequence of subglacial till, comparable to the first exposure. On top follows a one metre thick layer of well-sorted stone-supported gravel deposit. This gravel deposit is overlain again by subglacial till with the same characteristics as the underlying sequence. The absence of a fine-grained matrix material explains the non-compacted appearance of the gravels which alone can not be compressed. The upper 10 cm are cemented by CaCO₃.

Exposure (3), 140 m from the road junction, in a spur position, shows a silt-rich, compacted deposit with lateral and vertical transitions into a gravel-rich sequence of several dm thick. This is overlain by a coarser, nonsorted layer with a strong sandy and fine gravelly matrix. The whole sequence contains subrounded (sedimentary part) to subangular (metamorphic part) fragments of pebble size. The coarse material is partly cemented. The lateral transitions suggest that this must be regarded as an overridden and (partly) deformed sequence.

The fourth exposure is in average 5 m high and twenty metres wide. The following sedimentary units characterize this exposure:
- A subglacial till with a strongly compacted silty matrix, comparable to the material as encountered in the above mentioned exposures,
- A lateral gradual transition into a pocket existing of bouldery subrounded components. Within this unit enrichment of silty to fine sandy matrix material can be found; this matrix is, without exceptions, strongly compacted. The material could originate from an ablation deposit,
- A gradual transition from the former unit into a gravel-rich unit with a compact matrix. To the N. and to the S. it is flanked by subglacial till,
- A fluviatile gravel deposit, partly overlain by subglacial till. Compaction of the sandy matrix could not be demonstrated, although overriding is presumable in this case.

A distance of 250 m to the south along the road a deposit rich in crystalline components is exposed (number 5). The individual fragments are subangular to angular; the degree of compaction of the silty to fine-sandy matrix is high. Striking are the amounts of green amphibolites and red sandstones. The limestone percentage is also high. This material association is interpreted as a pro-glacially dumped ablation deposit that is subsequently overridden by the advancing Ill-glacier. Similar deposits can be found elsewhere in the Gamperdona-valley.

Figure 12: Section no.7 along the 'Haseltuala' forest-road showing a complex sequence of valley-fill deposits (Location: see Figure 10).
Near 6) again similar materials as described under 5) are exposed. Several smaller spots along the road expose alternations of subglacial till as described under 1) and 2) and the till as described under 5).

The situation at the spur (nr.7) is shown in figure 12: a coarse section of subangular to subrounded components with a varying amount of crystalline fragments. Depending on the the silty fraction, the matrix is consolidated. A striking sandy layer of gravel, strongly cemented near its top, overlies this unit. The complete sequence is overlain by a subglacial till. Twenty metres to the south the compact overridden ablation deposit is again exposed. A near-vertical sandbody is the result of deformation and/or overriding of the advancing Ill-glacier.

A continuous exposure (8) similar the Ill-till of 5) is smeared against the local Flysch (Planckner-Brücke Formation).

![Photo 5. Exposure of highly compacted lacustrine deposits near the end of the Haseltuala forest-road at 875m altitude (compare map sheet Gampberg, G3 and figure 10).](image)

![Photo 6. Detail of photo 5 showing ball and pillow structures; a sand layer is broken up into isolated pillows, floating freely in a silty-clayey matrix.](image)

The 'Gamperdona-conglomerate' is exposed at 9) on top of Flysch bedrock. It is characterized by subhorizontally, valley-outward dipping very coarse-grained layers. Erratic fragments are scarce: red chert and gneisses were found. Conglomerate fragments were found as well. The coarseness and the unsorted appearance within the sequence indicate high energetic fluviatile conditions during deposition. The strong cementation and the subhorizontal layering in the conglomerate are as in the 'older' conglomerate. The conglomerate is partly overlain by the till described under 5).
At the end of the road an exposure in lake-bottom deposits is present with a minimum thickness of five metres. It is characterized by:
- A high degree of compaction,
- An alternation of varve-like laminae existing of silt/clay and fine-sand with occasional dropstones,
- Syn-sedimentary deformation; ball and pillow structures,
- Position against and/or on top of the conglomerate,
- Overlying deposits similar to 5) possibly replaced by slope processes.

Summarizing the description of the exposures along this road the following interpretation and conclusions can be made: Compacted deposits related to overriding by the Ill-glacier during an early-glacial phase dominate the sequence along this road. Subglacial processes were responsible for the present configuration of the various types of sediments. The original appearance of these sediments is in many cases preserved; complete homogenisation did not take place yet, possibly due to the short transport distance. The various types of sediments found within the subglacial till prove the dynamic environment near the ice-front. In fact, these sediments are preserved remnants of valley-fill deposits in the lower V-shaped section of the Gamperdona-valley.

The foregoing descriptions and related interpretations were necessary to understand the descriptions and discussions of the map sheet areas in the following sections, as the geomorphological implications of these outcrops are outside the scope of existing geomorphological models.

**Summary of the geomorphological data of the individual map sheets and their implications for the geomorphological development**

In the next paragraphs a geomorphological description giving the highlights of the five enclosed map sheets will be given including the small section on map sheet Brand-Nord that belongs to the Gamperdona catchment. For easy reference, each map has its own reference grid and is subdivided into 1 km² quadrangles that are based on the original 1:10.000 topographical contourline sheets. Horizontally (west to east) the reference system is in alphabetical order; from north to south the grid is numbered.

The boundaries of the map sheets, the most important locations and topographic features like mountain tops and streams have been indicated in figure 2. For further details is referred to the topographical maps listed in Annexe II. The two adjacent map sheets Brand-Nord (apart from the NE part) and Brand-Süd have been mapped by VAN NOORD (1991).

Some selected topics will be discussed for the individual map sheets because they are highly relevant for the geotechnical and natural hazard overlay maps:
- Reconstruction of the glaciation and deglaciation history; the occurrence of rock-glaciers,
- Distribution of non-lithified materials which have been described in more detail in the previous section,
- Mass movements; deep reaching slope deformation etc.
- Karst development and its influence on slope stability.

Some catchments are represented on two or more map sheets. In that case the description has been given for the catchment as a whole.

**Map sheet Gurtis**

The ice-marginal relicts that are preserved on this northernmost area allow for a detailed reconstruction of the deglaciation history, in particular:
- Ice-marginal deposits near Stutzberg, the Samina-, Galina- and Mengbach outlet and Gurtis,
- Dead-ice development below 770m altitude,
- Restoration of the drainage network.

The topography below 1000 m near Gurtis and below 770m between Latz and Bazulwald is characterized by a series of larger and smaller half-open basins. Their origin must be attributed to glacial scour within the Flysch bedrock. Even the area between the Rabenstein hill (sector E/F4) and the valley flank to the south can be regarded as a basin that is open towards the east. To the west it gradually closes, apart from two major outlets, the incision of the Galina and the 'dry' valley of Gampelün. Flysch formations form the underlying bedrock topography below approximately 1200m; this is shown as a distinct knick in the southern slope of the Ill valley. The Gurtisspitze (1779m, sector B5) and its northern slopes are built of resistant rocks belonging to the East-Alpine nappe.

The basin in which Gurtis is located (sector C4) existed already before the last glaciation. This is proven by the occurrence of subglacial till at several places within the incision of the local Rofelbach that drains the Gurtis basin and joins the Galina in sector D4. The striking local WNW to ESE trending ridges north of the village are consisting of Flysch rocks with a minor cover of ablation deposits.

During a specific deglaciation phase the basin was apparently filled with a small and nearly stagnant lobe of the Ill-glacier. Interaction of both glacial and ice-marginal fluvial processes led to a characteristic morphology:
- Morainic ridges were formed at different levels (1000m, 960m and 930m), reflecting different stages of deglaciation,
- these ridges are interrupted by meltwater outlets at several places (995m, 950m and 945m); sediment accumulated to the west in a sand-like fashion in front of the former ice-lobe,
- The former presence of ice-marginal courses of the Galina is reflected in a series of terraces that are preserved at several places preferentially along the southern boundary of the glacial basins (e.g. at 1005, 995, 990m, 982m, 970m and 940m, see SIMONS 1985),
- The irregular and undulating topography in the central part of the Gurtis basin has probably to be interpreted as a dead-ice topography. Younger deposits of the local Rofelbach partly cover the older topography.

Photo 7. View from the 970m ice-marginal terrace (map sheet Gurtis, C4) to the SSE showing the prominent 990m terrace in C4. In the background the Galina valley outlet and the Gampberg (1709m).

Further to the west, near Stutzberg (sector B3), more evidence of ice-marginal relicts have been preserved: they can be connected with the terrace levels near Gurtis and even further east, towards Beschlingerberg (D5) and the mouth of the Gamperdona valley (map sheet Gampberg, F2). Near Stutzberg large gneiss blocks occur scattered on the surface of the ridges. The ridges and some corresponding ice-marginal fluvial terrace systems bend into the Samina valley at this height, confirming the idea of an ice-free tributary valley at that time. KELLER (1988) however, assumes a temporary rise in ice-level of approx. 10 m during the formation of the ridges at 900m altitude (A/B3), and deposition of gneiss blocks along the edge of the 886m terrace level by the Samina glacier.

The volume of sediments stored in the ice-marginal terraces diminishes going westwards from the tributary outlet into the main valley. This is also observed near the outlet of the Mengbach. Thicknesses range from more than 50m near the former gravel pit of Gadon (sector D4) to less than one metre near the 950m terrace in sector B3). This is explained by the sediment source and transport distance: most of the sediment is derived from the (ice-free) tributary valleys and immediately dumped in front of these valley outlets in the contact area between the southern flank of the Ill trunk glacier. This is evidenced not only by the geomorphological setting of the fan-terraces, but also by its petrographical composition. During the Late-Glacial temperature increase the trunk Ill-glacier level shrunk. Consequently the ice-marginal depositional level, i.e. the local erosion base, followed this lowering of the controlling level of the Ill-glacier.

The geomorphology near the outlet of the Galina valley is discussed in relation to the Galina catchment itself on map sheet Gampberg.

The area between Latz and the Mengbach is, as already mentioned, part of a large glacial basin. Its eastern edge, coinciding with the Mengbach outlet was therefore a favourable site for the development of the characteristic ice-marginal terrace morphology. The following reconstruction is conceivable:
- Below 770m a stagnant lobe of the Ill glacier was located between the Rabenstein hill (750m, E4), the 770m terrace (E5) and the 784m terrace (F5).
- The disintegrating ice-lobe became (partly) covered by sediments deposited by the former Mengbach River between 784m and 540m near the village of Beschling.
- The drainage direction successively shifted from a NW direction (S of the Rabenstein) to a northern direction; the gradually melting dead-ice gave rise to a characteristic morphology existing of dead-ice hollows, gravel knobs and ridges, and isolated terrace relicts (740m level, Bazulwald, sector F5),
- The space left by the melting dead-ice body in the central part of the basin between Latz and Bazulwald is partly filled by younger local fan-deposits. The eastwards sloping part of the fan on which the village of Latz is built indicates that a former course of the Galina followed this direction and flowed probably around the NW-SE stretching Flysch-underlain ridge just north of Latz (E4-5).

Reconstruction of the former position of the Ill-glacier in this area is thus complicated (see also Fig.16). The results of geo-electrical resistivity soundings and electro-magnetic conductivity traverses in this area confirmed the ideas on the morphological development in this area presented here (see chapter 3).

The reconstruction of ice-marginal drainage lines south of Frastanz in sectors C2/3 between 700m and 500m also poses some problems. It appeared that the position of ice-marginal drainage systems was affected by the occurrence of a deep reaching rockslide. According to HEISSEL et al. (1967), the area is completely covered by 'Moräneschutt' i.e. (morainic material in general) and must be underlain by Flysch strata, although exposures are lacking to confirm this hypothesis. Two individual rock-slide masses can be recognized in the area;

1) A smaller unit (450-250m in dimension) in sector C2 (altitude 490-535m) is located between the terrace of Mariex (494m in sectors C/D2) and the western continuation of the dry valley system of Gampelün. The subhorizontal upper surface of this slide is covered with unconsolidated deposits.

2) A larger upper unit that remained more or less intact was released from the slope at approximately 800m altitude (sectors C/D3). NE and W of this scar zone a 'normal' slope developed. The side scars have been indicated on the geomorphological map by tension symbols. Moreover, a small streamlet indicates the position of the westernmost side-scar although it is partly disguised by younger fluviatile sediments deposited by this streamlet. The space created by the sliding of this block has been partly filled with subglacial till; for instance, at 640m altitude the streamlet is actively eroding into subglacial till. Concentration of runoff above the upper scar zone has caused slightly steeper slope gradients; active solifluction processes and small slides developed on a veneer of subglacial till to approx. 900 m altitude. It may be concluded that the slope failure itself predates the last glaciation. The easternmost side-scar is indicated by a SW-NE trending incision that originates at approximately 700m altitude (sector C3) and merges with the dry valley at 600 m altitude. The front of this sliding block is mapped as a distinct glacially scoured 32°-34° slope segment (sectors C2-3). It bulges forward into the valley with respect to the adjacent slopes.

The peculiar bend in the dry valley of Gampelün in C2-3 can be explained by the following succession of events:

- The Originally SE-NW trending course of the dry valley has been disturbed by a deep-reaching slope failure that predated the last glaciation,
- An original course without this sharp bend, following the extension of the dry valley, is more logical. This former course went through sector B2, indicated on the map with blue arrows. A small peat area and two sub-recent alluvial fans cover the position of this 'buried' dry valley.

Map sheet Gampberg

The geomorphology displayed on map sheet Gampberg shows a wide range of phenomena including:

- The former contact zones of the Ill-glacier with the Galina and Gampbach valleys,
- Sediments deposited before maximum pre-Würm ice-levels,
- Sediments and landforms related to the deglaciation history,
- Deep-reaching slope deformation related to the occurrence of gypsum karst,
- Gypsum karst, collapse features, slope breccia and cementation processes,
- The geological half-window of Arosa-zone rocks within the Gampbach valley and its impact on slope development.

The catchments of the Galina and Gampbach dominate the area covered by this map sheet. They will be described separately. Further attention will be paid to the complex Neuwald area in the SE part of this map sheet.

Morphological development of the Galina catchment

The Galina valley is one of the smaller tributary valleys (approximately 11 km²) on the southern side of the Walgau (Fig.2). Its catchment is drained by the river Galina, a very active torrential stream before 1911. A series of stream controlling works were carried out by the Stream Control Department ('Wildbachverbauung'), particularly in the zone of non-lithified deposits in the middle and upper stream sections. Below approximately 1000m altitude a narrow fluvially eroded gorge bridges a height interval of 500m, from the glacial section of the Galina valley to the valley floor of the river III, within a distance of 3.5km. The 1000m contourline forms the approximate boundary of the tectonic contact of the East-Alpine and Penninic nappes (see fig.5).

Fixation of sediments by cementation processes, as occurred to a great extent in the neighbouring Samina-,
Gamperdona- and Brandner valleys is unimportant here; in the upstream section of the Galina valley (near surface) exposures of gypsum beds are lacking. This is supported by E.C. measurements carried out in the summer of 1990.

An enormous volume of sediments older than the last glacial maximum is preserved in the Galina valley. KELLER (1988) used the term 'prähochwürme Stausedimente' for these sediments and gave an indication of their distribution. Geomorphological mapping showed that they are more widespread than accepted earlier. Postglacial incision of the Galina River removed substantial amounts of these older valley fill deposits.
A first important exposure is located near the valley outlet on the eastern slope of the Galina valley, along the road from the village of Latz (map sheet Gurtis, D/E4) leading into the Galina valley (map sheet Gurtis, D5). At 890m altitude a debris-slide was triggered in the summer of 1989 and exposed a sequence in older deposits. A generalized profile of the exposed sediments is given in figure 13; the river Galina has incised itself approximately ten metres into the bedrock below the lowest observed deposits. Therefore post-glacial incision is restricted to a maximum of 10 m at this site; the erosional rate does not exceed 1 mm/year.

Lacustrine varve-like bottom set deposits directly overlie the Planckner-Brücke Formation at 855 m. The fine-grained sediments are heavily consolidated and alternate with coarse gravel- and sandy layers; erratic fragments from the Ill-glacier are lacking. The coarse-grained layers are interpreted as fluvial influxes of local (Galina valley) origin.

Figure 13. Valley-fill sequence near the outlet of the Galina valley, proving the blockage of the Galina valley and the formation of an ice-dammed lake

In a roadcut (map sheet Gurtis, D5 910 m) a 2 m thick sequence of lacustrine silt and clay was clearly exposed after road maintenance works in 1989. Within these lake-bottom laminae several gravel and cobble-rich zones occur; they consist exclusively of angular crystalline Ill-fragments. This sequence is overlain by a mixture of deformed subglacial till containing Ill-erratics and probably fluviolently transported gravels derived from a local source. This would fit in with the idea that the Ill-glacier subsequently overrode the lower deposits and partly reworked and deformed them. At the level of the road a relict ridge is present 30m above the present level of the Galina River, for the major part it is developed within these early glacial deposits. In his interpretation KELLER (1988, Bd.B:pp.210, fig. 29.13) assumes that this is a morainic ridge deposited by a Late-Glacial glacier advancing from the Galina valley outward during and after the so-called Weissbad-phase. The sedimentological structure, the petrographical composition and the position of the ridge however, are in favour of a secondary, denudational-erosional form.

A smaller exposure along the road on map sheet Gurtis in sector D5, 950m altitude and in a similar position on the western valley-side shows strongly compacted lacustrine clay and silt alternations at least a few metres thick. The sequence proves that the valley, at this site, has been completely filled with sediments at least to this altitude. JORDI (1977: pp.54/55) argues that similar deposits near the outlet of the Samina valley must be of Late-Glacial age, due to the fact that they do not contain pollen material. He disregards the degree of consolidation, that indicates ice- (and sediment) pressures belonging to maximum glaciation (see VAN GELDER et al.1990). Further evidence of the early-glacial penetration of the Ill-Glacier into the Galina valley is documented by the widespread occurrence of crystalline bearing sediments, preserved in comparable positions. Hundred metres south of the 'Filpritter Rüfe', a successfully stabilized erosional niche near the end of the Galina-road (C/D3), crystalline erratics suddenly become less abundant. The (mainly subglacially compacted) deposits are dominated by angular and subangular Hauptdolomite fragments. Although exposures are scarce at present, several strongly compacted silt/clay sequences could be ascertained between 1200 and 1240 m altitude. Crystalline erratic fragments (green amphibolites) and Bundsantstein fragments were found at 1340m altitude near Wissersand (C3), 2.25km into the Galina valley. In the northeastern edge of the incision leading from the river Galina to the Lohnspitz (1757m, D4), layered ice-contact deposits (probably debris-flows and/or lacustrine deposits) contain Ill-glacier fragments. They intercalate with deposits of local origin. At this site the early-glacial contact of the local advancing Galina-glacier and the advancing Ill glacier is defined as the 'Wissersand' phase. Theoretically it is possible that the contact zone is located slightly further valley inward; possible evidence could be buried by younger deposits.

An attempt to calculate the position of the contemporary snowline could be made assuming a Galina glacier (see figure 14) in contact with the Ill-glacier. Calculation of the local snowline using the AAR-method (GROSS et al., 1978), results in a value of 1580m; this means a snowline depression of approximately 900m relative to 1850. A full glacier network could only develop when snowlines fell below 900m at this site.

Using the paleo-sedimentological information and facies reconstruction the following sequence of events with reference to the early glacial development of the Galina-valley can be made:
- Numerous exposures prove the former existence of an ice-dammed lake during the early-glacial phase between 855m and approximately 1240m,
Blockage of the Galina-valley by the advancing Ill-glacier was responsible for existence of the lake, the early-glacial sediments within the fluvial gorges prove that they already existed in pre-glacial times; postglacial deepening is locally restricted to a maximum of 10m into Flysch bedrock.

The lake gradually filled with locally derived sediments and sediments related to the Ill glacier.

The Ill-glacier overrode these sediments to approximately 2.5km upstream into the Galina valley (C3).

The early-glacial contact zone between Ill- and Galina-glacier is located at 'Wissersand'; this corresponds to an approximate snowline depression of 900 ± 50m with respect to the 1850 snowline.

During the Würm maximum the Galina-glacier flowed northwards and overrode the older 'valley-fill' deposits because its glacial erosion base was determined by the Ill-glacier (see DE GRAAFF in: SEUFFERT 1989). If the glacial section of the Galina-valley is extended (fig.15), the base of the former Galina-glacier is approximately 1320m at Wissersand and lies between approximately 1000m and 1100m near the mouth of the valley (the boundary of mapsheets Gurtis and Gampberg).

There is clear evidence that the Ill-glacier penetrated the Galina valley again in the Late-Glacial situation. A morainic ridge, here defined as part of the Rossboden I phase, marks the highest level of the Ill-glacier and is located in the Rossboden basin (D3). The gradient is approx. 8° to the south. The ridge is preserved at 1440 m above the local gravelpit and gradually develops towards the SSE, and ends below the road to Aussere Gampalpe at 1420 m. Its continuation has been partly destroyed by sliding processes and is partly covered by younger deposits, for instance by rock-glacier deposits (D3). The development of this rock glacier complex could have started after the melting down of the Ill-glacier lobe from the Rossboden basin when enough scree and blocks were available. This implies that rock glacier activity in the basin of Rossboden could have started while the local snowline was at approximately 1550m altitude. More important, a connection between trunk and tributary glacier can be related to a (calculated) snowline of approximately 1550m.

The deposits in the gravelpit at 1420m are one of the highest preserved occurrences showing evidence of ice-marginal fluvial activity: layered sandy gravels containing up to 10 % crystalline erratics were deposited along a former ice-margin into the Rossboden basin. Similar deposits can be found near the upper margin of the Filpritter Rüfe, 60m below the level of the pit.
Figure 16. Fragment of geomorphological map sheet Gurtis (1:10,000) showing ice-marginal relicts and corresponding interpreted Ill-glacier levels.

Sh: higher levels of Stutzberg  G: levels of Gurtis  L: levels of Latz  B: levels of Beschling
Sl: lower levels of Stutzberg  T: levels of Tscharlund  Ga: levels of Garfrengen
The gravels in the pit are probably related to the lower ridge, the *Rossboden II phase* (top of the ridge 1392m). This ridge is strongly eroded at its western rim and severely attacked by erosion and denudation processes acting in the Filpitter Rühe. The irregular topography (with gneiss blocks) just south of the Rossboden II ridge is interpreted as a local dead-ice phase. The deepest part of the basin is filled with younger solifluction deposits.

Late-Glacial sediments of Ill-glacier origin on top of older deposits do not occur more upstream the Galina valley. This implies that the Ill-glacier penetrated 400m less far into the Galina valley compared to the early-glacial situation. This is possibly caused by at least two reasons:

- The existence of the gradually melting Galina glacier hindering the Ill glacier during its penetration into the valley,
- The volumes of early glacial sediments present in the lower and middle section of the Galina valley; the Ill-glacier enters the Galina valley at a higher level compared to an early glacial phase.

Glacier dynamics, i.e. the overall melting down in a late-glacial versus an active growing glacier system during early glacial times could also have its impact on this different behaviour.

The widespread occurrence of unconsolidated deposits near the mouth of tributary valleys in the southern Walgau (Samina-, Galina-, Gamperdona and Brandner-valleys) is striking. In the case of the Galina-valley the present surface morphology is the result of Late-Glacial and Holocene landscape evolution.

An attempt to reconstruct some of the most important phases during deglaciation with corresponding ice-levels is given in figure 16.

The first more or less continuous ice-marginal system that can be recognized after the Rossboden-II phase is located at 1030 m altitude (Gurtis, D5). This feature was recognized earlier by JORDI (1977), KELLER (1988) and interpreted in detail by SIMONS (1985 pp.111-112). He described the internal structure and composition of a local exposure in a small pit of a second ridge near to the valley slope at the 1030 m level. The deposits were interpreted as remnants of ice-marginal fluvial deposits and therefore not part of a morainic ridge. SIMONS's observations were verified and confirmed. Discontinuous remnants of older ice-marginal systems are sparse between these two phases, as may be caused by the steepness of the terrain north of the Brändle-Kopf-Gampberg mountain chain (D2-3, E2-3) and similarly north of the Gurtisspitze (map sheet Gurtis, B/E6).

![Photo of the outlet of the Galina valley into the trunk Ill-valley](image)

*Photo 8. The outlet of the Galina valley into the trunk Ill-valley, view to the SSE, showing the 901m fan-terrace (map sheet Gurtis, D4-5). The material was derived from the Galina valley and deposited against and along the ice-margin of the Ill glacier to the west. A lower fan-terrace is just visible near the left centre.*

**The Eckskopf-Neuwald area: mountain spreading and related phenomena**

The Eckskopf (1763 m, F5) is a local summit at the NE end of the Gamsgrat, the SW-NE trending valley divide between the Gampbach- and Gamperdona valleys (see fig.2). The geomorphology is depicted in sectors F/G4-5, SW of the confluence of the Gamp- and Mengbach rivers (see also Fig.17A). The area is of particular interest for its deep reaching mass-movement phenomena and glacial history.

A critical combination of geomorphological and geological factors favour deep reaching slope deformation and are responsible for the sub- and near-surface slope development. The geological factors that control the slope stability are:
- A competent rock-mass (Hauptdolomite Formation) overlying incompetent series belonging to the Raibler Formation,
- Stacking of sulphate bearing evaporitic rocks (gypsum) that was dragged up from a decollement zone along tectonical shear zones.

Figure 17A. Fragment of geomorphological map sheet Gamberg showing the situation in the Eckskopf-Neuwald area. The location of the cross section in figure 17B has been indicated. The numbers indicated along the road, refer to the descriptions in the text.
Geomorphological factors are:
- The effect of oversteepening of rock slopes due to glacial erosion and consequently tensional rebound features,
- The distribution of surface materials resulting from the interaction of former glaciers and post-glacial mass wasting,
- The position of small, steep-walled gorges formed by fluvial erosion carved into the so-called 'Gamperdona-' and Gampbach-conglomerates and into bedrock,
- Physical decomposition of material through weathering; cracking caused by freeze and thaw processes form huge scree accumulations at the toe of the Hauptdolomit peaks. These accumulations form the source area for generation of debris-flows,

The role of water is strongly influenced by the combination of these factors.

Geological factors
The Neuwald area tectonically belongs to the Fundlkopf-Scholle that is part of the Lechtal nappe (see fig.5). In the cross-section in figure 17B two lithological units are distinguished:

1) The Hauptdolomit Formation (age: upper Triassic)
2) The Raibler Formation (age: Triassic). The latter is of special interest for its gypsum bearing layers that are concentrated in the upper part of the formation, directly below the Hauptdolomit. This means that the bedrock is built of a 200-300 m thick sequence of competent dolomitic limestone overlying incompetent series of varying lithology (sandstones, breccias, gypsum, and dolomite). According to the "GEOLOGISCHE KARTE DES RÄTIKON" (HEISSEL et al. 1965/1967) three faults dissect the Hauptdolomit Formation in the Eckskopf area. Geomorphological mapping however, showed that these 'faults', and numerous other lineaments, are the result of deep reaching slope deformation. The presence of large volumes of gypsum is morphologically expressed by four huge collapse dolines in the area (E/F/G5); they can be connected by an imaginary straight line. Their size (diameter >100 m, depth to at least 50m), morphological setting (often near divides were they can 'survive' a glaciation) and in some case occurrence of glacial deposits within the actual collapse doline, prove that they are older than the last glaciation. In exposures the thickness of the gypsum locally exceeds 45m (e.g.sector B/C5 in the Gampbach valley). The original stratigraphic thickness of the gypsum beds does not exceed approx. 6m according to VERDAM (1928) and 20m-30m according to HARSCH (1968). In the Rells valley the primary thickness of the gypsum may reach a thickness of 200m. In this area it means that stacking of gypsum took place, in this case along a tectonic WSW-ENE direction, more or less parallel to the boundary of the Drei-Schwestern and Fundl-Kopf Schollen. References in literature (HANTKE 1980, referring to Bächtiger) mentioning an extraterrestrial genesis is therefore irrelevant.

Figure 17B. West-East vross section through the Eckskopf-Neuwald area. The location has been indicated in figure 17A
Geomorphological factors

A first classification can be made separating allochton and autochton pleistocene materials, deposited during three main time intervals of the Würmian (or older glaciations); early-glacial, late-glacial and post-glacial. During the early- and late-glacial periods the lower sections of the tributary valleys were penetrated and occupied by the Ill-glacier and partly filled with sediments. If the model proposed by DE GRAAFF (in: SEUFFERT 1989) is applied to this area, the following two scenarios are relevant in explaining the spatial distribution of the pleistocene sediments:
1) During the early phases of glacierization the Ill-glacier, developing from a higher firn accumulation area, blocked the outlet of the Gamperdona valley and penetrated its lower section. The Gamperdona-valley remained ice-free because the snow line depression (SLD) was insufficient to develop a glacier reaching downward to its valley outlet. The advancing Ill-glacier split into two branches at the confluence of the Gamperdona- and Gampvalleys, sending individual arms into these valleys. Since contact between the Ill-glacier and the Gamperdona-glacier was not established, ice-dammed lakes were formed. Their lake levels were linked to the ice-level in the main valley. These ice-dammed lakes existed until contact with the local glaciers was established. In the case of the Gamperdona valley this contact zone is located in the vicinity of the Grosstal outlet (map sheet Fundl-Kopf, sector E/F1). The contact zone of the Ill-glacier with the Gamglacier is located approx. 1.5km upstream from the confluence with the Mengbach (map sheet Gampberg, sector E4). On both flanks in the Gampbach valley the highest erratics were found at approximately 1490m altitude. These interactions imply that the lower parts of the area were covered by the Ill-glacier and sediments stemming from this period can be expected. The sediments from this Early-Glacial period are often characterized by their high percentage of crystalline fragments (see section: composition of the fine gravel fraction of glacial, ice-marginal and related deposits, chapter 3). Local sediment admixtures during this time interval are scarce. This is explained by the following:
- The greater part of the provenance area of the Ill-glacier is located within the crystalline part of the Upper East-alpine nappe,
- The adjacent Brandner valley was also penetrated by the Ill-glacier (VAN NOORD 1991) at that time and could therefore not supply sedimentary erratics to the Gamperdona valley,
- Sediment input from other sources was restricted; the production and transport of sediments released on pre-glacial slopes was more or less in balance,
- The already mentioned absence of local glacier systems.

During the Würm maximum a full glacier network was established. The flow-patterns belonging to this period are outlined in figure 18. The maximum ice-levels in this area cannot be deduced from sedimentological evidence. In literature (JORDI, 1977) values of 1400-1700 m are mentioned at Feldkirch. This implies maximum levels of >1800 m, complete coverage of the Eckskopf in this area. The higher slopes were glacially scoured and oversteepened during this period; deposition of subglacial sediments occurred in the lower parts and older, early-glacial deposits were reworked, consolidated and/or eroded.
Figure 18. Map showing the flow direction of the main glaciers during the Würm-maximum in the study area.

2) Slightly different situations accompany the Late-Glacial situation, when climate was deteriorating and overall melting down of glacier systems prevailed. The glacier network gradually disintegrated and tributary glaciers lost their contact with the trunk glacier. This implied that glaciers that appeared in the latest phase of the early-glacial period would vanish first in an early late-glacial period. The Ill-glacier had again the opportunity to re-enter the tributary valley systems, but was depending on the melting down of the tributary glaciers. It is likely that the renewed penetration reached less far in comparison to the early-glacial situation. This is caused both by the melting Gamperdona glacier, and the large volumes of sediments stacked in the lower sections of the Gamperdona and Gampbach valleys. The concentration of gneiss blocks near Kühbruck (map sheet Gampberg, sector F5) probably indicate the maximum extent of the Ill-glacier during this period.

The discontinuity planes above 1400m altitude were mapped as tensional fissures. Two directions prevail, a NNW-SSE and a W-E direction. Field measurements on joints and bedding planes (see Fig.36) showed a high correlation with the systems recognized from the aerial photographs. Measurements at seven locations to the north and east of the Eckskopf (for location see: natural hazard map Gampberg, F4, G5) were projected in a lower hemisphere Schmidt net (Fig.36). After contouring and comparison with orientation of fissures (data derived from the geomorphological map), it must be concluded that opening up of the rock mass preferentially occurs along already existing joint sets. The tension zones often serve as tracks for torrential streams and avalanches. Their observed vertical depth is in the order of two- to three-hundred metres. Intense weathering resulting in disintegration of the rock-mass into very angular dolomitic scree takes place; therefore these tension zones are also main scree producing sources. The Eckskopf Rüfe (sector E4) is an example of a scree- and debris cone that is controlled by such discontinuity lines.

Four factors are thought to trigger and/or accelerate mountain spreading in the area:
1) The gravity controlled mechanism of subsidence of the Hauptdolomite rock mass into the underlying Raibler Formation (see POISSEL & EPPENSTEINER 1988),
2) Tensional rebound of the rockslopes after the deglaciation,
3) Internal collapse of the Hauptdolomite roof caused by the dissolution of underlying gypsum,
4) The existence of the more than 200 m deep fluvially eroded gorges of the Gamp- and Meng rivers to the north and east.

The fissure planes are often accompanied by toppling and/or sliding blocks, e.g. the eastern flank of the “Schattentäle” cirque (sector D/E5) has disintegrated in a blockwise manner. The second largest major scree/rockfall accumulation cone, north of the Eckskopf (sector E4) is fed by toppling and sliding blocks.

Detailed morphological and sedimentological information was gathered along the so-called ‘Neuwaldweg’, a forest-road, constructed in the lower stretches of this area for the exploitation of the forests surrounding the Eckskopf. Along this road a variety of forms, materials and processes are met. Only a brief summary is given here (numbering see fig.17A).

Starting from the southern end of the road the following observations were made:
1) In sector E5 an approximately 40m high erosional cut exposes a sequence of coarse cross-bedded sandy gravels, alternating with sandy and silty subhorizontal layers, concentrated in the lower section. The fine-grained sediments are slightly compacted. The petrographical composition indicates a local origin, in this case the former raised Mengbach. The depositional environment was probably a shallow lake formed during a certain deglaciation phase. A crystalline-bearing subglacial till underlies the sequence.

2) Subangular hauptdolomite blocks on a slope that is protected from debris produced by upslope areas are interpreted as an ablation deposit, probably derived from the ‘Weisstal’ (Strübalpele) and Mitteltäle, two valleys on the eastern side of the Gamperdona valley (fig.2). It would prove a minor Late-Glacial advance of the Weisstal glacier. This probably occurred synchronously with the Buchboden advance of the adjacent Grosstal valley.

3) Numerous exposures below 1000 m show repetitions of overcon-solidated lacustrine silts and clays and gravel deposits, belonging to the younger Gamperdona conglomerate. A thick (>10m) cover of crystalline bearing subglacial till, deposited by the Ill-glacier, locally overlies the sequence. Above 1000 m the equivalent deposits have been removed by erosion and denudation or have been covered by younger slope debris.

4) In the NW corner of sector G5, the following observations can be made: The detailed morphology is determined by numerous chaotically arranged minor slides. According to the ‘GEOLOGISCHE KARTE DES RÄTIKON (HEISSEL et
al., 1967), these slides have developed in breccias of the Raibler Formation. The breccias are mainly composed of dolomitic fragments. A major semi-circular surrounding scar has formed in subglacial till at its northern boundary and in scree (partly cemented) at its western boundary. The height difference along this fresh scar reaches 5-7 m. The scar was expressed as a step in the road of 70 cm in late August 1989. Two months earlier this step was only 35 cm. No material is given off to the Meng River. Mature pine trees (80-100 yrs in age, E.SONDEREGGER, pers. comm. 1989) within this area show distinct curvatures, often in more than one direction, thus indicating several periods of active movement. The niche itself is exactly located on the imaginary straight line that connects the upslope collapse dolines. Based on these observations, the niche is interpreted as an active collapse doline (fig. 17B).

5) The exposures of subglacial till along the road, show sequences of vaguely layered subglacial till, deposited by the Ill-glacier (see samples 25, 28, 30, 31, 32, see Annexe IIIB). Within the relatively sandy matrix, dense silt- and clay-rich layers or pockets may occur. Scratched limestone fragments occur abundant throughout the sequence.

6) The northern edge of the Eckskopfrüfe scree/debris flow cone is severely attacked by sliding processes. The material is exclusively composed of dolomitic scree (debris flow deposits) and overlies subglacial till of the Ill-glacier. The deposits of the local "Wildbach" coalesce with a solifluction fan at the level of the road. Below approximately 960 m altitude the Younger Conglomerates are continuously exposed on the western side of the incision of the Mengbach. They are characterized by:

- Fine-grained lake bottom deposits, in places rich in crystalline Ill-erratics (dropstone layers),
- Northward dipping topset-beds, containing <5% Ill-fragments,
- Deltaic foreset-beds deposited from the Gamperdona valley and the Gamperdona valley.

7) Various glacial and ice-marginal sediments were observed between 1050 and 1150 m altitude in sector F/G4. Depending on the position in the field the following types of sediments and structures were present:

- Crystalline bearing subglacial till, upto 10 m thick; contacts with hardrock were observed,
- Non-lithified sorted fluvial gravels, probably relics of alluvial fan systems deposited by the Gamperdona river,
- Filled channels overlying basal till of Ill-origin; a basal cemented gravel layer is overlain by 3-4 m sand and gravels.

8) This complex subhorizontal area is characterized by the following elements:

- Small 3-6 m deep sink-holes without exposures of gypsum or limestone (covered karst),
- Within the sink-holes conglomerates, breccias, gravels or slope debris were observed,
- Slides and fissures dissect the area. At present, the area has been stabilized.

9) West of this area the material cover changes into large dolomitic blocks derived from rockfall that is related to an active toppling/-sliding zone at the northern side of the Eckskopf. To the west conglomerate blocks indicate a different source area; they were produced by an isolated exposure of conglomerates that is dissected by numerous fissures.

The hydrological situation

The hydrological conditions are strongly interwoven with the geological and geomorphological conditions. The main factors that control the aquifer body of the Eckskopf region are:

- Geological and structural relations: a permeable rock mass (Hauptdolomite) overlying a partly impermeable rock mass (Raibler Formation),
- Mass movement; the deep fissuring creates a secondary permeability. The fissures reach into the underlying gypsum-bearing beds and therefore serve as lines along which solution and collapse preferentially take place. The surficial mass movement activity also prevents the development of a normal drainage network. The spatial distribution of surficial materials, especially the occurrence of impermeable subglacial till, is a crucial factor.
- Crack- and fissure-controlled groundwater flow is directed towards the contact zones of the Hauptdolomit and Raibler Formations or towards the contact between valley fill and bedrock. From the Buderh/he outlook, a series of springs can be observed near the base of the conglomerates, just above the level of the present Mengbach (G4).

Only a few spring-fed streams above 1100 m altitude are perennially waterbearing. A direct link between precipitation and surface runoff exists; during high intensity rainstorms debris flows are an abundant phenomenon.

Morphological development of the Gamperdona valley

The Gamperdona valley is an approx. 8 km² tributary catchment to the Gamperdona valley. It is enclosed by the Eckskopf, the Ausserer (2063 m) and Innerer Alpelekopf (2122 m), Scheienkopf (2159 m), the Mattlerjoch pass (1867 m), the Galinakopf (2198 m), the Lohnspitz (1758 m), the local transfluence pass at Äussere Gampalpe (1562 m) and the Gamperg (1709 m) (see fig.2). The geomorphological situation is outlined on the map sheets Gampberg and Fundl-Kopf. Based on these maps and geological information (HEISSEL et al. 1967) two cross-sections have been constructed in the central and upper Gamperg valley (fig.19). These schematic sections illustrate the close relation that exists between the geological substratum and the near-surface processes. The valley itself has developed on the tectonic contact of the Drei-Schwestern Schuppe (northwest of the Gamperg) and the Fundlkopf-Schuppe (south-west of the Gamperg). Rocks belonging to the Arosa-Zone have been dragged upwards along this contact and now form a tectonic half-window (KOBEL 1969) on the central southeastern slopes below approximately 1700 m altitude (see Fig.5). The Hauptdolomit Formation dominates the waterdivides >1700 m in the Gamperg valley; lower divides, passes and slopes are built of Raibler Formation, Arosa-Zone material or locally of Muschelkalk Formation or Partnach-Schichten.
The occurrence of the gypsum bearing Raibler Formation is of special interest; solution, infilling, cementation and relief inversion can be observed in the Gampbach valley in different stages of development.

In general the geomorphology and the distribution of non-lithified sediments within the catchment of the Gamp valley is determined by the following features:
- The interaction between the local Gampgletscher and the trunk Ill- and Gamperdona-glaciers,
- Gypsum karst and its influence on slope stability,
- Deep-reaching slope deformation,
- Fixation of sediments in the lower and central valley.

A striking difference in slope development exists between the northeastern and the southwestern valley slope. The southeastern slopes above approximately 1700 m altitude have maintained their original glacially scoured appearance. They developed more or less according to the dip slope in the Hauptdolomit Formation. In the southernmost part of the catchment huge scree slopes, fed by active erosional/denudational niches, have filled the cirque basin from which the Gampgletscher developed (map sheet Fundl-kopf, sector B/C2). At this site the terrain gradients exceed the geological dip; therefore numerous discontinuity planes are exposed, favouring the impact of weathering processes and therefore scree production. The dolomitic scree fragments accumulate in cones and scree slopes with gradients between approximately 27-33 degrees. At their toe they merge into slopes with lower gradients; this is often the accumulation zone of debris flows, a common process within the cirque of the Scheienkopf.

Photo 10. Upper Gampbach valley with the Innerer Alpele Kopf (map sheet Fundl-Kopf, 2122m, C2). Backscarp of deep-reaching slope failure in C1-2 is clearly seen to the right of centre.

In sector C1/2, map sheet Fundl-Kopf, the geomorphological situation is characterized by the following elements (see also fig.19):
- A 45 m high exposure of intensely folded gypsum and a corresponding karst spring,
- The presence of gypsum in the adjacent subsurface to the SW is accentuated by numerous smaller and larger dolines, that developed in the Formation but included a collapse of the surficial cover of local ablation till and/or scree (covered karst). It can be observed in places that, despite the active infill by debris flows, the dolines develop faster than the accumulation of the scree cones,
- the solution of gypsum in the subsurface triggered an enormous rock-slide; a more than 75 m deep tensional crack forms the backscarp of a 500 m long, 125 m wide and at least 100 m deep rock-failure (see fig.19).

The steep dolomitic walls are almost directly overlying an incompetent gypsum base. Slabs of dolomite have already toppled over and merged into local rockfall, partly filling the dolines. AMPFERER (1936b) only mentions and did not explain the origin of this rockslide. He proposed a model for the formation of cirques initially formed through the development of these kind of rockslides,
- To the west the Mattlerjoch pass is underlain by an important gypsum-bearing zone; the local valley divide has developed in gypsum and in rocks belonging to the Arosa Zone; the overlying bedrock has been removed, mainly by solution processes.

The tectonic half-window of the Arosa-Zone strongly affected the morphological development of the southeastern slopes of the Gampbach-valley (fig.19B). The transition of the glacially scoured slopes in the Hauptdolomit Formation to the underlying rocks of the Arosa Zone is characterized by an abrupt step in the terrain, often exceeding 50m in
height. This SW-NE trending step can be followed over a distance of 2 km in the terrain and is interpreted as the upper scarp of a slowly (deep-reaching) downward slope movement (German: Talzuschub).

The side-scars can also be depicted from the geomorphological map with high accuracy; the SW side-scar (sector C1) connects a semi-circular depression with a small lake (possible collapse doline?) along a linear depression with the Gampbach.

Figure 19: N-S Cross sections through central (top section) and upper Gamp-valley (lower section).

Photo 11. Debris flow track developing from the Scheienkopf cirque (map sheet Fundl Kopf, B/C2). The width of the tracks remains remarkably constant over hundreds of metres before deposition takes place, in this case in the karstified, gypsum underlain upper Gamp-valley.
Photo 12. Upstream view in the incision of the Gampbach at approximately 1430m (map sheet Gampberg, D5). The Gampbach is incising into valley fill deposits, here consisting of conglomerates (block in centre of picture), debris flow/alluvial fan deposits (fan surface just seen top right of conglomerate block) and local till (not seen). At this site the Gampbach is pushed to the north (right), due to slow valley downward slope movement. Therefore a local valley floor cannot develop.

This tectonic contact is activated as a shear zone. Similarly, the NW side-scar (sector D5) coincides with a tectonic contact and is morphologically expressed as a difference between glacially scoured slopes and irregularly arranged individual slides, fissures etc. at a lower terrain level. The river Gampbach forms the lower NW boundary of this complex mass movement area.

Within this zone the following observations were made:
- The hydrological system is disturbed and controlled by mass movement processes; only a few spring-fed streams are present. Water stagnation on (rotational) slide units is a common feature and seepage zones are related to active solifluction,
- Small and shallow, linear tensional systems prevail just below the backscarp zone parallel to the contourlines,
- Below this zone, the morphology is determined by smaller and larger slides, or by solifluction processes, depending on the availability of water,
- A number of larger sub-units can be distinguished, mainly delineated by a major large surrounding niche; they have been indicated by heavier lines on the geomorphological map,
- The local valley floor of the Gampbach is interrupted at two sites (NW part of sector D5 and the lower central part of sector C5); it is thought that at these places the mass movement is relatively more active than in the adjacent area.

The northwestern slopes of the Gampbach valley (sector C/D4/5) are in mere contrast to the southeastern slopes. Cross section B in fig.19 schematically represents the situation on the northwestern slope of the Gamp-valley: the morphology is here determined by a series of coalescing debris/solifluction fans. They originate from a series of niches developed in the Hauptdolomit, that here forms a face-slope.

A striking phenomenon is the occurrence of cemented debris pillars and debris bodies in a zone directly below the Hauptdolomit Formation. They exclusively exist of dolomitic fragments. According to HEISSEL et al. (1967) they belong to the Raibler Formation. The origin of debris pillars and their geomorphological setting was discussed by CAMMERAAT et al. (1987). They propose an alternative genetic model and describe pillars at three locations in Vorarlberg and distinguish the following phases in their developments:
- Initial supply of debris and dissolved carbonates in water over gypsum bedrock; beginning of gypsum funnels,
- Development of gypsum funnels; filling of funnels with debris and cementation of the debris, due to the mixing of 'gypsum' and carbonate-water,
- Further development of funnels and fill with debris; continuing cementation,
- Relief-inversion after solution of surrounding gypsum; cemented funnel infillings form debris pillars.

The debris pillars described near Aussere Gamptalpe are in so far different in their genesis that the last stage in the development, i.e. the removal of surrounding material, has taken place not by erosion, but by mass movement (CAMMERAAT et al. 1987).

The extensive breccia-bodies, often more than 100 m high, represent former cavities that were formed by the dissolution of gypsum and subsequent collapse of the overlying dolomitic caprock. In fact, this situation could be compared with the huge collapse dolines such as the Bärenloch (map sheet Gampberg, sector E5) and the Kessiloch (map sheets TschenglaDünza, sector C5-6 and Brand-Nord, sector C1). These huge collapse dolines are presently being filled by scree produced from the steep dolomite walls within the depression itself. In fact the scree is filling the space created by the collapse. Enormous amounts of gypsum must have been dissolved in the subsurface; it is assumed that the scree fragments that fill the subsurface cavities are cemented through the process described by CAMMERAAT et al. (1987). Similar subsurface fillings are now exposed in the northern slope of the Gamp-valley and show as breccia bodies. These breccia bodies could survive a glaciation, but the isolated pillars were formed after the last glaciation, either as an original singular form or developing from breccia bodies through weathering processes.

Most of the karstified zones in the Gamp-valley are of the ‘covered-karst’ type. The sinkholes have developed in the Formation below a cover of slope-debris or morainic deposits, depending on the geomorphological position in the valley. In exposures along the Gamp-river subglacial till deposited by the Gampglacier, underlies debris derived from
the northern Hauptdolomit slopes. Locally, the scree deposits are cemented by CaCO₃, an indication that gypsum-bearing layers are present in the near subsurface.

At several sites along the Gampbach, conglomerates and lake-bottom deposits are exposed. These deposits are related to the blockage of the lower section of the Gamp-valley by the trunk-glacier.

Above 1750 m four cirques have developed, with N to NE exposition. Within the two NE exposed cirques (sectors B5 and map sheet Fundl-Kopf, B1) morainic ridges have been preserved, belonging to a Late-Glacial phase, when snowlines were approximately 1850 m.

Photo 13. Southward view (stereo-pair) from the Mondspitze (1967 m) towards the Schillerkopf (2006 m) showing the surface expression of gypsum karst near the valley divide that separates the Brandner-valley (left hand side) from the Gamperdona-valley (right hand side). The overlying Hauptdolomite Formation collapsed into the subsurface cavities and formed collapse dolines that can reach diameters of 200 m and depths of 70 m. These features predate the last glaciation.

Map sheet Fundl-Kopf

The topics that are of main interest in this map sheet area are:
- The former contact zone of the Ill-, Gamperdona- and Grosstal glaciers near the outlet of the Grosstal valley,
- Valley-fill sediments in the transition of the lower to the middle section of the Gamperdona valley,
- The upper part of the Gampbach valley (see description map sheet Gampberg),
- Fossil rock glaciers east of the Ochsenkopf summit and in the NE part of map sheet Brand-Nord.

The outlet of the Grosstal valley

From the chapel of Kühbruck viewing upstream a huge fan-shaped sediment body can be seen, in front of the Grosstal valley outlet (E/F1-2). It nearly blocks the Gamperdona valley in this stretch. This almost 200 m high accumulation of sediment is strongly eroded at its western frontal part by the Mengbach. Large erosional and denudational niches subsequently developed, thereby exposing the internal structures and sediment composition.

The position of the sediment fan is crucial: it is located on the transition of the middle U-shaped section to the lower V-shaped section of the Gamperdona-valley (see also fig.15). In this position, the former contact zone of the Ill-, Gamperdona- and Grosstal-glaciers existed, which can be reconstructed from the sediment exposures in this area.

KELLER (1988, Bd.I pp.90/91 Bd.II fig.27.6) describes the Late-Glacial situation in this area. New details could be added after morphological mapping and sedimentological investigations. It appeared that a multiphased development, starting in an early-glacial period, was responsible for its present configuration.

The geomorphological situation is shown in sector E/F1-2. The major form of the sediment body resembles a fan. The original upper surface has a twelve degree gradient to the NW. The oldest non-lithified sediments are exposed at the
present level of the Mengbach at 1085 m altitude, approximately 1.75 km from the Kühbruck chapel (map sheet Gampberg, sector G5). They contain a wide variety of angular metamorphic fragments in a sandy matrix (see metrographical sample: No.12). The absence of a significant percentage of Triassic dolomite fragments proves that neither the Gamperdona- nor the Grosstal glacier was responsible for deposition; this implies that these glaciers at that time did not develop yet. Direct sedimentation by the Ill-glacier was responsible for deposition. This deposit probably originated as an ablation deposit and was subsequently overridden by the advancing Ill-glacier; compaction occurred during maximum ice-levels.

Photo 14. View to the SW showing the actively eroding niches in the frontal part of the "Grosstalfan" (map sheet Fundl-Kopf, F1) that developed in the former contact area of the Ill-, Gamperdona- and Grosstal-glaciers. The original fan surface is seen in the upper right corner. The material composition reflects a complex sedimentation history covering at least the period Early- to Late-Würmian (see text).

An ice-dammed lake existed in front of the Ill-glacier arm in the Gamperdona valley. Lacustrine sands, silts and clays are exposed near the outer SW. edge at 1120 m altitude. This 10-15 m thick sequence of lake bottom deposits is exposed in a central position relative to the present valley cross-section. The fine-grained deposits intercalate and interfinger with well-rounded and sorted gravels of fluvial origin. These gravels were deposited by the Mengbach, whose natural drainage was blocked by the Ill glacier. The petrographical composition of the sediments (samples 7+8+10, Annexe IIIB) confirms this idea. They contain a remarkably low amount (50<%) of Triassic dolomite; for t three kilometers upstream the geology at both valley sides is exclusively built of Hauptdolomit. At present extremely active so-called 'Rüfen' (denudational/erosional niches) produce large amounts of angular Hauptdolomit debris (for instance the fault-controlled Bärenrüfe, sector D4). It must therefore be concluded that the adjacent slopes were quite stable during the sedimentation of these gravels. From the Late-Glacial situation between the Grosstal outlet and Nenzinger Himmel it is known (see description of map sheet Nenzinger Himmel) that gravels with a similar composition were deposited in front of the Gamperdona-glacier, who's snout was located at the Schafbrücke (KELLER 1988) and just N. of the Virgloriatobel. The morainic ridges south of the Virgloriatobel (map sheet Nenzinger-Himmel, D/E2) exclusively exist of Hauptdolomit fragments, deposited by the Salaruel-glacier. Therefore it is assumed that the gravels were derived from sediments released at the margin of the Gamperdona-glacier in a position north of the Virgloriatobel.

The intercalation and interfingering of fine-grained lacustrine sediments with these fluvial gravels could reflect minor fluctuations of the lake level. Measurements on the compaction of subglacially consolidated sediments by VAN GELDER et al. (1990) in the Garfetschentobel, approximately 500m NW of this exposure at 1055m and 1125 m altitude, proved that >500m of ice was responsible for this degree of compaction. When these fine-grained sediments are compared to the exposure 'Garfetschentobel', it must be concluded that the degree of compaction cannot merely result from the overlying deposits plus a Late-Glacial Grosstalglacier. The lower 'Grosstaldeposits', the morainic deposits of the Ill glacier, the fine-grained lake deposits and fluvial Mengbach gravels are therefore placed in an early-glacial phase, probably early Würmian. The central position of these deposits in the valley show that they were not completely removed by glacial erosion during the Würm maximum but that they were subject to compaction and partially to deformation resulting from ice-pressure. The top of the lake-bottom deposits therefore reflects the minimum base of the Gamperdonaglaciers. This implies an early-glacial valley fill to at least 1140m at this site. Crystalline erratics have not been found on top of the fluvial deposits, nor could a subglacial till of the Gamperdona glacier be found. This could indicate that during the so-called Würm Maximum ('Hochwürm') the Gamperdona glacier worked erosively in the older valley fill sediments. The erosional transition to the overlying younger deposits takes place within a few metres (see petrographical samples nos. 8/9, Annexe IIIB). The total volume of material stored in the lower section of the Grosstal valley therefore belongs to both an early-glacial period and the late-Glacial period. Sedimentation above the erosional surface in the older valley fill deposits took place in front of the Grosstal glacier.
Photo 15. Detail of a valley fill sequence in the Garfetschentobel (map sheet Fundl-Kopf, F1) at approximately 1140 m altitude. At this height horizontally laminated lacustrine clays and silts alternating with sand layers have been deposited in a local glacial lake that was formed by the blocking Ill glacier. Slightly higher in the sequence a crystalline bearing till overlies this sequence.

At that time the Gamperdona valley was already ice-free in this stretch (see also HANTKE 1980, KELLER 1988, and DE GRAAFF in: SEUFFERT 1989). The next phase is characterized by the building of a huge sediment fan above 1120 m altitude. By interpretation of the geomorphological map two reasons arise that can explain the inability of the Mengbach to remove the material supplied from the Grosstal valley at that time: 1) The presence of either a valley-fill or 2) Ill glacier-(dead)-ice in the Gamperdona valley north of the sediment fan or a combination of these two possibilities. The latter seems most likely. It is supported by the 12 degree gradient of the original fan surface to the N. The concentration of gneiss blocks near Kühbruck (map sheet Gampberg, sector G5) probably indicates the southernmost position of the Ill-glacier during the deglaciation phase.

The sediment fan in front of the Grosstal valley accumulated to a level of 1150 m caused an upstream blockage of the Mengbach. This is reflected by valley-fill sediments just SW of the valley outlet (terraces in sector E1,2). They correspond to several upstream terraces and can be linked up to a glacier front that was probably located at the Schafbrücke (see KELLER 1988).

The Late-Glacial Grosstal glacier advancing into the Gamperdona valley is correlated with a calculated snowline of 1725 m, which is a SLD of 810 m compared to the 1850 snowline. The position of the former snowline is affected by the narrow, north-directed trend of the Grosstal valley. This results in a corrected SLD of 710 m (see also KELLER 1988), which is 50-100m lower than was originally calculated.

Summarizing, the following events took place in the vicinity of the Grosstal outlet:
- Deposition of till by the Ill-glacier in, at that time and place, ice free Gamperdona and Grosstal valleys. Probably the lower Grosstal valley section became filled with Ill-deposits!
- A locally formed shallow ice-dammed lake became filled with fine-grained lacustrine deposits and subhorizontally layered gravels of the Mengbach river,
- Contact of local and Ill glacier was established; a full glacier-network developed. The local glacier mainly reworked, consolidated and eroded the older deposits above 1140 m,
- During the Late-Glacial phase the Ill glacier re-enters the lower Gamperdona valley section; this time not further than Kühbruck, were the contact with the Gamperdona glacier is lost,
- The ice-free area in front of the Grosstal valley becomes filled, mainly with proglacial washed sediments and eventually with ablation deposits of the advancing Grosstal glacier. Blockage of the Gamperdona valley upstream of this point was the result (see also KELLER 1988). The raise of the local erosion base caused a blockage of the Mengbach drainage and the formation of a valley floor to a level of 1155 m. An ice-marginal drainage channel was active during this period and is preserved at the southern edge of the morainic ridge of the Grosstal glacier,
- Erosion of the Mengbach could start after the disappearance of the blocking Ill-glacier near the outlet of the Gamperdona-valley. The original valley floor has not been reached yet.

Fossil rock-glaciers
Recently DE JONG and KWADIJK (1988) described fossil rock glaciers from two locations in Vorarlberg, with special reference to their surface shapes and the geomorphological setting in which they occur. Their definition of rock glaciers is also used here: a rock glacier is a tongue-like or lobate body usually of angular boulders that resembles a small glacier, it generally occurs in high mountainous terrain, and usually has ridges, furrows and sometimes lobes on its surface, and it has a steep front angle of repose. In their study they recognized two generations of rock glaciers, and proposed a Late-Glacial Egesen age for the younger and a Late-Glacial Daun age for the older generation.
In the Gamperdona valley several fossil rock glaciers could be recognized. In this section the fossil rock glaciers on map sheet Brand Nord will be dealt with also. Many of these forms have previously been interpreted as morainic ridges, belonging to local Late-Glacial phases e.g. Gschnitz (HEISSEL et al. 1965/1967, KELLER 1988). A series of rock glaciers in the cirque valleys of the Mitteltäle, Weisstal, Ob.Tritt, Alpila cirque and Schillerkopf cirque (map sheet Brand-Nord, sector A/B/C1-2) are of special interest. Similar conditions prevailed during the time of formation of these rock glaciers. All valleys/cirques are characterized by:
- NW to NNW exposition,
- Headwalls developed in the Hauptdolomit Formation,
- Large production of dolomite debris, reflected by surrounding talus/scree cones,
- A complete fill of the valley floor with an intricate pattern of ridges (10-30m high), depressions and furrows, arranged in various orientations and ending in curved, lobate forms. The surface material of these accumulations exists of very coarse fragments, mainly boulders and large blocks.

The Mitteltäle rock glacier complex possibly exists of two separate bodies, overlying each other. The outer tongue has a steep front (30 degrees), and rests on the older front of a comparable accumulation. The younger tongue is composed of small block-rich almost parallel trending walls that almost coalesce in the centre of the valley, a strong indication that a glacier could not be responsible for deposition.

The Weisstal complex shows a number of well developed curved ridges that could resemble, at first glance, morainic ridges. The intervening knobs, the numerous smaller ridges in various orientations, the widening of the lobe near its lower end, the position of parallel ridges in the centre of the valley (especially in the upper part) are however, indication for a rock glacier origin. The ridge in the SW corner of the valley is interpreted as a protalus rampart deposit. The ridge runs parallel to the foot of the scree slope. The fresh boulders and blocks (only at the SW side) indicate recent activity.

In the Ob. Tritt cirque, two main accumulation bodies seem to be present, an older one covering the full width of the cirque and a younger one, which is confined to the lower end of the cirque. This does not immediately imply that two separate generations of rock glacier activity have been responsible for formation. The pattern of ridges and knobs of unconsolidated Hauptdolomit debris is arranged in such an irregular way, that it is impossible to fit a small glacier within the area left between the closely spaced ridges. In front of the rock glacier complex, morainic deposits are present, as a more gentle cover creating a hummocky surface, without displaying accumulation forms as clear ridges or walls.

The two smallest rock glaciers to the NE, have a simple tongue shaped lobate form and do not reach far from their source. Part of the proximal end is actively being covered by younger debris. Within the overall lobate form, arcuate and straight ridges occur, the latter parallel to the cirque headwall.

The most intriguing situation exists northeast of the Ochsenkopf. In sector C3-4 a horizontal area is covered by an irregular pattern of Hauptdolomit debris, with numerous chaotically arranged depressions, small hillocks and ridges. The maximum difference in elevation is 15 m. The western upslope area is covered by a series of well developed ridges, alternating with zones less pronounced, subdued morphology, again characterized by discontinuous ridges and in some cases, clearly lobate flow patterns in apparently, morainic ridges. The interpretation here is that the lower rock glacier complex developed out of moraines, in a phase that a glacier occupying the Ochsenkopf cirque was hanging over the steep cirque rock step that separates the two subhorizontal zones.

To allow comparison with the rock glaciers described by DE JONG and KWADJUK (1988) a similar table (1) is given here. No attempt however, is made here to subdivide rock glaciers into different generations.

The possible implications for the development of rock glacier complexes in this region can be summarized as follows:
- As soon as the glaciers had melted down in the local cirques and valleys, rock glaciers could develop, depending on the production and availability of debris.
- Possible development of local moraines and rock glaciers could already have taken place after the renewed Late-Glacial penetration of the trunk Ill glacier into the tributary valley. The lowlying rock glacier in the basin of Rossboden could be one of the oldest rock glaciers in the region in this respect, developing when the Ill glacier was still occupying the Ill valley.

Photo 16. Fossil rock glacier complex (semi-forested zone) NNE of the Lohnspitz (1757m) in the basin of Rossboden, (map sheet Gampberg, D3). To the right the transfluence col connecting the Gamp-valley with the Gallina-valley is seen.
Table 1. Data of fossil rock glacier complexes

<table>
<thead>
<tr>
<th>Location of rock glacier</th>
<th>Aspect point (m)</th>
<th>Highest Point (m)</th>
<th>Lowest elev. (m)</th>
<th>Mean</th>
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<td>1570</td>
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</tr>
<tr>
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<td>NW</td>
<td>1760</td>
<td>1520</td>
<td>1640</td>
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<td>NW</td>
<td>1800</td>
<td>1700</td>
<td>1750</td>
</tr>
<tr>
<td>Alpila cirque</td>
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<tr>
<td>Schiller Cirque</td>
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</tbody>
</table>

Map sheet Dünza-Tschengla

Four geomorphological subareas can be recognized on this map sheet:
- The valley floor of the river III between Nenzing and Tschalengaau with a number of smaller and larger alluvial fans; the lowest part of the alluvial fan of the river Lutz, deposited from the Gross Walser valley (fig.1) is just represented north of the river III along the NE boundary with map sheet Schnifis-Bludesch (DE GRAAFF, RUPKE & SEIJMONSBERGEN in prep.),
- Part of the northwestern Brandner-valley including Tschengla, Dünza, Furkla and part of the catchments of the Plattenbach and Mühlebach, east of the waterdivide that connects the Kessloch-Mondspitze-Schwarzkopf summits,
- The northeastern flank of the lower section of the Gamperdona valley including the small catchments of Dunkeltobel and Sägertobel, Käserlisboden, Falscherinaalpe and Nenzingerbergalpe,
- The southern Ill valley flank (Planetental) between Groferberg and Tschalengaberg.

The northwestern part of the Brandner valley.

The morphology in the surroundings of Tschengla and Dünza in sectors F/G4-5 is superposed on a subhorizontal surface underlain by bedrock belonging to the Raibler Formation (HEISSEL et al. 1967). Exposures of bedrock are scarce, due to the extensive cover of Quaternary deposits. Following the observations and reasoning of SIMONS (1985) and using new data supplied by the geomorphological map, the situation may be summarized as follows:
- A small glacially eroded basin in sectors F/G5 with numerous small ridges and knobs is covered by a scatter of large erratic gneiss blocks; during deglaciation these blocks have been deposited by the declining Ill glacier that filled the space created by the melting Brandner glacier,
- Corresponding ice-marginal drainage systems developed; a complex mosaic of ice-marginal ridges and intervening fluvial, mainly erosive patterns was formed. These patterns originated either directly at the ice-front, or reflect former courses of the Mühlebach, that deviated to the NE and to the NW, following the important outlet into the direction of the Mottenkopf. A slightly older, thus higher located comparable dry valley 100m parallel to the SW corresponds to the small terrace just north of the Plattenbach on the central eastern edge of sector E4. The presence of gneiss blocks (see also SIMONS 1985, HEISSEL et al. 1967) on the morainic ridges at Tschengla, Dünza and Ronaalpe indicate that the III glacier was responsible for deposition. A situation in which a glacier developing from the Alpilakopf (2155m, map sheet Brand-Nord, B3) followed the Mühlebach valley and made contact with the Brandner glacier in the so-called Tschengla phase, as KELLER (1988, Bd.II, pp.257, fig. 34.8c) postulates, is unlikely.
- The adjacent western area, between 1450 and 1260 m altitude in sector E5 and the corresponding zone on map sheet Brand-Nord in E1 (see VAN NOORD 1991) has a special appearance. Innumerable smaller and larger depressions within mainly morainic deposits have created a ‘moonlandscape’. Gypsum is only exposed at two sites in the vicinity: at 1300m altitude just north of the Mühlebach, accompanied by a series of karst springs, and near the springs in the SW corner of sector F5. Erratic crystalline blocks occur at the surface to a height of 1485m. The original surface, indicated in orange with an ablation cover, could be reconstructed at only a few places. The collapse of morainic material into the karst hollows is still active at numerous places. Within this area KELLER (1988, Bd.II, pp. 203) distinguishes a sequence of ice-marginal ridges in a SW-NE direction. From the geomorphological map it can be read that several other directions without a link to deposition along an ice-margin occur; they can only be regarded as relict ridges, tensional fissures and disrupted slide masses caused by the solution of subsurface gypsum. Striking is the orientation and clustering of karst depressions, especially in the higher area in D5. Lineaments within the gypsum were already observed on map sheet Gampberg and are probably related to tectonical thrustplanes.
The slopes underlain by the East-Alpine nappe (C/D2-3, E/F/G2-3) are characterized by:

- For re-afforestation at the cost of hay lands.
- Weathering products of the Flysch bedrock, or on the cover of subglacial till. Comparison of land-use practice as presently described above, could not be verified, but cannot be excluded.

The rock-glacier complex in sector D4 has developed within the zone surrounded by morainic ridges and is thus younger than this phase. DE JONG & KWADIJK (1988) recognized a number of fossil rock-glaciers in north-oriented cirques in the Gross-Walser valley and tried to date them using snowline-calculations on morainic ridges in one of the cirques. Following the same reasoning, the rock glacier complex here must be younger than a snowline of approximately 1650 m, which corresponds to a SLD of 910 m relative to A.D.1850 (compare MAISCH 1982 and KELLER 1988). This is slightly more than DE JONG and KWADIJK (1988) calculated.

The southern Ill valley flank between Groferberg and Tschalengaberg

This subarea is largely underlain by formations belonging to the East-Alpine nappe. The contact with the Vorarlberger Flysch (Arosa Zone has not been indicated on the geological map of HEISSEL et al. 1967) shows through differences in morphology, processes and landuse on both sides of the contact. It runs eastwards through sectors A/B3 (1160 m), approximately N on the boundary of B/C2 and eventually eastwards through the centre of the alluvial fan in sector C2.

The Flysch-underlain slopes in A2-3 show a step-wise arrangement of (sub)horizontal surfaces and gentle connecting slopes. The sub-horizontal surfaces are not primary sedimentary forms: they reflect lithological differences that were accentuated by the process of glacial erosion. The cover with glacial sediments, either of subglacial or supraglacial origin, is varying in thickness. Ice-marginal fluvial sediments are scarce; this is caused by the 'upstream' absence of sediment input sources. There are no important tributary valleys to the east that could supply gravels; moreover, the production of sediment along the eastern slopes mainly occurred as rockfalls and by sliding processes. At present, surficial flow processes are moderately active in A2-3, especially at places where ponding occurs, either on the weathering products of the Flysch bedrock, or on the cover of subglacial till. Comparison of land-use practice as recorded on the 1956 aerial photographs and the 1954 topographical sheets with the present situation shows a tendency for re-afforestation at the cost of hay lands.

The slopes underlain by the East-Alpine nappe (C/D2-3, E/F/G2-3) are characterized by:

- Steep slopes and vertical, west to east trending cliffs that follow the strike of competent formations such as the Muschelkalk and Arlberg Formations.
- Rockfall deposits and mantles of large blocks, the latter related to tensional spreading resulting in 'in situ' disintegration of the rock-mass (see also RUPKE & SELIMONSBERGEN 1991).
- Deep reaching slope deformation, mainly in the Muschelkalk Formation (C/D2), leading to broken-up slide segments, disturbed drainage patterns and the above mentioned mantle of large blocks. Comparable processes within the Muschelkalk Formation were observed on map sheet Nenzinger Himmel (C3). Isolated spots with glacial deposits overlying these deep reaching slope failures are possible indications of a pre-glacial age.
- Extensive scree production and accumulation, building scree slopes or only a veneer of scree on glacially modelled slopes.
- Concentrations of gneiss blocks were found on surfaces that were protected from the above mentioned processes, e.g. in D3, E3 and G3. The Ill-glacier had the possibility to dump its block load at these sites; they must not be regarded as important recessional phases during the deglaciation.

The north-eastern flank of the lower section of the Gamperdona valley

The evidence that the small catchments of the Dunkel- and Sägertobel (see Fig.2) preglacially existed is given by the presence the Gamperdona-conglomerates in their lower sections and the distribution of crystalline bearing glacial deposits e.g. near Falscherina Alpe (C4) and Käserlisdobden Alpe (B5). This also means that at least their lower sections were filled with sediments and their catchments taken in by the Ill-glacier to levels of at least 1360 and 1225 m respectively.

The triangular slope segments in between these small catchments (A3 and B/C4) are clear examples of glacially formed facets. A cover of ablation-like material with gneiss blocks at the surface covers the bedrock. Below approximately 1120m altitude these facets merge into less steep and/or (near)horizontal surfaces. These are dissected by numerous denudational/erosional niches that now show hardly a sign of mass wasting activity. The relict spurs that consequently formed are underlain by either hardrock or conglomerates. They have been covered by subglacial till or by gravel deposits of a predominantly local origin (A4). Similar relict spurs can be found on the opposite valley slope (map sheet Gurtis, F2-3) where they are also covered by non-lithified deposits. Taking into account the valley cross section at this site, it is likely that these spurs reflect the position of the base of the Gamperdona-glacier (glacial valley floor). The
gravels found on top could then belong to a Late-Glacial valley floor of the Mengbach at this level. This corresponds well with the position of the (fan)terrace at the western outlet of the Gamperdona-valley and the terraces between the Galina and Mengbach below approximately 1100 m.

The situation at Falscherina Alpe (C4) probably reflects an ice-marginal phase of the Gamperdona-glacier; crystalline fragments were not observed above 1400 m altitude on this side of the Gamperdona-valley. The 14 degree westward dipping terrace is built of local washed subangular to subrounded fragments (dolomite, limestone) and is partly cemented. However, Bundsandstein and gneiss were observed at 1360 m, proving that the Ill-glacier reached this position probably during an early-glacial phase.

Map sheet Nenzinger Himmel

The southernmost map sheet covers an area of more than 40 km² and includes adjacent frontier areas of Liechtenstein to the west (Malbun valley, sectors A/B1-2-3) and Switzerland to the south and southwest (sectors A6-7, B6-7, C7, D6-7, E6-7, F6-7, G6-7, H6-7). The upper Gamperdona-valley is dominated by waterdivides reaching over 2000 m altitude (see fig.1, Kuhgrat 2003 m, Augstenberg 2359 m, Naafkopf 2571 m, Salaruelkopf 2841 m, Panüelerkopf 2859 m, Blankuskopf 2334 m, Windeggerspitze 2331 m). The only active glacier in the Rätikon, the Brandner-glacier, develops from a plateau-like area and separates the Brandner- and Gamperdona valleys (sector G/H 5-6). The present snowline in this area is approximately 2610 m (KELLER 1988).

South of the Hauptdolomit mountain range of the Rauherberg (2094 m) and Fundl-kopf (2401 m), the U-shaped Gamperdona-valley suddenly widens into the basin in which the summer residence Nenzinger-Himmel (1370 m) is located. The catchment splits up into two valleys, the actual Mengbach-valley and the Salaruel-valley. The Hornspitze (2537 m) - Strahleck (2068 m) divide and the plateau-like elevation of Inner Panüel separate these two valleys.

The morphological conditions are in places strongly related to the underlying bedrock. The major forms often reflect and are adapted to geological-tectonical structures, and to differences in rock type. The Trübbach and opposite Virgloriatobel valleys have developed on the tectonic contact between the Fundl-Kopf-Alpila Scholle to the north and the Augstenberg and Gorvion-Schuppe to the south (see fig.5). The upper catchment of the Salaruel valley has fully developed in the Zimba-Schesaplana-Schuppe, the upper catchment of the Mengbach valley is located in the Gorvion Schuppe and Falknis nappe. Along the contact zones between the individual slices and nappes the Arosa-zone appears in smaller and wider zones.

Recessional morainic complexes within the basin of Nenzinger Himmel

Following KELLER (1988) an ice-margin can be reconstructed from ice-marginal relicts that are preserved along the eastern valley-side in sectors E2-3. Despite younger disturbance by mass movement, two ice-margins can be reconstructed, an upper phase that corresponds to the Schafbrücke phase and a lower second phase, here defined as the
Virgloriatobel phase. On the basis of ice surface gradients KELLER (1988) postulates the glacier front of the upper phase at the Scharfbrücke (maps heet Fundl-kopf, bridge in D3). The ice-front corresponding to the younger phase was probably located just north of the alluvial fan of the Virgloriatobel.

Relicts of valley fill deposits belonging to the Schafbrücke phase do not occur south of the ‘Schafbrücke’ bridge. It must be kept in mind however, that post-glacial removal and accumulation in this stretch of the Gamperdona-valley is substantial and former relicts may have been eroded or covered by debris-flow deposits, e.g from the Bärentüle (map sheet Fundl-Kopf, D4) or by the alluvial fans of the Trübbach and the Virgloriatobel (E1).

Photo 18. The summer residence Nenzinger Himmel is built on a series of morainic ridges deposited by the Salaruel glacier, thus protected by avalanches from the side terrain and flooding by the Tschalanzerbach. View to the NW, showing the Hauptdolomit divides with the Rauher Berg and the Trübbach catchment, running from top left to lower right.

The slightly younger Virgloriatobel-phase corresponds with three fan-terraces (E2) that were formed approximately 40 m below the Schafbrücke phase. The ice-marginal relicts on the eastern side of the valley, the fan terrace near the outlet of the Trübbach (sector D1, 1330m), and the ice-marginal morainic ridge at Zigerbödele (sector D3, 1420m) fit into the Virgloriatobel-Phase.

Photo 19. View from the alluvial fan of the Trübbach (fore-ground, map sheet Nenzinger Himmel, D1) to the SE, showing the ice-marginal relicts belonging to the Schafbrücke phase (transition forest-grass) and younger recessional phases, witnessed by a series of morainic ridges (hummocky terrain central fore-ground).
The topographic levels of the valley-fill deposits in front of the Gamperdona-glacier which are related to the Schafrüecke phase (1190m map sheet Fundl-Kopf, sector D3), correspond to the 1150 m level just SW of the Buchboden sediment fan (Fundl-Kopf, sector E2). The gradient of the former valley floor was 1.5-2 degrees, which is comparable to the present situation. The petrographical composition supports this correlation; Hauptdolomit fragments do not exclusively dominate the composition of the former valley floor deposits. The contact between the Salaruel and Mengbach glaciers was still existing during this phase; on the eastern flank of the valley rocktypes other than Hauptdolomit (Muschelkalk, Partnach-Schichten, Arlberg-Schichten and Raibler Formation) can be brought in by the Salaruel glacier. Using this correlation the Buchboden advance from the Grosstal must be accepted as almost equal with the recessional 'Schafrüecke' Phase. Almost, because the actual blocking of the Gamperdona-valley was caused by the sediment produced from the Grosstal-valley and not necessarily by the Grosstalglacier itself. Moreover, it is even acceptable that (dead-)ice downstream of Buchboden could have caused the initial rise of the erosion base.

Photo 20. View to the west in the Salaruel valley (map sheet Nenzinger Himmel), depicting the morphological situation in sector F4. The valley floor is covered by numerous morainic ridges, consisting mainly of Hauptdolomit fragments. On the background a small path crosses huge scree cones developing from the Oberzalimkopf (2340m) - Salaruel Kopf divide. These Late-Glacial ridges are responsible for the formation of the Hirschsee, the small lake seen in the centre of the picture

The younger recessional complexes in the Nenzinger Himmel basin are characterized by chaotic arrangements of blocky ablation deposits and are almost exclusively composed of Hauptdolomit fragments. This implies that contact with the Meng-glacier was lost. The complex further shows numerous depressions, abandoned meltwater outlets and an almost continuous cover of large erratic blocks. The internal structure of one of the hills that was leveled for the construction of a forest road in 1989 (location: E2, just south of the alluvial fan of the Trübbach), showed a disturbed vaguely layered sequence of very angular to (sub)angular gravel to cobble-sized Hauptdolomit fragments in a sandy matrix. The large amount of material was produced from slopes that gradually became ice-free and gave off substantial volumes of rockfall and scree. In the frontal part of the glacier this could easily lead to ice-cored masses of ablation deposits that were disconnected from the active glacier.

The Mengglacier lost contact with the Salaruel glacier probably during or just after the Schafrüecke phase. This is supported by the moraines of the Salaruel glacier that bulge southward into the direction of Güfelalpe (sector D3). The southernmost ridges are composed of Hauptdolomit fragments (see exposure in old gravel pit D3) as SCHMIDEGG (in HEISSEL et al. 1965, geol. map) already observed, and were not formed by the Güfelalpe glacier as suggested by KELLER 1988, Bd.I, p.89 and map: 'Die Vergletscherung der Nordabdachung des Rätikon im mittleren Spätwürm, Gauen Stadiums). The front of the Güfelalpe glacier was probably located just to the east of Güfelalpe (sector C/D5) were a complex of ablation deposits was formed at 1550 m altitude.

The next younger phases of glacier retreat within the Salaruel valley are documented by a series of morainic ridges between 1500 m (500 m west of the Tschalanzerbach spring-zone, F4) and 1800 m altitude (F4). At least five sub-phases can be distinguished. One of the more pronounced phases led to the formation of the 'Hirschsee', a local lake in F4, that is fed by springs at the foot of immense dolomitic scree- and debris-cones developed below the Oberzalimkopf (2340 m) and Spusangangcharte.

Ascending towards Panüelalpe (E4), the morphology is determined by ablation deposits of the Salaruel-glacier; a series of ice-marginal morainic ridges and terraces up to a level of 1800 m within the Panüelalpe depression (sector E4), must be attributed to the Late-Glacial decline of the Salaruel-glacier. If we consider this sequence which was also
described by KELLER (1988, Bd.I, pp. 90 and 195, Bd.II, pp.153), we must conclude that we deal with an almost undisturbed deglaciation sequence without indications of an advancing glacier. This would fit well with observations on ice-marginal remnants further downstream. KELLER attributes these 1800 m ice-marginal deposits to his Weissbad phase.

Within the small basin of Panieralpe the deposits of the Salaruel glacier have only partly been covered by a veneer of avalanche and rockfall deposits from the local Strahleck summit (2068 m, E4-5); the "Rundhöcker" at the northern edge of the depression are covered with blocks that were deposited along the Salaruel ice-margin.

Other important local Late-Glacial morainic ridges in the wider area of Nenzinger Himmel can be found at Inner Paniél in sectors D4/5 and E4. The outer ridges mark a distinct phase with a glacier snout freely hanging over the steep cliffs between the Stüberfall waterfalf (D4) and Galamant (1730m, E4) at a level of 1550m. There was no contact between the Paniél and Güfel Alp glacier at that time. The western outer ridge evolves at a level of 2130 m. Its narrow, elongated trend indicates that local conditions deviated rigorously from the 'model' glaciers that follow the AAR=0.67 ratio, presumably due to the northwestern exposition and the local colder climate created NW of the cliffs of the Paniél Schrifen. Therefore, correlation with regional Late-Glacial deglaciation phases based on snowline calculations is merely speculative here.

The Trübbach catchment.

The Trübbach catchment measures approximately 2km² and is located in sectors C/D 1/2, NW. of Nenzinger Himmel. Although its areal distribution is restricted, the morphological diversity is overwhelming. This is, in the first place, caused by the complex bedrock lithology. Tectonically, the Trübbach valley has developed on the boundary between the Fundlkopf-Alpila Schuppe to the north and the Gorvion Schuppe to the south, with Arosa-Zone rocks discontinuously exposed along the contact (see Fig.5).

The divide towards the basin of Malbun (Liechtenstein) is built of Raibler Formation (dolomite, limestone and gypsum). This implies that typical forms and processes are active, partly comparable to the situation in the Gampbach valley. This zone can be followed from the Gampbach valley over the Mattlerjoch into Liech-tenstein, bending eastwards again into the Trübbach valley further towards the Virgloriatoval valley/Amatschonjoch pass (G1). The second exposure (sector B2) is restricted to the divide just north of Sareiserjoch (ALLEMANN 1985).

North of the Trübbach stream the morphological development is a reflection of the Hauptdolomit overlying Raibler gypsum. The zone is followed from the Gampbach valley over the Mattlerjoch into Liechtenstein, bending eastwards again into the Trübbach valley further towards the Virgloriatoval valley/Amatschonjoch pass (G1). The second exposure (sector B2) is restricted to the divide just north of Sareiserjoch (ALLEMANN 1985).

The Trübbach catchment.

The drainage system has adapted to the morphological development; a series of springs and ponors occur in the steeply incised Trübbach. The stream itself behaves as a torrential stream (Wildbach); large amounts of non-lithified material can be mobilized during rainstorms along the channel and is introduced to the stream by slope failures. Blockage of the stream channel by debris, wood or other remnants can easily occur, especially in the stretch just west and east of the springs, where the channel is narrow and the activity of the slopes is highest. The alluvial fan in front of the catchment is composed for approx. 10-15% of gypsum fragments.

An intricate pattern of tensional systems has formed, the main systems trending NW-SE, the subordinate systems trending parallel to the local slope (in general E-W). These systems delineate deep-reaching failures within the gypsum; smaller surficial slides resulting from slope-parallel tensional systems determine the detailed morphological conditions.

Active erosional cuts that trigger planar slope failures have developed within unconsolidated deposits along the steeply incised Trübbach.

The drainage system has adapted to the morphological development; a series of springs and ponors occur in the sinkhole landscape, perennial streams are absent. The geochemical waterbalance is controlled by the gypsum-equilibrium in the subsurface north of the Trübbach. This is reflected in the electric conductivity: values over 2000 mS/m were measured. 'Normal' values, not exceeding 500 mS/m were recorded in springs south of the Trübbach.

A remarkable occurrence of large conglomerate blocks at the junction of the Trübbach channel and the important northern incision in gypsum in C1 (1580 m) explains the presence of red Verrucano-like sandstones downstream in the stream channel; they are common within these conglomerates. The geological map of HEISSEL et al. (1967) mentions the equivalent of a Mindel-Riss conglomerate at this site. In this position it seems more plausible that they fit into bedrock series of the Arosa-Zone. Blockage by a glacier at this altitude is doubtful here and a source for these red sandstones is lacking.
Only the upper part of the catchment has not been altered by mass movement, solution and erosion and kept its
glacial appearance. Three morainic ridges witness the Late-Glacial period when snowlines temporarily stabilized at
1880-1900 m with W to NW exposition (sector C1-2).

The northern boundary is formed by the steeper slopes bordering the Trübbach, its eastern boundary is a relict spur,
that separates the area from the 200m heigh slope segment from the present level of the Nenzinger Himmel basin.
Erosional/denudational slopes border the Trübbach stream. The groundwater table is cut by the surface here, which is
demonstrated by several springs and wet zones; solifluction is an active process and is favoured by the large amount of
fines in the material involved. This material originates from weathering mainly of the Raibler-Formation and Arosa-
Zone and locally, from morainic material.

Deep reaching slope failures

In the area SE of the Spitz summit (2186), Güfeleck, Füliwand, and Sieben Brunnen (sectors C3-D3) deep-reaching
slope failures determine the morphology. To the north the cirque of 'Beim Schopf' (C2-3), to the south the Stafeldon
Alpe area (C3-4) delineate the instable area. The area has subsurface drainage, apart from the 'Siebenbrunnen'. This is a
series of springs on the western contact of Arosa-Zone rocks and Anisien Limestone (Muschelkalk). The Arosa-Zone
reflects the tectonic contact between the Gorvion- and the Augstenberg Schuppen (Fig.5). According to LOACKER
(1971) internal water movement along the base of the Gorvion-Scholle is responsible for the series of springs located
between Stüberfall (sector C4) and Nenzinger Himmel. From the geomorphological map it can be seen that the area
without surface drainage coincides with the mass movement zone. This also explains the absence of major alluvial fans
below these slopes. Two subzones are recognized within the area affected by deep reaching slope failure:
1) A southern zone underlain by Muschelkalk; deep-reaching fissures, some of them more than 400 m long, dissect the
Muschelkalk. Their observed width locally exceeds 15 m. Their observed depth is in the order of several hundred
metres. Separate bedrock slabs moved down in a predominantly SE direction. The local slope is oversteepened by
glacial erosion of the Stafeldon-glacier. Below 1600 m altitude the steep-sided cliffs that surround the Nenzinger
Himmel basin, are accompanying destabilizing factors.

A major slightly curved 1 km long SE-NW trending discontinuity plane (D3-C3) forms the abrupt transition towards
the northern subzone:
2) This area has developed further with respect to 1). A steep backscarp that accompanies this fissure plane has given
off large rockfall masses. Therefore the area downslope towards Zigerbödele (D3) is more or less continuously covered
by rockfall debris. Older sliding rock-masses that presumably predate the last glaciation, have been buried. The present
fill of the Nenzinger Himmel basin, locally >100 m of non-lithifird material (see chapter 3: geophysical measurements),
contributed to partial stabilization of this deep-reaching slope failure.

Photo 21. Active deep-reaching rock-slide (Code: MRTR in the hazard zonation legend) re-shaping the oversteepened
cirque slope in Couches Rouges (map sheet Nenzinger Himmel, B5-6). Numerous fissures on the southern adjacent
plateau indicate future instable development.

The subarea east of the Naalfkopf (2571 m)

The larger part of this subarea is formed by the plateau-like planation surface of Barthümelalpe and is underlain by
Cretaceous Couches-Rouges (limestone), Gault-Flysch (sandstone) and Tristel Formation (limestone) (ALLEMANN
1985). The area is located above 2100m, which is also above the timberline (1800 m). The surface morphology is characterized by undulating elongated ridges and intervening depressions that are controlled largely by the direction of the geological strike. Folding axes between the Trübbach catchment and this area run E-W to SW-NE (RICHTER 1958). This is reflected in the direction of the cirque development (compare the cirques of Vermales, Stafeldon and the valley just northeast of the Naafkopf (sector B4-5-6). The southern central valley slope has been altered by deep-reaching rockslope failures. Elongated slabs of bedrock have been released from the steep rock-cliff and partially merged into rockfall. Movement continued until the opposite valley slope was reached; this valley closure process is still active at present. A ridge in a central position in the valley is indicated as a morainic ridge on the geological maps of ALLEMANN (1985) and HEISSEL et al. (1967). In fact this ridge is part of the valley closure and consists of coarse rockfall debris released from the southern slope. From the aerial photographs slightly curved discontinuities that dissect the plateau can be traced. They are often accompanied by distinct steps in the terrain and probably indicate initial movement.

The slopes southwest of Panüelalpe are underlain by Arosa-Zone bedrock (HEISSEL et al. 1965, ALLEMANN 1985). However, a distinct gypsum karst depression with a diameter of 50m, has developed on this southwestern flank. It must therefore be concluded that locally gypsum of the Raibler Formation is mixed up with the Arosa-Zone rocks, a tectonic process that was described earlier by KOBEL (1969) and is similar to the slopes underlain by the Arosa-Zone half-window in the Gampbach valley.

Two other small catchments have developed on the eastern flank of the Nenzinger Himmel basin; the Virgloria valley to the north and the Setch valley to the south. Ice-marginal relicts are scarce within these catchments. During the formation of the ice-marginal terraces on the eastern flank of the main valley in sector E2, the contact with the Gamperdona-glacier was already lost. The upper section of the Setch valley could have been occupied by a small glacier with a snout at approx. 1600 m, fitting into the small morainic ridge that is preserved at 1680 m in the NW corner of sector F3. Contact with the Gamper-dona glacier only existed during the Virgloriatobel phase and older phases.

On the northern flank a SE-NW trending succession of shallow karst depressions were formed; some of the depressions are related to (former) spring activity. Unlike gypsum karst depressions their morphology is not pronounced (low-gradient inner slopes) and their depth is restricted to several m. The geological position however, in close relationship with the Arosa-Zone and Raibler Formation (few exposures), does not exclude that gypsum is involved here.

The Virgloria valley shows a typical lower fluvial section below approximately 1650 m altitude, mainly developed in bedrock series belonging to the Raibler Formation. The steep SE slope above 1900m (Setscher Freschen, F/G2) between the Blankuskopf and the Windecker-spitze exists of Muschelkalk limestone, Partnachschiefer and Arlberg-schichten. The less steep intermediate zone is underlain by bedrock from the Arosa-Zone Formation. The lower section has partly been filled by subglacial till of the Gamperdona-glacier (E1-2). This is supported by its petrographical composition (amongst others: red limestone, green-sandstone). South of the Virgloriatobel, opposite to and slightly higher than the apex of its alluvial fan, compact debris and mudflow-like (overridden?) deposits were observed directly overlying bedrock.

One must take into account the possibility that the lower section of the Virgloriatobel catchment was blocked by the advancing early-glacial Gamperdona-glacier, a similar interaction as existed between the Ill-glacier and its tributary valleys.
3. Appraisal of the geotechnical units

Introduction

In this chapter it will be shown how the geomorphological map can serve as a basis for the interpretation and appraisal of geotechnically homogeneous soil and rock units. The distribution of the non-lithified materials is given special attention. Geotechnical maps show the distribution of homogeneous engineering soil- and rocks-units at the (near) terrain surface. In many cases additional information, presenting specific properties of the materials involved has been included. Traditionally such maps are based on, and derived from available geological maps of the same area (YU IL HYON, 1983, RENGERS et al. 1990). In Vorarlberg however, where a large part of the landscape has been covered by Quaternary deposits, it appeared that the representation of surficial deposits on the available geological maps is too general and partly based on mis-interpretations of the sediments involved (see also SIMONS 1985). The geotechnical maps have not been constructed for a specific purpose, but must be regarded and used as general purpose maps, with possibilities for further maps which emphasize more specific characteristics (e.g. RUPKE and SEIJMONSBERGEN, 1991). Forestry organisations in Vorarlberg already make use of the available geotechnical maps for future planning; results thus far (unpublished data, Agrargemeinschaft Nenzing) indicate conformity between terrain units differentiated on the basis of parent material (geotechnical units) and homogeneous vegetational units. An obvious follow-up would be further research, focussing on this landscape-ecological relationship (VAN NOORD, in prep.) and processing the data using a GIS.

The geomorphological map enables one to determine and delineate relevant geotechnical units, because it shows the discontinuous transitions that exist between and within land-units. The rock-type is derived from the available 1:25,000 scale geological maps (HEISSEL et al.1967, ALLEMANN 1985). In the next sections the method of map construction will be explained. The dimensions of the mapped area and the available time were such that it was impossible to accomplish a complete description and sampling programme covering all geotechnical legend units. This goal is any how difficult to achieve. The variability of relevant soil and rock parameters within geomorphological units or terrain mapping units (MEYERINK 1988) that have been used here, with the emphasis on material distribution, is such that far more samples should be taken for a complete and statistically relevant picture. The additional information given here should therefore be evaluated as a quick reference for general use, also seen in the light of the fact that "site data" cannot simply be transferred to other terrain units that are thought to have similar conditions. The geotechnical maps are a mosaic of approximately 3000-3500 polygons. The emphasis is lain on the determination of relative rock-strength using a Schmidt-Hammer device, sedimentological/petrographical information and geophysical data. Descriptions of comparable units surveyed by SEIJMONSBERGEN & VAN WESTEN (1986/1988), who based their descriptions on the method used by the ITC (see RENGERS et al.1990), have also been used and are supplemented with literature data and own observations.

A method of defining geotechnically homogeneous soil and rock-units

The steps leading to the construction and representation of the transparent geotechnical overlay maps cannot be defined. The diagram (Fig.20) shows the major steps involved in the construction of these maps.

Figure 20. Steps visualizing the preparation of the geotechnical maps.
The main steps can be further explained:

step 1) Engineering soil units are directly depicted from the geomorphological map sheets. In the first place, the surficial materials were examined. Their recognition and areal distribution is strongly based on the cartographic representation of materials as they have been presented in figure 7. In most cases the identification of homogeneous units was a matter of delineating landforms and materials; most interpretation has already been stored in the geomorphological maps. In some cases however, additional interpretation, requiring some pattern analyses is necessary. In these situations the following considerations were made:

- Ice-marginal drainage activity is often associated with coarse-grained fluvio-glacial outwash-material and fluvial deposits (sand, gravel). In some circumstances only erosive forms, without evidence of corresponding deposits, have been preserved. The constituting material is then depending on the surrounding land-unit,

- Covered-karst areas have been mapped in brown colours, emphasizing the collapse processes acting there. The constituting materials however, can exist of glacial, ice-marginal or scree products that, in most cases, have not substantially been altered by the collapse processes,

- On the basis of local and regional knowledge of ice-flow patterns and extrapolation of minimum-maximum heights of valley fill deposits, certain (sequences of) unconsolidated materials (e.g. lake-bottom clays/silts) can be expected in special positions. As these special sediments have often been indicated as subglacial till (they have been overridden by ice), large variations in geotechnical properties can be expected,

- The occurrence of residual soils is interpreted indirectly because they have not primarily been indicated by special symbols. Their occurrence is closely related to subhorizontal surfaces such as glacially scoured transfluence cols and other flat-lying bedrock and preserved surfaces (e.g. relict ridges) in mass movement zones,

- Areas with more than one type of material are indicated when these materials are present in a discontinuous manner or when the underlying unit is known. For instance, a subarea underlain by subglacial till can be covered by a discontinuous mantle of solifluction material as a result of the susceptibility of the till to this type of mass movement. The solifluction mantle will always be superposed on the subglacial till; therefore the code belonging to the solifluction mantle (LES) will be placed above the till in the corresponding unit represented on the geotechnical map.

Whereas the spatial boundaries of locally produced scree- and rockfall deposits can directly be taken from the geomorphological map, the composing rock-type is extracted from the geological maps and checked in the field during the mapping programme.

step 2) The formations and boundaries of rocks that are exposed in the area were examined with the available geological maps and literature. These boundaries were not merely adapted but were carefully compared with the position of morphometrical elements on the geomorphological maps. This can give additional information on differences in resistance and to weathering and erosion, such as escarpments and the presence of solution hollows in the case of covered karst. The need to do this emerged largely from the scale difference between the geomorphological maps (1:10.000) and the geological maps (1:25.000). Moreover, it appeared that typical glacially scoured surfaces that were mapped as hardrock overlain by a restricted mantle of scree on the geomorphological maps, were not indicated on the geological maps as hardrock. A combination of soil and rock codes was used in these cases.

A substantial part of the study area has been presented on the geological map of HEISSEL et al. (1967) and on the map prepared by ALLEMANN (1985). For certain areas, they show substantial differences in the geological information presented. The ultimate choice of the data used in the geotechnical maps is fully this author's responsibility.

step 3) In order to arrange and subdivide the hardrock units according to their Unconfined Compressive Strength (UCS), simple measurements were made in the field by means of a Schmidt-Hammer device. Based on these values the rock-types were ordered in a legend containing three rock-strength classes.

Special attention is paid to areas that are underlain by disintegrated hardrock. The disintegration is caused by relatively deep-reaching slope deformation. The vertical transition of the non-altered hardrock towards the weathered rock-mass is often a vaguely defined transitional zone with qualities of both rock- and soil-units. The degree of mechanical decomposition of the rock-mass is expected to be much larger in such areas. A dotted signature is used to indicate these areas, which can be derived directly from the geomorphological map.

step 4) The field programme emphasized a restricted number of topics. Sedimentological descriptions proved very useful in determining some additional geotechnical properties of a number of non-lithified material units, such as textural differences, layering, roundness of particles and sorting characteristics. The field descriptions were supplemented with the outcome of geophysical profiles, petrographical sample analyses, E.C.-measurements and supporting data from literature. Additional field sampling and testing as was performed in the Hintere Bregenzerwald area by SEIJMONSBERGEN & VAN WESTEN (1986/1988) using field vane, cone- and pocket penetrometer, proved unsatisfactory in the present area. These tests require fine-textured materials, which are very scarce here.

After the completion of the final legend the geotechnical maps were drawn using a light-table. The structure of the legends is explained in the next section.

The classification of geotechnically homogeneous soil units

The legend for geotechnical soil units is given in figure 21. Only those units occurring in the study area have been given. At first, groups have been separated: non-lithified materials (soil units) versus hardrock (rock units). All
Quaternary materials are regarded here as soils, including the partly cemented 'Gamperdona' conglomerates and equivalent breccias.

The basic distinction amongst the geotechnically homogeneous soil units is related to genesis, depositional process and evolution in time. It is assumed, that the initial geotechnical properties of the engineering soils recognized, in most cases depend on the geomorphological environment in which they were formed. Exceptions are the cemented and compacted deposits that both have properties acquired after deposition.

<table>
<thead>
<tr>
<th>Code</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA</td>
<td>Antropogeneous materials, refuse dumps</td>
</tr>
<tr>
<td>LO</td>
<td>Peat and organic rich material</td>
</tr>
<tr>
<td>LV</td>
<td>Residual soils, derived from:</td>
</tr>
<tr>
<td>LVK</td>
<td>Limestone</td>
</tr>
<tr>
<td>LVD</td>
<td>Dolomite</td>
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<tr>
<td>LVS</td>
<td>Sandstone</td>
</tr>
<tr>
<td>LVM</td>
<td>Marls</td>
</tr>
<tr>
<td>LVV</td>
<td>Various rocktypes</td>
</tr>
<tr>
<td>LF</td>
<td>Fluvial deposits (Postglacial)</td>
</tr>
<tr>
<td>LFF</td>
<td>Valley-fill</td>
</tr>
<tr>
<td>LFS</td>
<td>Alluvial fan deposits</td>
</tr>
<tr>
<td>LFT</td>
<td>Terraces</td>
</tr>
<tr>
<td>LE/B/S</td>
<td>Mass movement deposits</td>
</tr>
<tr>
<td>LE</td>
<td>(Earth) flow material</td>
</tr>
<tr>
<td>LES</td>
<td>Solifluction deposits, colluvium</td>
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<td>Earthflow material</td>
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<tr>
<td>LEM</td>
<td>Debris flow material</td>
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<td>LS</td>
<td>Fine scree material:</td>
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<td>LSK</td>
<td>Limestone</td>
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<tr>
<td>LSD</td>
<td>Dolomite</td>
</tr>
<tr>
<td>LSDb</td>
<td>Dolomite breccia, cemented</td>
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<tr>
<td>LSS</td>
<td>Sandstone</td>
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<tr>
<td>LSM</td>
<td>Marl</td>
</tr>
<tr>
<td>LSV</td>
<td>Various rocktypes</td>
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<tr>
<td>LB</td>
<td>Rockfall material and very coarse scree:</td>
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<td>LBK</td>
<td>Limestone</td>
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<tr>
<td>LBD</td>
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<td>LBS</td>
<td>Sandstone</td>
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<tr>
<td>LBV</td>
<td>Various rocktypes</td>
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<td>LG</td>
<td>Glaciolacustrine and –fluviatile deposits</td>
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<td>LGT</td>
<td>Terraces (fluvial and deltaic)</td>
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<td>LGF</td>
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<td>Lake bottom deposits</td>
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<td>LMA</td>
<td>Ablation till</td>
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<tr>
<td>(z)</td>
<td>Cemented deposits other than K and B</td>
</tr>
<tr>
<td>K,B</td>
<td>The distribution of the so-called Gamperdona-conglomerates and breccias</td>
</tr>
</tbody>
</table>

_Figure 21. Legend of the geotechnical soil units._

On the highest level, the units of the legend are a direct translation of the terms used for the materials represented on the geomorphological maps (see fig.7). Ten groups/classes were recognized. At a lower level they comprise a total of 30 soil units.

Group 1 (LA) and 2 (LO) have not been subdivided on a lower level.
The residual soils (LV) are indirectly derived from the geomorphological maps. They have been subdivided according to the parent material from which they develop. The type of parent material (limestone, sand-stone, dolomite) is determined from the geological maps and checked during the field programme.
Photo 22. Example of classification of rock and non-lithified deposits. Typical view from the Rätikon mountains (Salaruel valley, map sheet Nenzinger Himmel, E3): waterdivides existing of Triassic Hauptdolomit (code: GHD), corresponding scree cones (code LSD) merging into a valley floor, covered by ablation deposits. Morainic ridges (code: LMA) have been partly eroded and covered by fluvial deposits (code: LFS, foreground).

The Flysch Formations and the Raibler Formation consist of alternations of marl, sandstone, limestone and transitional rocks. The residual soils that develop from those formations have been denoted separately with the notation LVV.

The fluviatile deposits have been divided in the first place according to the period in which they were deposited (Holocene=LF versus Pleistocene=LG) and in the second place on geomorphological setting. Three classes were recognized within the Holocene fluviatile sediments: valley floor deposits, alluvial fan deposits and terraces. It must be reminded that alluvial fans seldom are composed of merely fluviatile sediments in mountain environments. Debris-flows and avalanches often contribute more than 50% to the accumulated material, as was observed for instance in an artificial exposure in the alluvial fan on map sheet Dünza-Tschengla in sector D2, which is used as a rubbish-dump.

The materials that originate from mass movement activity have been divided according to the type of movement into flow material (LE) and fall material (LS/LB). This type of movement leads to soil units that are characterized by their own specific geotechnical parameters, contrary to slide-processes, in which the soil elements remain more or less intact within the relevant terrain unit. Therefore, "slide-materials" were not separated.

Photo 23. East-Alpine Arlberg Formation (code: GMVf) overlain by consolidated lacustrine lake-bottom deposits (code: LGSk) along the road Stellfeder-Nenzinger Himmel.
Solifluxion deposits (LES) comprise all materials that were formed by the slow downhill movement of water-saturated, predominantly fine-grained detritus. The diverse nature of the parent material is of great influence on the material properties of this legend unit. Two other mass flow deposits could be recognized on the geomorphological map and have been entered in the geotechnical legend as debris-flow deposits (LEE), including earth-flow deposits, and mud-flow deposits (LEM). They are differentiated mainly on textural variations.

The separation into fine scree material (LS) and rockfall material (LB) is based both on process and on fragment size. The material classified as LB is mainly composed of blocks larger than 0.5m³. Their spatial distribution is derived from the geomorphological maps. Similar to the sub-classification of the residual soils (LV) the scree and rockfall materials have been subdivided according to their composition. Group 8 includes glacio-lacustrine and -fluviatile deposits. The main difference between legend unit LFT (holocene terraces) and LGT (ice-mar-ginal terraces) is the abundant occurrence of (older) glacial sediments in the LGT-units. The raised position of the ice-marginal systems in the terrain and the different hydrological regimes are additional reasons to assume that the geotechnical properties and thus the behaviour of these materials will be different. Another difference is e.g. expressed in the presence of organic material in the LFT units and the absence of organic matter in the LGT units. Legend unit LGT also includes the coarse-grained deltaic deposits (top- and fore-set beds). The fine-grained fraction of the ice-dammed lake deposits have been subdivided according to their state of consolidation (LGSk, LGSKn) which is a discriminating geotechnical factor and of major importance in the appraisal of slope stability. Some geotechnical data published by VAN GELDER et al. (1990) have been reproduced in table 2.

The materials that have been deposited directly by glaciers have been separated only into subglacial- (LMG) and ablation-till (LMA), although other types of glacial deposits were also met in the field, such as flow-tills’ (debris-flows derived from the ice-margin, see DE JONG & RAPPOL 1983). The main differences in geotechnical properties however, are sufficiently reflected in the simple subdivision in the units LMA and LGM.

### Table 2. Some properties of geotechnical soil unit LGSk (after VAN GELDER et al. 1990). Samples 1-3 are from the study area.

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>CaCO₃ (%)</th>
<th>Texture¹</th>
<th>M.C.⁵ (%)</th>
<th>P.L.⁶ (%)</th>
<th>L.L.⁷ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mengbach</td>
<td>?</td>
<td>sl</td>
<td>16.6</td>
<td>16.8</td>
<td>29.4</td>
</tr>
<tr>
<td>2</td>
<td>Garfetschentobel</td>
<td>67.1</td>
<td>s</td>
<td>12.9</td>
<td>17.9</td>
<td>30.4</td>
</tr>
<tr>
<td>3</td>
<td>Garfetschentobel</td>
<td>58.1</td>
<td>sl</td>
<td>14.2</td>
<td>21.1</td>
<td>37.2</td>
</tr>
<tr>
<td>4</td>
<td>Dafins</td>
<td>44.8</td>
<td>s</td>
<td>15.9</td>
<td>-</td>
<td>26.5</td>
</tr>
<tr>
<td>5</td>
<td>Frutzbach</td>
<td>28.6</td>
<td>s</td>
<td>21.2</td>
<td>26.9</td>
<td>30.5</td>
</tr>
<tr>
<td>6</td>
<td>Ebneterache N</td>
<td>43.9</td>
<td>s</td>
<td>18.7</td>
<td>22.8</td>
<td>38.2</td>
</tr>
<tr>
<td>7</td>
<td>Ebneterache S</td>
<td>36.1</td>
<td>s</td>
<td>18.1</td>
<td>20.8</td>
<td>35.6</td>
</tr>
<tr>
<td>8</td>
<td>Bizau</td>
<td>52.3</td>
<td>s</td>
<td>19.0</td>
<td>23.0</td>
<td>25.0</td>
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<td>9</td>
<td>Schwarzenberg</td>
<td>49.4</td>
<td>s</td>
<td>12.6</td>
<td>17.3</td>
<td>22.7</td>
</tr>
</tbody>
</table>

¹Texture: s-silt, s-silt/loam, cl-clay, sc-silty clay
²Texture before decalcification
³Texture after decalcification
⁴CaCO₃: carbonate content
⁵M.C.: moisture content (field)
⁶P.L.: plastic limit
⁷L.L.: liquid limit

A fragment of the geotechnical map sheet Gampberg is shown in figure 22. The geomorphological situation was discussed earlier (chapt.2) and visualized in Fig.17a. Some remarks should be made here:
In certain cases combination of soil and rock units is only logical. The Gumperdona conglomerates (K) or the Raiber Formation (GMVe) produce scree material of varying composition, the corresponding code will always be scree material (LSV) or rockfall material (LBV) of various rock types. This reflects the heterogeneous nature of these parent materials.

In certain areas only the code LM has been used; this implies that interpretation of the type of till was not assured.

For areas where only thin patches (thickness <0.5m) of loose material were observed the underlying bedrock has been represented.
Table 3. Summary of geotechnical properties of soil units.

<table>
<thead>
<tr>
<th>Code</th>
<th>L Per.</th>
<th>Inf. Cap.</th>
<th>CP</th>
<th>Dens KN/m³</th>
<th>WPB %</th>
<th>WPC %</th>
<th>WPG %</th>
<th>WPS %</th>
<th>WPF %</th>
<th>UCSC Class</th>
<th>suit. constr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m)</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>LA</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LO</td>
<td>A,F</td>
<td>L-vH</td>
<td>L</td>
<td>A-sR</td>
<td>10-15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>var</td>
<td>Pt,OH</td>
</tr>
<tr>
<td>LVK</td>
<td>A</td>
<td>vL</td>
<td>L</td>
<td>A</td>
<td>18-22</td>
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<td>&lt;5</td>
<td>95%</td>
<td>CH,CL</td>
<td>?</td>
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<td>L</td>
<td>A-M</td>
<td>L</td>
<td>A</td>
<td>12-17</td>
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<td>&lt;15</td>
<td>&lt;60</td>
<td>&gt;10</td>
<td>SW,SM</td>
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<td>A-M</td>
<td>M-L</td>
<td>A-P</td>
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<td>&lt;10</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>&lt;55</td>
<td>CH,SM,CL</td>
<td>-</td>
</tr>
<tr>
<td>LFF</td>
<td>C</td>
<td>H-vH</td>
<td>H</td>
<td>R-sR</td>
<td>16-25</td>
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<td>&lt;20</td>
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<td>H</td>
<td>sA-R</td>
<td>16-25</td>
<td>&lt;15</td>
<td>&lt;25</td>
<td>&lt;55</td>
<td>&lt;30</td>
<td>&lt;25</td>
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<tr>
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<td>sR-R</td>
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<td>&lt;30</td>
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<td>GW</td>
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<tr>
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<td>vH</td>
<td>vH</td>
<td>A,B</td>
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<td>vH</td>
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<td>vH</td>
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<td>vL</td>
<td>A-R</td>
<td>17-20</td>
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<td>0</td>
<td>?</td>
<td>&lt;30</td>
<td>&lt;95</td>
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<tr>
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<td>imp.</td>
<td>vL</td>
<td>sA-R</td>
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<td>&lt;45</td>
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<td>&lt;45</td>
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<tr>
<td>K,B</td>
<td>F,vL</td>
<td>M-H</td>
<td>L-vH</td>
<td>sA-R</td>
<td>19-24</td>
<td>&lt;15</td>
<td>&lt;35</td>
<td>&lt;55</td>
<td>&lt;20</td>
<td>&lt;10</td>
<td>GW,GP</td>
</tr>
</tbody>
</table>

Layering (A-absent, F-faint, C-clear, Cr-crude stratification)
Per. Permeability (vL-very low, L-low, M-medium, H-high, vH-very high, imp. impermeable)
Inf. Cap Infiltration capacity (vL-very low, L-low, M-moderate, H-high, vH-very high)
CP Shape of coarse particles (A-angular, sR-subrounded, P-platy, R-rounded, B-blocky)
Dens. Density
WPB Weight percentage boulders (>20 cm), C-cobbles (7.5-20 cm), G-gravel (4.5 mm-7.5 cm), S-sand (0.075 mm-4.75 mm), F-fines (<0.075 mm)
USCS Class UCSC classification
suit.cons. suitability as construction material (use as fill, roadstone, armourstone (++ very useful, +possible use, -no use)

The classification of geotechnically homogeneous rock-units

The rock-units have been subdivided on the basis of their compressive strength properties. The compressive strength is the ultimate strength at failure under a compressive stress. In engineering circles it is a common parameter, in geomorphology it can be an indication of the competence and resistance against erosion or denudation of the rocks. In many unstable situations, in which tensile fissuring or toppling prevails, the tensile strength properties will be of greater importance. The results of the strength measurements presented here are intended only for local classification purposes and should not be adapted as absolute figures. Field testing was done using an 'L-type' Schmidt-Hammer. The localities of field measurements have been indicated on the geotechnical maps. The instrument measures the rebound value of a spring-impelled hammer striking a rock surface. The values obtained by Schmidt-Hammer rebound tests are depending on the open-ness, joint frequency and freshness of the rock tested. The test surface must be free of algae, weathering crusts, moisture, joints and other irregularities. These conditions however, could not always be fulfilled. To arrive at reliable results 15 readings were taken which should be within 3.5% of the average value. The ultimate rebound number (R) is then calculated according to:

\[ R = \frac{\Sigma r \times 74}{\Sigma r} \]

where \( \Sigma r \times 74 \) is the sum of all readings and \( n \) is the number of readings taken. The instrument measures the rebound value in lab.
In literature correlations are given between the Schmidt-Hammer rebound number and the compressive strength. Taking into account the rock density and the angle under which the rock surface has been tested, the Unconfined Compressive Strength (UCS) was determined for most of the rock-types. In figure 23 the percentage (central Y-axis) Schmidt-Hammer rebound values per class (classes of five, indicated below X-axis) and the corresponding UCS classes (weak, moderate, strong, below X-axis) have been plotted. This was done for six of the most important rock formations. The rocks have been subdivided on the basis of the following UCS values:
- Rocks with low and very low Unconfined Compressive Strength (U.C.S. < 20 MPa),
- Rocks with moderate U.C.S. values (20-60 MPa),
- Rocks with high to very high U.C.S. values (>60 MPa).
subdivisions cannot be represented in mapform, and are best included in the Formation.

Leaving out these boundaries would reduce the eloquence and use of the map drastically. An exception to this rule is the occurrence of gypsum within the Raibler Formation. Its crucial role in the geomorphological evolution justifies its classification as an individual legend unit,

- access to the available literature will be easier, especially without the support of all geological maps.

The legend codes for the rock-units are constructed as follows: (note: the capitals used are abbreviations of the German definitions)

for legendcode GHKg: G = Rock (Gestein); K = Limestone (Kalk) H = high U.C.S. (Harte Gesteine); g = suffix indicating the Muschelkalk Formation

Material descriptions of the distinguished rock-units have been compiled and are given in table 4.

### Rocks with High Strength (U.C.S. = >60 Mpa)

<table>
<thead>
<tr>
<th>Legend Code</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHKd</td>
<td>Kössenerkalk, Rätoliaskalk, Rote, Liaskalk</td>
</tr>
<tr>
<td>GHKe</td>
<td>Couches Rouges</td>
</tr>
<tr>
<td>GHKf</td>
<td>Plattenkalk</td>
</tr>
<tr>
<td>GHKg</td>
<td>Muschelkalk</td>
</tr>
<tr>
<td>GHD</td>
<td>Hauptdolomit Formation</td>
</tr>
<tr>
<td>GHS</td>
<td>’Gault’ Formation</td>
</tr>
</tbody>
</table>

### Rocks disintegrated by mass movements

- Location of geophysical profile
- GE = geo-electrical resistivity sounding
- EM = electro-magnetic profile
- Location of Schmidt-Hammer measurement
- Location of petrographical sample
- Quarry, pit

### Rocks with moderate strength (U.C.S. = 20-60 Mpa)

<table>
<thead>
<tr>
<th>Legend Code</th>
<th>Name</th>
</tr>
</thead>
<tbody>
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<td>GMKe</td>
<td>Aptychenschichten/Rote Radiolarite</td>
</tr>
<tr>
<td>GMS</td>
<td>Reiselsberger Sandstein Formation</td>
</tr>
<tr>
<td>GMSb</td>
<td>Buntsandstein Formation/Verrucano</td>
</tr>
<tr>
<td>GMVb</td>
<td>Flysch Formations</td>
</tr>
<tr>
<td>GMVe</td>
<td>Arosa zone Formations</td>
</tr>
<tr>
<td>GMVd</td>
<td>Kreideschiefer</td>
</tr>
<tr>
<td>GMVf</td>
<td>Albergschiechten</td>
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<tr>
<td>GMVg</td>
<td>Partnachschiefer</td>
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<tr>
<td>GGMMe</td>
<td>Allgäu- and Kössenerschichten Fromations</td>
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<tr>
<td>GGMf</td>
<td>Liasfleckennergel Formation</td>
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<tr>
<td>GGG</td>
<td>Gypsum</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Legend Code</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGG</td>
<td>Gypsum of the Raibler Formation</td>
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</tbody>
</table>

Figure 24. Legend of the geotechnical rock units.
Table 4. Summary of geotechnical rock properties.

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<th>col. fract.sp. (CM)</th>
<th>layer th. (CM)</th>
<th>permeabi-lity</th>
<th>blocksize (cm)</th>
<th>density (kN/m³)</th>
<th>suit. constr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHKd</td>
<td>57-115</td>
<td>G,R sm-m, wide</td>
<td>5-40</td>
<td>high</td>
<td>16x20x13</td>
<td>23-25</td>
<td>++</td>
</tr>
<tr>
<td>GHKe</td>
<td>not det</td>
<td>R,G sm-wide</td>
<td>20-200</td>
<td>very high</td>
<td>10x10x15</td>
<td>22-25</td>
<td>+</td>
</tr>
<tr>
<td>GHKf</td>
<td>not det</td>
<td>IG-dG small</td>
<td>10-100</td>
<td>very high</td>
<td>5x7x10</td>
<td>appr.25</td>
<td>++</td>
</tr>
<tr>
<td>GHKg</td>
<td>50-245</td>
<td>dG-BG m.w-wide</td>
<td>10-100</td>
<td>very high</td>
<td>blocks ?</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>GHD</td>
<td>45-255</td>
<td>Ig-dG small</td>
<td>10-300</td>
<td>very high</td>
<td>5x7x10</td>
<td>appr.25</td>
<td>++</td>
</tr>
<tr>
<td>GHS</td>
<td>34-130</td>
<td>Gr-dG sm-m.wide</td>
<td>15-75</td>
<td>very high</td>
<td>17x19x14</td>
<td>20-26</td>
<td>+</td>
</tr>
<tr>
<td>GMS</td>
<td>38-140</td>
<td>BG-IG sm-m.wide</td>
<td>20-200</td>
<td>very high</td>
<td>21x15x14</td>
<td>23-26</td>
<td>+</td>
</tr>
<tr>
<td>GMSb</td>
<td>not det</td>
<td>R, Gr wide</td>
<td>&lt;100</td>
<td>high</td>
<td>not det ?</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>GMVb</td>
<td></td>
<td></td>
<td>6-75</td>
<td>very low</td>
<td>20-27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sst</td>
<td>62-95</td>
<td>IB-G m.small</td>
<td>&lt;50</td>
<td>medium</td>
<td>14x10x5</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Lst</td>
<td>43-145</td>
<td>IG-dG m.small</td>
<td>&lt;30</td>
<td>high</td>
<td>12x9x10</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>20-50</td>
<td>dG-B v.small</td>
<td>&lt;15</td>
<td>very low</td>
<td>platy fr.</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>GMVc</td>
<td>20-266</td>
<td>R,G,B varying</td>
<td>variable</td>
<td>very low</td>
<td>-</td>
<td>21-25</td>
<td></td>
</tr>
<tr>
<td>GMVe</td>
<td>15-110</td>
<td>IG-B varying</td>
<td>&lt;150? medium</td>
<td>-</td>
<td>20-26 -</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMVf</td>
<td>35-105</td>
<td>dG,B sm-m.wide</td>
<td>15-175</td>
<td>low-high</td>
<td>5x10x15</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>GMVg</td>
<td>16-94*</td>
<td>G,B v.small</td>
<td>&lt;50</td>
<td>low</td>
<td>5x5x10</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>GGMe</td>
<td>10-40*</td>
<td>B,G v.small</td>
<td>10-50</td>
<td>low</td>
<td>small</td>
<td>21-24</td>
<td></td>
</tr>
<tr>
<td>GGMf</td>
<td>not det</td>
<td>G,dG v.small</td>
<td>&lt;50</td>
<td>low</td>
<td>platy fr.</td>
<td>21-24</td>
<td></td>
</tr>
<tr>
<td>GGG</td>
<td>&lt;20</td>
<td>W-dG</td>
<td>&lt;5</td>
<td>very high</td>
<td>-</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>

S-H.UCS = Schmidt Hammer Unconfined Compressive Strength, * = literature
Col. = Colour 1 = light, d = dark, G = Grey, B = Black, W = White, B = Brown, R = Red, Gr. = Green
Fract. sp. = Fracture spacing: very wide > 200 cm, wide = 60-200 cm, moderately wide = 20-60 cm, small = 6-20 cm
Layer th. = Layer thickness
Sst = Sandstone, Lst = Limestone, M = marl
suit,cons = Possible suitability for construction, use as fill, armourstone or roadstone. ++ = suited, + = possible use,
- = no use
10-40* = UCS-value taken from literature (LOACKER 1978)

Composition of the fine gravel fraction of glacial, ice-marginal and related deposits

A restricted number of samples was taken from the various types of non-lithified deposits. They were selected on the basis of depositional environment, morphological setting and landform. Most samples originate from gravel deposits and subglacial tills and were preferentially taken from unweathered occurrences. They were grouped according to the following classification:

- (fan)terrace deposits
- (fan)terrace deposits (cemented)
- alluvial fan deposits (Holocene)
- subglacial till
- ablation deposits
- washed till deposits
- complex valley fill deposits
- complex valley fill deposits (deformed)
- lacustrine valley fill deposits
- massmovement deposits

The distribution of the Quaternary deposits in the southern Walgau and northern Rätikon is, for a large part, related to former ice-flow patterns, in particular to the behaviour of the Ill-glacier. The Silvretta region, in the SE-part of Vorarlberg that is partly underlain by the crystalline Silvretta nappe (see fig.4), served as the main provenance area for the Ill-glacier. Its deposits can be found in the lower tributary valleys (see chapter 2: geomorphology). Most samples have been taken from glacial, ice-marginal and related deposits near the tributary valley outlets and in the lower tributary valley sections. The composition of these sediments in such positions is difficult to forecast because both local and remote glaciers contributed in varying amounts to the accumulated material. Another complicating factor is the reworking and redistribution of older sediments that could be taken up in the younger deposits. For example, the alluvial fan terraces near the outlet of the Galina-valley (map sheet Gurtis, D4-5 and fig.16) contain crystalline fragments that were originally carried into the tributary valley by the Ill-glacier and were subsequently washed out during the Late-Glacial development.

A standard method for gravel countings does not exist. Different gravel fractions, number of counted gravel fragments and rock-type groups may be used (see De JONG 1983). Mainly for practical reasons the 4.8-8 mm fraction has been
chosen here for analyses, which is comparable to the 5-8 mm fraction that was used by DE JONG (1983) in the alpine foreland. At least 300 gravel particles were counted; less particles were included only in some samples of very compact subglacial till. In figure 25 the classification that was used to analyse the petrographical samples, is given. The samples have been classified into three simplified groups in figure 26. In Annexe IIIB the individual percentages of the rock-type fragments have been labelled for each sample.

<table>
<thead>
<tr>
<th>Igneous and metamorphic rocks</th>
<th>Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>a: granite, gneiss, schist, quartz*</td>
<td>h: red* and green sandstone</td>
</tr>
<tr>
<td>b: amphibolites, epidotes</td>
<td>i: other sandstone</td>
</tr>
<tr>
<td>c: quartz*</td>
<td>Other</td>
</tr>
<tr>
<td>Carbonates</td>
<td>l: cemented fragments</td>
</tr>
<tr>
<td>d: calcite</td>
<td>m: undeterminable</td>
</tr>
<tr>
<td>e: dark coloured limestone</td>
<td>* rock-type not present in the area</td>
</tr>
<tr>
<td>f: light coloured limestone</td>
<td>j: dolomite</td>
</tr>
<tr>
<td>g: red limestone*</td>
<td>k: shale</td>
</tr>
</tbody>
</table>

A large volume of gravels is stored in the ice-marginal terraces and fan terraces near and at the western slopes of the outlet of the Gamperdona- and Galina valleys. These could be of substantial local economic value. However, gravel production is concentrated in the Schesatobel, the largest artificially induced erosion/denudation niche in Europe (ÜBLAGGER 1988, VAN NOORD 1991, map sheet Brand-Nord, sector F1-2). The petrographical composition of the present deposits that built the landforms interpreted as Late-Glacial (fan) terraces, is remarkably constant. The influence of the material derived from the tributary valleys is reflected in the high amount of dolomitic fragments, which fluctuates between 50% and 75%. Admixtures of crystalline fragments lie between 8% and 23%.

The subglacial till samples show a wide variety in composition: A cluster with exceptional high limestone values (samples 40,60,71a,72,73,90 Annexe IIIB) in positions near the Samina- and Mengbach outlet and in the Rofelbach (Gurtis, C4) must be attributed to the Ill-glacier. Other subglacial till samples showed more differentiation, mainly due to overriding, incorporating and reworking of older, already available sediments.

Figure 25. classification used to analyse the fine gravel fraction

Figure 26. Ternary diagram showing the percentages of (A): crystalline, (B): limestone and (C): dolomitic fractions for all samples.

(A) includes a, b and c of figure 25
(B) includes d, e, f and g of figure 25
(C) includes j of figure 25
The remaining rock-types have not been included.
Summarizing the results of the petrographical analyses:
- On the basis of composition alone it is not possible to distinguish between ice-marginal fan terraces deposited from a tributary valley and ice-marginal terraces along a tributary glacier as is suggested by KELLER (1988),
- The contact zones of the local and remote glaciers have been defined with great certainty,
- A differentiation into groups of sediments of local and remote provenance is partly possible; morphogenetical knowledge however, is decisive.

**Geophysical measurements**

Geophysical measurements were applied in the field with the aim to support and supplement the geomorphological and sedimentological data stored in the maps by depth data. Especially when geomorphological mapping failed to give reliable insight in the relationships between form, material and process, these techniques were used. For three reasons selected cases were surveyed:
- The identification and lateral distribution of materials,
- The internal composition (structure) of unconsolidated sediments and their depth to hardrock,
- The use of geophysical techniques in (former) mass movement areas.

Three examples will be described below using geo-electrical resistivity and electro-magnetic measurements.

Measurements using geo-electrical resistivity equipment supply an artificially generated current in the subsurface. Deeper penetration in the subsurface can be achieved by increasing the electrode distances. The resulting currents and potential differences are recorded in the successive electrode distances; from these data the apparent resistivity is calculated. A graph of the apparent resistivity as a function of the distance between the current electrodes (AB/2) can be constructed. The computer programme "RESINT31" (BIEWINGA 1989), that was developed for the interpretation of so-called 'fourpoint Schlumberger' soundings, was used to calculate the resistivity-depth model.

The subsurface terrain conductivity can also be measured with electro-magnetic methods. Traverses were carried out with the Geonics EM-34. A transmitter coil generates a primary time-varying magnetic field. This field induces very small currents in the subsurface. These induced currents generate a secondary magnetic field. The receiver coil measures both primary and secondary field (Geonics, Technical Note TN-6, 1980). The conductivity is measured in mS/m, for example 10 mS/m equals 1000/10 = 100 Ohm.m. It was decided to measure in the vertical coplanar mode because anomalies arising from relief differences could then be avoided. In the vertical orientation penetration depth can be approximately 0.75% of the intercoil spacing, which can be set at 10m, 20m or 40 m.

**Rossnis-Mittelberg-Halden: distribution of materials**

The electro-magnetic profile nr. EM-1 was taken with a Geonics EM-34 apparatus in the summer of 1989 after a two week period of completely dry weather conditions. The aim was to distinguish units on the basis of conductivity and to relate them to geomorphological units. The location of profile EM-1 is indicated on the geotechnical map sheet Gurtis (sector C2-3). On the 'GEOLOGISCHE KARTE DES WALGAUES' (HEISSEL et al. 1967) a cover of 'moraine in general' (Moräne im Allgemeine) is indicated. The depth to the glacially scoured paleorelief of the Flysch is varying. Exposures are scarce in this area. In the summer of 1988 an excavation of 4m below terrain surface for a house under construction (Gampellüner-Strasse) exposed a sequence of waterlain fine to coarse horizontally layered gravels overlying cross-bedded medium coarse to coarse-grained sands. These probably ice-marginal fluvial sediments were separated by an erosional surface from an underlying dense matrix-supported subglacial till, at least 2m thick.

![Figure 27. Electro-magnetic profile EM-1 near Rossnis-Halden. For location of the profile see geotechnical map sheet Gurtis (C2-3).](image-url)
The petrographical composition suggests that the till was deposited by the Ill-glacier. Flysch rocks were not exposed. Referring to an excavation in the western end of the ridge flanking the dry valley of Gampelünn, (map sheet Gurtis, C1-2, D3) SIMONS (1985, pp.106-107) described an exposure of ice-marginal deposits that were affected by mass wasting. Other minor exposures invariably confirmed the unconsolidated nature of the surface materials. A simple interpretation is given in figure 27. During the measurement of EM-1 the contourlines were crossed more or less at right angles. The inter-coil spacing was set at 20m; each 10m a reading was taken. Three morphologically different units were crossed during the electro-magnetic traverse:

1) A small peat-zone is depicted easily from the graph; peak conductivity values of 6-10 mS/m separate this zone clearly from the adjacent areas. The internal differences within the peat zone correspond probably to thickness variations relative to the underlying subglacial till.

2) The geomorphology is interpreted as slumped ice-marginal gravel deposits. Values of 3.5-7 mS/m are found here. Boundaries of individual sliding units show as distinct and vague steps in the terrain. Drainage is internal except for some wet zones at unit boundaries. Slightly higher values were found at such boundaries. Values ranging between 3.5-
4.5 mS/m characterize the subhorizontal upper parts of the slumped gravel masses. This suggests that, with the material being equally homogeneous, differences must be attributed to moisture variations that are caused by disturbances due to sliding. Above the contact of subglacial till and overlying gravel deposits a saturated zone may exist. Locally this is reflected in the vegetation, even in a strongly cultivated area like this. For instance, Juncus, Carex and Equisetum grow abundantly at the edges of these terrain units.

3) Values of 5.5 to 7.5 mS/m were recorded on the ridge south of the peaty zone; geomorphological evidence of (former) mass movement activity is lacking. Own observations lead to the conclusion that at several places a veneer of gravel covers a subglacial landscape in similar morphological terrain conditions. In this stretch of the profile conductivity values are probably influenced by the depth to the subglacial till. For instance, were the steepest slope gradient occurs, the lowest value (5.5 mS/m) is found, indicating absence of gravels and/or less thick cover of till due to surficial mass wasting processes at this site.

**Latzwiesen: buried topography**

The profile (EM-5) is located on map sheet Gurtis, sector E4-5. Two main geomorphological units can be distinguished at the surface within a local, glacially eroded basin in Flysch bedrock (see also geomorphological description of map sheet Gurtis, chapter 2): - A dead-ice landscape in the eastern part,
- An alluvial fan body that partly fills the basin and possibly overlies (parts of) the dead-ice landscape.

A combination of a geo-electrical profile and an electro-magnetic traverse was chosen to answer the following questions:

- What is the (absolute) depth to bedrock,
- What lateral and vertical material changes take place and what are the dimensions of the 'buried' dead-ice landscape.

Measurements were made both in the horizontal and vertical coplanar mode. The depth values to bedrock were expected within 20-50m, figures that are based on geomorphological considerations. Therefore the intercoil spacing was set at 40 m, to enable a larger penetration depth. The results in figure 28 show four exceptional values (between 520 and 680 m), a disturbance caused by the subsurface pressure tunnel that deroutes Mengbach waters to the electricity plant north of the Rabenstein hill (LOACKER, 1986).

![Figure 28. Electro-magnetic measurements near Latzwiesen, map sheet Gurtis, E4-5 (see also geotechnical map sheet Gurtis).](image-url)
Between 0m and 520m the conductivity values vary between 3 and 4.2 mS/m in the vertical coplanar coil orientation. In the horizontal coplanar orientation (depth penetration 60 m), lower figures (1-2.5 mS/m) were recorded. These low values show that the influence of bedrock on the apparent conductivity dominates the influence of the surface sediments. Slight differences in electro-magnetic conductivity using horizontal orientation could therefore correspond with the undulating rockhead topography. The alluvial fan deposits (mainly sands and gravels derived from ice-marginal fluvial and glacial deposits eroded upslope) show fairly constant values between 3 and 5 mS/m, which is in accordance with the EM-1 results.

The interpretation of the eastern part of the graph, between 680m and 840 m poses some difficulties. Apparently material with higher conductivity is responsible for higher values measured in the horizontal coil system. The morphogenetical situation can provide some explanations:
- buried (early-glacial?) valley systems filled with relatively highly conductive sediments and/or subglacial till may be present,
- the sediments could be glacio-tectonically disturbed or deformed by dead-ice so that a complex mixture of various sediments may exist close together, as was found in similar situations on the eastern flanks of the Mengbach (see e.g. Fig.11).

Figure 29. Geo-electrical profiles Latzwiesen (GE-3, map sheet Gurtis, E4-5), Nenzinger Himmel (GE-2, map sheet Nenzinger Himmel, DE-1) and Studaloch peat (GE-4, map sheet Gurtis, G5). Explanation: see text.

Geo-electrical profile GE-3 was taken nearly parallel to the geo-magnetic traverse EM-5. The length of the maximal current electrode distance, 350 m, enables a theoretical vertical penetration of approx. 60 m, depending on the resistivities of the materials involved. Curve fitting RMS errors <5% could only be obtained when a five-layer model was simulated. The two upper layers were fixed with contacts at 1m respectively 2.5m. The thickness of the third layer could be interpreted between 10m and 15m. It is thought that this material is the main constituent (saturated gravels, sands) at the lower end of the alluvial fan body. The fourth layer has a definitely lower resistivity (220-270 Ohm.m), indicating either subglacial till or fine lacustrine deposits (clays, silts) and has an interpreted thickness of 22m in the graph given in figure 29. The rockhead, characterized by resistivities exceeding 1060 Ohm.m, was found at a depth ranging between 28.5m-40.8m. Intermediate interpretations are possible for all the layers, but are restricted to these boundaries. The depth can be regarded as a mean value over the measured interval. Using the results obtained from the electro-magnetic traverse (horizontal coils) one can determine whether bedrock is located deeper or more shallow in reference to GE-3 (about 35m).

Nenzinger Himmel: valley fills

The basin of Nenzinger Himmel is underlain mainly by Triassic series of the Raibler Formation and by rocks belonging to the Arosa zone. The basin was originally glacially scoured and became filled with glacial and fluvial sediments (see description map sheet Nenzinger Himmel). The depth is uncertain but geometrical considerations indicate at least some tens of metres. Two geo-electrical profiles were taken in order to determine the depth to hardrock.

Profile GE-1 was taken on the lower end of three coalescing alluvial fans in sector D2 and has a maximal current electrode distance of 400 m. Profile GE-2 (figure 29) is located on the alluvial fan of the Trübbach valley in sector E1, total length 700 m. The width of the valley floor equals 700m. Interpretation of the profiles is rather complicated, it may be hampered by the complex internal sediment composition and/or by the various rocktypes (Arosa-Zone formation).
that are present in the subsurface; profile GE-2 also crosses the tectonical contact of the Ochsenkopf-Fundlkopf and Augstenberg ‘Schuppen’ (Fig.5).

Table 5. Resistivity values compiled from data of RUPKE et al. 1987/1988, SELMONSBERGEN & VAN WESTEN (1986) and own measurements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flysch sandstone (desintegrated)</td>
<td>130-210 ((\Omega)m)</td>
</tr>
<tr>
<td>Flysch marls (desintegrated)</td>
<td>30-60</td>
</tr>
<tr>
<td>Flysch marl/sandstone complex (desintegrated)</td>
<td>55-70</td>
</tr>
<tr>
<td>Molasse marl/sandstone complex</td>
<td>120-220</td>
</tr>
<tr>
<td>Marls from the Molasse</td>
<td>21-40</td>
</tr>
<tr>
<td>Peat</td>
<td>37</td>
</tr>
<tr>
<td>Subglacial till</td>
<td>119-200</td>
</tr>
<tr>
<td>Earthflow material (moist)</td>
<td>25-65</td>
</tr>
<tr>
<td>Earthflow material (saturated)</td>
<td>12-30</td>
</tr>
<tr>
<td>Topsoil (undifferentiated dry, coarse-grained)</td>
<td>530-1450</td>
</tr>
<tr>
<td>Topsoil (undifferentiated, wet, fine-grained)</td>
<td>31-225</td>
</tr>
<tr>
<td>Solifluction deposits</td>
<td>22-83</td>
</tr>
<tr>
<td>Alluvial fan deposits (sand &amp; gravel)</td>
<td>100-600</td>
</tr>
</tbody>
</table>

However, all interpretations indicate depth values of more than 50 m. The interpretation of GE-2 ranges between 65-70m. One solution is given in figure 29.

Based on the results of the geophysical measurements it is concluded that electro-magnetic methods are useful in the determination of lateral material transitions. To obtain in-depth information it is useful only when the measurements are integrated with data derived from the geomorphological map. A draft model can then be tested and adapted when necessary. In the case of Latzwiesen the presence of some buried channels, probably eroded by a course followed by a late-glacial Galina or Mengbach becomes acceptable. The combination with geo-electrical soundings proved valuable.

The properties and spatial distribution of the various materials described in this section form important input factors for the appraisal of hazard zones as will be discussed in the next chapter.
4. Appraisal of mountain hazards with special reference to slope stability

Introduction

Here, a brief overview of the "state of the art" is first given. Hazard zonation maps show the areal extent of any threatening process (HANSEN 1984). The natural hazard maps (German: Naturgefahrenkarten) of the N Rätikon mountains and S Walgau show the areal extent (zonation) of actual and dormant/fossil mountain hazards in the area. The term zonation in this instance, applies to the division of the land surface into areas and the ranking of these areas according to actual or potential hazard by landslides and other mass movements on slopes (VARNES 1984). Many types of hazard maps and various methods of analyzing techniques have been published at different scales. Broadly speaking these techniques can be separated into qualitative evaluation (relative mapping) and quantitative assessment (absolute methods) techniques. Rarely these two approaches have been successfully combined, mainly due to given financial, political or time restraints. Irrespective of the techniques used, the surveyed area has to be subdivided into hazard zones, which for most slope hazards at least, correspond to homogeneous geo-units or terrain mapping units, that group natural associations of geology, geomorphology, morphometry and soil distributions (materials), and is independent of scale (MEIJERINK 1988). In the method used here, a geo-unit is equal to a geomorphological unit. These are based on processes of flooding and mass movements including avalanches. Special reference is made to slope or instability hazards, since they can be extracted directly from the geomorphological maps. Seismic hazards, although recorded in the past, were not examined in this study. According to the earthquake-intensity map of Austria for the time-span 1201-1982 (DRIMMEL 1986 in: ÜBLAGGER (Ed.), the entire area falls within two intensity classes of the Mercalli-Sieberg scale. South of Nenzinger Himmel the area is classified as 6-7 (moderate damage to buildings such as small cracks in walls, falling roofing-tiles), N of Nenzinger Himmel into the 5-6 class. Meteorological hazards were not examined either.

During the last decade the development of hazard zonation maps at the University of Amsterdam, mainly relying on detailed geomorphological inventories is in steady progress. RUPKE & DE JONG (1983) initiated this type of analysis with the presentation of two separate maps, emphasizing on deep seated mass movement (rock sliding, toppling, slumping) and surficial mass movement (fast moving debris, solifluction). Both maps were directly derived by them from the geomorphological map, without any re-interpretation. A first series of 1:10.000 scale combined geomorphological and hazard zonation maps evolved from the work of SEIJMONSBERGEN & VAN WESTEN 1988. Large scale (1:2.000-1:500) geomorphological site investigation indicating a.o. slope hazard zones served as advisory consultancy work for governmental services ('Wildbachverbauung') in Switzerland (RUPKE et al.1987,1988, RUPKE & SEIJMONSBERGEN 1992) and Austria (RUPKE & SEIJMONSBERGEN 1991) for local forest and stream control services. These investigations were applied in planning schemes for torrent control works, and showing slope stability in planning of roads. STAKENBORG (1986) started with the digitizing of geomorphological maps and the extraction of simple derived maps. VAN DIJKE & VAN WESTEN (1990) assessed rockfall hazard using a DTM (digital terrain model) and compared their results with digitized geomorphological data at 1:50.000 scale, converted from the original maps of SEIJMONSBERGEN & VAN WESTEN (1988). The power of GIS in mountain hazard assessment lies in the possibility to tackle the problem at different scales, from regional (1:100.000-1:200.000) to site investigation scale (1:10.000-1:2.000), each scale requiring its own input maps and mapping unit parameters (attributes). VAN WESTEN (1992a/b) is working on a further integrated system of mountain hazard mapping using GIS. This project aims at the development of a methodology for regional, medium and large scale maps (RENGERS, 1992). The capabilities of a GIS integrated with, in this case, hazard assessment techniques should aim at the enhancement of the possibilities of using the interpreter's expert knowledge (BOCCO and VALENZUELA 1988).

Other systems of mountain hazard zonation

For a detailed 'state of the art' reviews on landslide hazard analysis is referred to SCHUSTER and KRIZEK (1978), VARNES (1984), HANSEN (1984) and especially for scale related GIS techniques to VAN WESTEN (1992b) amongst others. Most definitions that are commonly being used in hazard zonation studies were recently defined in the UNESCO paper by VARNES (1984). In this section only a brief outline will be given, dealing with some recent trends in hazard zonation.

Geomorphological mapping methods use the relations that exist between geomorphological units and hazard zonation. The distinguished zones are then, if possible, extended with additional information, e.g. with avalanche records, that could not directly be derived from the geomorphological maps. One of the first representatives of such a qualitative direct mapping approach was KIENHOLZ (1977), who, using a shortened legend, published both a basic
Figure 30. Fragment of the geomorphological base map of the Grindelwald area in Switzerland (A) and corresponding part of the combined hazards map (KIENHOLZ 1977 in HANSEN 1984).
geomorphological map and a combined geomorphological hazard map for the Grindelwald area in Switzerland. A combination of these maps, one with observations and a second showing the analyses and classification, seems to be most appropriate way in tackling the problem of hazard zonation. Black and white fragments of his maps are reproduced in figure 30. In his geomorphological base map only those processes, and forms deriving from them, that constitute a serious danger or obstacle to human activities, have been entered. This was done for clarity. Therefore his geomorphological legend is strongly relying on erosion/denudation and mass movement. Relatively little attention is paid to morphography/morphometry and genesis. In the present study however, morphometry/morphography and genesis are more emphasized, not only because they are important in the delineation of unit areas, but also because they enable a detailed pattern analysis between neighbouring morphological elements. Further-more, a thorough evaluation of hazards must also deal with processes and forms that do not constitute a direct danger to human activity. Consequently, a full representation may improve the quality and thus the use of the geomorphological map and the derived maps. The information on avalanches in KIENHOLZ’s map is printed on the geomorphological base map and in fact reproduced in the end product, the combined geomorphological hazards map. On the hazard zonation maps of the Rätikon and Walgau, the additional avalanche information is brought in only in the end product for reasons of legibility and practical considerations.

The combined geomorphological hazard map of KIENHOLZ (1977) is intended to form the cartographic base for land-use zoning and shows areas subject to different types of intensities of hazard. The unit area method (terrain mapping unit) was employed to indicate and evaluate areas with a certain degree of danger. The determination of degree of hazard was principally based upon interpretations of field indications of former and actual mass movements (“dumb-witness method”) and evaluated by means of column-wise check lists and auxiliary tables, especially to be used in the Grindelwald area. Tendencies of slope instability were determined by weighting parameters such as type, speed and depth of mass movement, bedrock and loose material characteristics, slope inclination, hydrology, morphology and vegetation of the unit area. The eventual degree of danger of landslide was then determined by annotating a rating of 0-3, depending on the kind of danger an object is subject to (is it located on the moving mass, will it become an obstacle in the path of the moving mass or is it undermined by erosion). Using this standardized method a certain 'leading line' was followed along with an estimate of the expected activity. In the map the degree of danger is given by colour, whereas the type of hazards is given by capital and/or small letters, depending on its relative importance in that unit.

Other geomorphological approaches of direct mapping have been worked out; for instance the french 1:25.000 ZERMOS maps. The degree of hazard is indicated by colour and based on geological, geomorphological and hydrological factors. Division into subzones is possible on the basis of type and (potential) future instability. Again these maps only show landslide-oriented geomorphological features.

The geomorphological maps of Brunsden et al. (1975) show the areal extent of (potentially) unstable slopes, active and old failures, alluvial forms, drainage, talus and some geological information. These maps were directly used in the evaluation of slope hazard along a proposed road alignment in Nepal.

Another, indirect approach, that is often being used, combines statistical methods to arrive at landslide susceptibility maps. This method requires a landslide distribution map and a land-unit map as input data (VAN WESTEN 1992a/b). They are aimed at identifying the controlling parameters of the stability of slopes. These parameters can subsequently be stored as coded terrain attributes (e.g. geology, slope, hydrology etc.) in a GIS database. The slope system is simulated in order to predict stable and unstable situations according to indirect mapping methods. Areas can be subdivided into grid cells (which become the units of reference) so that computer processing of the terrain attributes becomes feasible and the problem can be tackled in a statistical way. The field interpretation (without delineation of unit areas) is often included in data collection using standardized check-lists or forms. CARRARA & MERENDA (1976) used grid cells of 200x-200m in an area of 600km², the slope instability hazard map was derived from statistical examination of more than 30 attributes. Advantage of this approach is that data can be obtained of the potential hazard in areas that have been stable in the past. A serious disadvantage in handling data this way is often the lack of sufficient information that is used for statistical analyses and more important, the absolute absence of a relationship to geological or geomorphological field boundaries. An example of the output of one of CARRARAS maps is shown in figure 34 (from HANSEN 1984). An improvement of this approach would be the use of terrain mapping units (MEYERINK 1988) or geomorphological units to achieve more 'ground truth', especially when the scale is enlarged. Recently VAN WESTEN (1992b) described a method to analyze landslide hazard at a medium scale using the ILWIS (GIS system) developed at the ITC (VALENZUELA 1988). Using checklists to record photo- and field information, landslides were interpreted. Parameter maps (containing e.g. geomorphological main- and subunits, distance to drainage, distance to faults, slope classes and others) were used to find relations between parameter classes and landslide types via map crossing. A weighting factor was introduced to evaluate the landslide density per parameter class. The most significant parameters were selected and combined for use in landslide susceptibility maps. In this way only the most significant classes are used to determine homogeneous subareas that fulfill the criteria that have been set when classifying the factors. It must however be kept in mind that the evaluation of parameters and the creation of a (semi-)quantitative hazard map in this way is in the first place depending on the selection of terrain mapping units and necessary field checks.
Numerical rating systems, that weight the various factors that contribute to slope instability have also been used, e.g. by STEVENSON in Tasmania (see VARNES 1984). The resulting values however, were used experience-wise.

Recently CARRARA (1992) rejects all methods that involve hazard evaluation based on identification of former and recent landslide bodies through direct mapping methods. These methods would be too subjective and therefore unreliable. He reviewed a method of hazard assessment, based on both GIS techniques and statistical methods. It is based on the relationship that exists in mountainous regions between landsliding, main slope units and drainage and divide lines. The land unit used is therefore either a subbasin, or a main slope unit. These land units are automatically generated and form the basis of further statistical steps. A serious disadvantage lies in the fact that expert-knowledge and experience is lost and replaced by mathematically derived land units. So-called 'appropriate' values were assigned to threshold parameters (subbasin/main slope-units area, slope, aspect etc) to improve the soundness of the statistical treatment and the spatial resolution of the predictive model. In a GIS each slope unit was then associated with geological and geomorphological data that were collected in the field and by aerial-photography. The validation of the model was however, tested by comparison to a manually derived landslide map.

Numerical or absolute methods are increasingly being used in hazard assessment and commonly express the hazard in terms of e.g. safety factors or probability. Such deterministic and statistical methods have been used mainly on a detailed site investigation scale because here one requires specific information on material properties and hydrological data. VAN ASCH and MULDER (1988) presented a strategy for a quantitative hazard analysis of landslides in forested areas using infinite slope analysis. They pointed out that the spatial hazard analysis should be preceded by a sensitivity analyses, in which the effect of the various parameters on the stability in the equilibrium models used, should be mutually compared. In their case it was determined that slope inclination produced the largest effect in the separation of stable and instable slopes. Other parameters, such as angle of internal friction, cohesion, depth to potential sliding plane, rootstrength cohesion, thickness of the soil contributed less to instability if compared to slope inclination. A conclusion was that in this area, underlain by "terres-noires", the best strategy for the construction of a hazard map is the division of the area into slope classes.

Taking into account the variability of all factors that control slope stability, the procedure to make a prognosis of landslides is complicated, even in simple terrain. To work out a hazard zonation for a rather complex large terrain at a detailed scale it would yet require too much different models and assumptions. The difficulty in handling absolute slope stability data (e.g. expressed in safety factors or probability of occurrence of a landslide using site values of soil properties and hydrological data), lies in the extrapolation to areal units. This quantitative approach requires far more data and is not yet suited for regional or medium scale hazard zonation mapping programmes.

The integration of the time factor in hazard studies (temporal hazard) requires even more effort: detailed measurements over long time periods should be linked to meteorological records, with the aim to forecast future hazards (landslide
frequency). The importance of the role of water in landslide hazard analysis and the modelling of groundwater fluctuations in time and space, and its limitations, were recently emphasized by VAN ASCH (1992). The study of VAN GENUCHTEN (1989) in the French Alps is a good example of this approach. The movement mechanisms of two slides in varved clays, of which all relevant geotechnical parameters and hydrological data were measured, were monitored during 9 years. The plot results were extrapolated over the area underlain by varved clay for hazard mapping by means of computerized delineation of danger zones. It was shown that the calculated danger zones were comparable with those obtained from geomorphological surveying. A complete picture was obtained, the value for hazard zonation is however restricted to these varved clays.

Taking into account the advantages and disadvantages of the various hazard zonation analysis techniques, a relative direct mapping procedure was followed here because:
- Selection and drawing of terrain boundaries is a critical step in hazard zonation at this scale and needs thorough verification,
- The use of geomorphologically based terrain mapping units is of great value in many other fields: academic geomorphologic modelling, geotechnical and forest planning,
- Complex terrain as in the Alps of Vorarlberg can be evaluated using base information that strongly relies on genesis, processes and materials and can thus deal with inhomogeneous landscapes,
- Preparation of detailed hazard zonation maps is a relatively rapid procedure after the completion of the detailed 1:10,000 geomorphological inventory,
- Large areas can be evaluated without the difficult step of 'generalizing' or extrapolating site knowledge to wider surroundings,
- The practical field use of the maps (combination of both geomorphological and hazard zonation maps) proved already satisfying when non-earth scientific users versed in other disciplines are introduced in the method during short field visits,
- Experience with this method was already available.

The methods and legend used in the evaluation of hazards according to this approach will be outlined in the next sections.

A method for construction of the hazard zonation maps

The 1:10,000 geomorphological maps form the starting point in the preparation of the hazard zonation maps. According to VARNES (1984) the most powerful geomorphological characteristic to be considered is the presence or absence of former landslides, of course keeping in mind the principle that past and present events are keys to future development. The evaluation of slope hazard in this study has been based mainly on the analysis of geomorphological patterns and the interrelations existing between morphological units at the same time keeping record of material properties. This implies that the quality of the slope hazard zonation is directly linked to the correctness and accuracy of the geomorphological map. It must be remembered that in almost every system of hazard zonation the initial step is the drawing of terrain boundaries, this selection of terrain mapping units is critical for all other procedures. In this respect it must be mentioned that the original slope hazard data as they have been crystallized in the geomorphological maps, can always be linked to the hazard zonation map by means of overlaying the transparencies. This already proved useful in practice and is an important condition for experienced users. Moreover, re-interpretation of data can be continuously executed. Still, the fidelity one should have in any hazard zonation map has still to be proven in time and practice. In figure 32 the input data that have been used to construct the hazard zonation maps are shown. The lines along which they were constructed can be summarized as follows:
- a geomorphological approach, which is the most important source of information here. It comprises the thorough interpretation of all geomorphological signs of mass movement, flooding and avalanches. KIENHOLZ (1977) referred to this method as the 'silent witnesses method'. Pattern analysis is emphasized in the present method, the geomorphological map represents a total material and time model of the specific areas,
- the historical approach; additional information including all known historical hazards involving flooding, avalanches and mass movements were gathered using community chronicles, personal interviews, existing maps and other written sources. It appeared that only 'major' events that damaged infrastructural works or the lives of human beings were recorded or remembered,
- A fieldwork programme, running parallel to the mapping scheme, in which the relative activity of homogeneous geomorphological units was taken into account. Short notes, describing the situation, were used next to map data, when the final hazard zonation map was drawn, rather than using more rigid standardized forms or checklists. Since the hazard zonation maps at this scale (1:10,000) contain over 3000 interpreted mapping units, this way of gathering data, which is well suited for computer (GIS) processing would lead to an enormous load of data; it was left out.

The legend of the hazard zonation maps is given in figure 33.

It was beyond the scope of this study to incorporate numerical models that can simulate slope stability problems and calculate safety factors, the restraint being the purpose of the maps, time and scale, heterogeneous character and dimensions of the area (150 km² at 1:10,000 scale).
Figure 32. Diagram showing the step-wise construction of the hazard zonation maps

<table>
<thead>
<tr>
<th>W</th>
<th>Endangering by torrential streams</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR</td>
<td>Highly endangered</td>
</tr>
<tr>
<td>WG</td>
<td>Less endangered</td>
</tr>
<tr>
<td>L</td>
<td>Endangering by avalanches</td>
</tr>
<tr>
<td>LR</td>
<td>Highly endangered</td>
</tr>
<tr>
<td>LG</td>
<td>Less endangered</td>
</tr>
<tr>
<td>M</td>
<td>Endangering by mass movement</td>
</tr>
<tr>
<td>MS</td>
<td>Endangering by rockfall</td>
</tr>
<tr>
<td>MSR</td>
<td>Highly endangered</td>
</tr>
<tr>
<td>MSG</td>
<td>Less endangered</td>
</tr>
<tr>
<td>MF</td>
<td>Endangering by flow processes</td>
</tr>
<tr>
<td>MFR</td>
<td>Highly endangered</td>
</tr>
<tr>
<td>MFG</td>
<td>Less endangered</td>
</tr>
<tr>
<td>MF</td>
<td>Stabilized flow-zone</td>
</tr>
<tr>
<td>MRA</td>
<td>Endangering by sliding</td>
</tr>
<tr>
<td>MRT</td>
<td>Deep-seated sliding</td>
</tr>
<tr>
<td>MRT</td>
<td>Highly endangered</td>
</tr>
<tr>
<td>MRTG</td>
<td>Less endangered</td>
</tr>
<tr>
<td>MRTA</td>
<td>Old slide mass</td>
</tr>
<tr>
<td>MRU</td>
<td>Shallow sliding</td>
</tr>
<tr>
<td>MRUR</td>
<td>Highly endangered</td>
</tr>
<tr>
<td>MRUG</td>
<td>Less endangered</td>
</tr>
</tbody>
</table>

If known the following suffices can be added:
- (r) rotation slide
- (w) wedge failure
- (t) toppling
- (k) endangering by karst/collapse
- (K) Combination of hazards inside incisions
- KR Highly endangered
- KG Less endangered
- V Wet areas
- N Not endangered area
  - * location of discontinuity measurement

Combination of hazard codes is possible.

Figure 33. Legend of the hazard zonation maps
The existing hazard zonation plans (German: Gefahrenzonenpläne) that are being used community-wise in Austria make use of a simple legend that expresses both the type of the hazard and the degree of endangering. Evaluated are avalanches (L), flooding (W) and seldom mass movement (B). The classification of the degree of endangering falls into three sub-classes:

- red (R): highly endangered area. In these zones is to be reckoned with serious damage to buildings or part of buildings. Inside these buildings the lives of human beings are also endangered (Tschann 1980). Areas that are subject to smaller, but more frequently occurring hazards, are also included in this class,
- yellow (G): less endangered areas. Endangering to various degrees prevails in this zone. The damage of objects is possible, although destruction of buildings is not to be expected if certain precautions are fulfilled. Endangering of persons inside such protected buildings is unlikely, outside these buildings however, possible in varying degrees.
- not endangered zones (N). In these zones there is, so far human knowledges reaches, no endangering to be expected by avalanches or flooding or they are so small that precautions are needless.

In exceptional cases brown zones are distinguished (B). These areas can be subject to slides, fall or ponding.

A serious disadvantage of the existing hazard zonation plans in Vorarlberg is that data of non-inhabited areas are lacking. This means that approximately 80% was not covered by these maps. As much as possible the classification described above has been integrated in the set-up of the hazard zonation legends developed in the Hintere Bregenzerwald region by SEIJMONSBERGEN & VAN WESTEN (1986, 1988). Small adaptations to this legend have been made. The processes that have been distinguished here will be separately dealt with in the next sections.

**Flooding**

A constant threat to human lives and a serious maintenance problem in the mountain environment is exercised by floodwaters and debris flows. The floodwaters generally contain a substantial volume of sediment and are generated in torrential streams (German: Wildbäche) during sudden peak discharges. A torrential stream is a high-gradient ephemeral or perennial water course in mountainous terrain which is characterized by sporadic and sudden discharges of debris (EISBACHER & CLAGUE 1984). It was estimated in channels, streams, brooklets and from material composition on debris fans, that the debris in debris flows, is for approximately 95% derived from non-lithified deposits. Therefore, the spatial extent and thickness of these kinds of deposits is of major importance. The mobilization of debris is known to depend on the intensity and the cumulative total of the precipitation. This regularly occurs during cloudbursts and sustained regional rainstorms in the summer months, when peak precipitation values exceeding 100mm/hr have been recorded (HYDROGRAPHISCHER DIENST OESTERREICH 1973) and in spring, when large volumes of meltwater are released (EISBACHER & CLAGUE 1984). The fact that large volumes of unconsolidated materials are available at many unfavourable positions with regard to erosion and denudation, is an indication of the potential sources that can be activated to contribute in debris flow activity. A well known example is the erosion/denudation niche of the Schesatobel (map sheet Brand-Nord, sectors F1-2,G1) where 40x10^6 m^3 of non-lithified material was removed, since the clearance of forest in 1804 at this site. This illustrates the close balance that exist between the vegetation cover, water and subsurface.

The main water courses, the Galina and Meng, have been regulated by the governmental service 'Wildbachverbauung' since the early twenties of this century. Especially the Galina was feared for its flooding and debris flow activity.

Two ways of indicating flooding/debris flows have been used in the hazard zonation maps. In the first place by the codes WR (highly endangered) and WG (Less endangered) and in the second place by the code KR (combined hazards inside incisions, highly endangered) or KG (combined hazards, less endangered). In this case other hazards such as avalanches or slides occur in the same incisions.

The following morphological criteria were evaluated in order to determine if and to what degree endangering by torrential streams is to be expected, using data from the geomorphological map, aerial photographs and field observations:

- The occurrence and nature of non-lithified materials in the catchment area, which forms the potential sediment source for debris,
- The expected order of thickness of the unconsolidated material was taken into account,
- The occurrence and activity of mass movement that can serve as sudden sediment supplying mechanisms towards streams, e.g. disintegrating river banks, the presence of steep block and scree producing walls, the size and steepness of the catchment area; in general smaller catchments react more rapidly to sudden peak discharges and are therefore expected to generate more frequent events,
- The occurrence and position of non-vegetated surfaces,
- Signs of former flooding and debris flow activity (presence of debris fans, scour-tracks of debris flows)
Figure 34A: Fragment of geomorphological map sheet Gampherg, showing the central Galina valley near Rossboden and Wissersand (C2).
Figure 34B: Corresponding fragment of geotechnical map sheet Gampberg. For legend see Figures 21 and 24 or Annexe I.
Figure 34C: Corresponding fragment of natural hazard map sheet Gampberg. For legend see figure 33 or Annexe I.
Photo 24. Alluvial/debris fan, map sheet Nenzinger Himmel, sector D3-4. Upstream blockage of the local high gradient stream during a high intensity rainstorm in the summer of 1988, initiated sedimentation outside the active fan surface.

Supplemented with additional information from interviews, chronicles and actual visits after two peak discharge periods (summers 1988, 1991), a rather complete view was obtained on the location and dimensions of flooding and debris flows related to incisions.

Mass movement

Most attention in the hazard legend is given to mass movement. The subdivision into mass movement processes is partly based on the classification as proposed by VARNES (1978) and adapted for this area. Three principal types of movement have been distinguished here:

- **fall**, the mass in motion travels most of the distance through the air. It includes free fall, movement by leaps and bounds, and rolling of fragments of bedrock or soil,
- **slide** the movement involves shear displacement along one or several surfaces, or within a relatively narrow zone, which are visible or may reasonably be inferred,
- **flow** movement within displaced soil mass such that the form taken by moving material or the apparent distribution of velocities and displacements resemble those of fluids.

Lateral spreads have not been recognized. Topples, separately grouped by VARNES (1978), are indicated here by a suffix (t), which can be used in combination with the slide legend codes, because it appeared that topples are often linked to sliding blocks and tensional fissuring. The complex movements are subdivided as much as possible into one of the three principal movement types, if clear delineation is not possible, a combination of codes has been used. The material in which the slide is (or has been) taking place can be checked from the geotechnical map.

Avalanches

The geomorphological map does not contain much direct information on avalanche hazards. At certain locations, e.g. SW of Gurtis (C5), the position in which blocks and scree is present, can neither be explained by rockfall or by ice-marginal deposition, but were interpreted as accumulation resulting from avalanches. Still, these blocks and scree deposits were represented on the map as mass movement deposits.

Damage to the vegetation cover in the break-off zones of avalanches could be detected most reliably from the 1:9.000-1:11.000 scale false-colour infrared aerial photographs and linked to the avalanche tracks. These surficial slides often comprise the grass-cover and the upper portion (1m) of the weathering mantle. In the geomorphological map these appear as small slides, mainly on slopes between 25 and 50 degrees, on which avalanches are known to occur most frequent (MELLOR 1978, ÜBLAGGER 1988). The development of avalanches is however, also depending on factors other than slope inclination, e.g. slope aspect, wind velocity and direction, and amount and temperature of the snow. These factors lie beyond the scope of this study and cannot be represented in mapform. Avalanches pose a serious and difficult danger to be recognized. The interval over which various triggering factors can cause an event can take
generations. Other sources of information were opened up in order to obtain the locations and areal extent of the avalanches, irrespective of its type.

In Austria the occurrence and location of avalanche tracks is registered in community-wise annotated 1:50,000 scale avalanche maps (german: Lawinenkataster). A historical record is kept and updated when necessary, legalised according to a 1975 law (ÜBLAGGER 1988); in most areas longer records exist. The objective is: data collection for the working out of hazard zonation plans. These plans form a legal basis for planning. A serious disadvantage in these avalanche records is again the lack of information in the non-inhabited areas. The information obtained is thus limited and further information had to be gathered. Local residents of Gurtis and Nenzing were questioned in order to attain data on the travel distance on alluvial and solifluction fans. The most valuable information was brought up by Dipl.Ing.Dr. E.SONDEREGGER, head of the forestry department and 'Agrargemeinschaft' Nenzing. His personal knowledge of and experience resulted in the detailed limitation of 90% of the areas endangered by avalanches. Firstly, the position of avalanches were drawn onto the available 1:10,000 and 1:5,000 scale ortho-photo maps. These maps
consist of a compilation of black & white panchromatic aerial photographs and have been overprinted with contourlines and some other topographical information. Although some misfits occur between drainage and contourlines, these maps serve as excellent base-maps for this purpose. Secondly, these preliminary boundaries were carefully calibrated by taking into account the geomorphological situation (slope inclination, escarpments, signs of damage). The last step was the transfer of these avalanche tracks onto the hazard zonation maps, which are thought to give a better representation of the actual situation if compared to existing maps.

Figure 36: Lower hemisphere stereographic projection of discontinuities in the surroundings of the Eckskopf-Neuwald area (individual pole-plots left part of figure, to the right: after contouring)

A distinction has been made in the degree of endangering of avalanches. The known tracks and runout zones mentioned above, have been indicated by LR (highly endangered). The frequent occurrence of such avalanches is responsible for the isolation of Nenzinger-Himmel during the winter period. Less endangered zones, in which smaller snow-slips and falls may occur, are denoted either by LG, but commonly by an arrow, since exact delineation is often impossible and would bring in a non-existing accuracy. It is not attempted here to subdivide the avalanches in type classes, since reliable data on this topic is lacking. In the opinion of SONDEREGGER (pers.comm.) the majority of the avalanches are of the dust-avalanche type and may occur also in forested zones.

Fall

The endangering of fall was basically determined by the interpretation of the geomorphological signs of former rockfall events and by judging the situation in the production zone from the geomorphological and geotechnical maps. The following questions were asked:

- Are there signs of open fissures, joints or faults within the bedrock that may lead to rockfall,
- Is the rock face oversteepened by glacial erosion, so that tensional rebound is to be expected,
- What is the rock type and what are the rock properties such as layering thickness and joint interval (important for the expected block-size),
- What is the aspect of the slope and its relation to the geological attitude of strata,
- Is the accumulated material randomly distributed, are scree cones formed, or is the material cover only a surficial mantle over bedrock,
- How is the water movement in the rock,
- What is the extent, the morphological position and thickness of the downslope accumulated material (could it freely fall down, did more than one event occur),
- Are there any other special locally important reasons that could have influence on the potential production of scree and blocks.

During the mapping programme the presence of fresh scars and of freshly accumulated material was recorded; from the aerial photographs the present vegetation cover was determined. The state of freshness is thought to have a more or less direct relation to the degree of activity.
Photo 25. Typical scree cone in the Grosstal valley, map sheet Fundl-Kopf, on which highly active and less active zones can be seen (code: MSR and MSG)

The weighting of the answers to these questions depends often on the local conditions. A numerical validation for each possible factor would be too much a generalisation of the flexible terrain data stored in the geomorphological map. For example, in the area of Planetenwald (map sheet Dünzt-Schengla, sectors C/D1-2-3) the surface is extensively covered by large blocks derived from numerous rockfall events. Concentrations of blocks seem to be present at several height intervals in this zone and less abundant on the lower slopes near to the present valley floor, although there seems no obvious reason for blocks to halt in the middle of the overall slope. Present activity is restricted to steep non-forested cliffs. It is inferred that the activity through time has diminished since the gradual melting down of the Ill-glacier. Rockfall started directly after the higher oversteepened slopes became ice-free. Rockfalls were triggered and deposited along the gradually lowered ice margin. The slopes below approximately 900m altitude were probably subject to deep-reaching slope deformation after they became ice-free and merged into irregular slopes with (sub-)horizontal surfaces that could diminish the velocity of falling blocks. With the growth of a vegetation cover and the 'dying out' of the rebound effect, the activity of fall becomes more and more adapted to 'normal' factors of mechanical weathering. Despite the overwhelming presence of visible geomorphological witnesses, the highly endangered areas are relatively restricted.

Another approach of evaluating the fall hazard is by means of calculation. VAN DUKE & VAN WESTEN (1990) argued that the determination of rockfall-producing slopes from topographical maps that were used to generate DTM's and gradient maps may deviate from delineation of these slopes using detailed aerial-photo interpretation on a geomorphological map. KIENHOLZ (1977), who used both methods, arrived at the conclusion that careful interpretation of the dumb witnesses concerning rockfall will lead more rapidly to the same goals.

Deep-seated slope failures

In this area deep-seated slide failures are almost synonymous with rock slides. The movements is slow, up to the time that a critical value is reached at which historical slopes are witness, and occurs along distinct slide planes that are deeper than approximately 5m but may reach many hundreds of metres depth. The slowly valleyward sliding slopes (german: Talzuschub) are examples of deep-seated slope failures. Three groups were distinguished on the hazard zonation maps:

- A group of present-day active rock slides indicated by the code MRTR,
- A group of stabilized (dormant) rock slides that however could become reactivated in the future by natural or man induced processes indicated by MRTG,
- A group of fossil rock slides for which one can estimate that no reactivation danger exists in the near future are indicated by MRTA.

The delineation of the deep seated rock slides is based on the interpretation of the geomorphological map. The additional degree of activity (R, G or A) was determined from the geomorphological map, field observations and directed airphoto-interpretation. Published measurements on "Talzuschube" (HAUSWIRTH et al. 1979/1982) mention values of maximum 7 mm/yr, which is thought to be an active valleyward sliding slope. Since there were no possibilities for measuring and monitoring, evaluation of the stability of deep seated slides was depending on morphological signs. The following questions were asked to estimate the stability from the map:

- Are the rock slides accompanied by open fissures and or by rockfalls, especially in their upper back scarp zones, indicating that movement will progress in the future,
- Is the area destabilized by undercutting processes,
- Are there morphological signs that the position and incision of streamlets/riders is affected by adjacent slope movement (e.g. 'pushing' away of streamchannels etc.),
- Is there a cover of glacial or ice-marginal sediments present that indicates time relationship (e.g. side scar-depressions that have been filled by subglacial till),
- Are there special hydrological destabilizing factors (spring zones, ponding zones, water loss into the area from streams that are being 'manipulated' by the slope movement and therefore cannot develop and incise freely),
- What is the geometry of the slide surface, the slope height and the slope angles, so that an estimation on the in-depth dimensions and shear planes can be obtained,
- What type of rock is involved (geotechnical map),
- Are there signs of mantles existing of blocks related to in situ disintegration of the rock mass,
- Are there any other factors controlling the stability (e.g. presence of gypsum in the subsurface),
- Are there possibilities of (increased) activation by natural processes (loading by rockfall, undercutting and incision by rivers, solution of gypsum etc.),
- Is it possible to subdivide complex slides into subzones of different activity and process (spatial distribution of stability within the landslide complex).

These questions can be answered rapidly from the geomorphological and geotechnical maps, so that an estimation of the present stability can be produced, and the rock slide can be grouped according to the above mentioned classification. This grouping, which is mainly based on surficial pattern analysis can serve as a basic framework for other methodologies, such as the modelling of the temporal frequency, or stability analysis using advanced computer programmes that use a wide range of input parameters.

The MRTR group is not widespread; in the upper Gampbach (map sheet Fundl-Kopf, C1-2) a failure zone is related to the coincidence of several factors, such as presence of gypsum in the subsurface, the NW dip of strata and an important glacial oversteepening factor (see also Chapter 2, section map sheet Gampberg).

**Shallow mass movements**

These groups contain both the slides, either in rock or in unconsolidated material (MRU) and flows (MF). Again a subdivision has been followed into R (highly endangered), G (moderately endangered) and A (old flow or slide area). The distinction of deep versus shallow mass movements is here tentatively drawn at 5 m, but most shallow slides and flows do not exceed 2.5m. When dealing with the interpretation of the activity of solifluction processes, the following factors should be evaluated:

- The deposition of fresh material. Since the boundaries of the youngest active process have been drawn, the areal flow deposits (solifluction fans, mudflow deposits) can be evaluated on their activity relative to adjacent patterns,
- The type of underlying material. The susceptibility to mudflow and solifluction is high in materials containing relatively high percentages of fines. In the Flysch underlain area (mainly impermeable sequences of marls, shales, limestone and sandstone layers) and in the areas covered by subglacial till these processes dominate. Attention is also given to the possible presence of impermeable layers, for instance compacted lake-clays and silts,
- Erosion at the toe of the flowmass. This factor could maintain the flow process if material would be available upslope. Erosional and denudational processes can be evaluated from the geomorphological maps,
- The role of water; this is probably the most important factor for the evaluation of activity if accumulation and erosion rate at the toe are set equal in time. It must be evaluated if there are indications of permanently saturated conditions. Evaluated are the occurrence and position of ponding zones, spring zones, drainage density in relation to underlying material and slope angle,
- The position in the terrain. In certain zones solifluction deposits and relatively wide and shallow niches occur. Their formation is linked to former raised groundwater table conditions. Flow processes along the ice-margin (area

*Photo 26. Active slope failures (debris slides) along the southern Trübbach river (map sheet Nenzinger Himmel, D1) in unconsolidated slope debris, initiated by undercutting. These features contribute substantial volumes of sediment to the Trübbach channel, often blocking the drainage and initiating debris flows on the downstream fan.*
Tschardund, Gampberg, E1-2) were active, probably also related to the absence of a vegetation cover. Nowadays other hydrological regimes prevail and water from upslope areas can rapidly be drained (indication on the hazard maps: MFA/MFG). The niches bordering the gorge of the Mengbach (e.g. map sheet Gampberg, G2-3) were formed at the time that this gorge was (partly) occupied with sediments and again other groundwater conditions prevailed. Present activity is absent to moderate (indication MFA/MFG). The existence of solution hollows in the solifluction-debris fans on the northeastern Gampbach valley slope (map sheet Gampberg, D4-5) are clear indications of former flow activity (MFA),

- The appearance of flow-determined areas on the false-colour infrared aerial photographs. Quick reference was made to obtain additional data on the soil moisture conditions at the time of flying. In some areas this proved very useful.

Theoretically the activity of flow processes should be related to periods with the highest rainfall intensities and the melting period of the snow, respectively summer and spring. The occurrence of (small) mudflows is restricted to some isolated spots in the area underlain by Flysch and subglacial till.

Debris flows form a special 'flow type' hazard. For theoretical considerations on debris flow movement is referred to JOHNSON (1984). In the study area their source areas can be well defined. These source areas are confined to dolomitic scree producing (Hauptdolomite) slopes, in most cases to relatively short and steep gradient tributary valleys and steep niches. Their runout zones are restricted in most cases to a connected debris fan, where lobeate debris bodies accumulate (e.g. the Bärenrüfe, map sheet Fundl-Kopf D4). In several cirques but also in forested areas (Neuwald, map sheet Gampberg, F/G4-5) single small tracks of debris flows can be observed. These were in fact unmappable. The debris flow events are related to high intensity rainstorms as was ascertained many times in the field. The frequency of these events is such that the activity is estimated to be high and destructive in most cases. In fact the process needs exceptional water runoff to be triggered (VAN ASCH 1992, referring to VAN STEIJN). Therefore these areas have been indicated on the hazard zonation maps as WR or WG, a similarity with the building of fan bodies. Since the debris flows in this area occur mostly on non-vegetated zones, aerial photographs combined with field visits proved to be welcome additional information sources next to the geomorphological maps.

Surficial sliding is, in general, restricted to soil slopes in the study area. Although the stability of individual slides is ruled by unique geotechnical properties, a qualitative estimation of the activity can still be given by thorough interpretation of some factors that can be derived from the geomorphological base map. The spatial distribution can be identified rapidly by incorporating the area represented in the geomorphological map by general symbols and by already delimited terrain units. This recognition aims at the identification and evaluation of stress increasing and strength decreasing factors. Those that can be evaluated are:

- The possibility of external loading, for instance by rockfall or other depositional processes,
- Undermining caused by stream erosion, backward developing niches and seepage/spring zones,
- The presence of tensional cracks in the upper zone of slide development and ponding of water within these cracks,
- The availability of water by evaluation of the the drainage network; are the positions and gradient of drainage lines determined by normal fluvial development or by mass movement processes, the occurrence of important spring zones or infiltration areas,
- The expected sequence of materials in the subsurface; shallow failure planes can develop when sudden transition of impermeable and permeable materials occur,
- The presence of gypsum in the near subsurface, although this is a special hazard often combined with collapse (see next section).
The importance of these individual determining factors may vary from place to place and a 'mental processing' method, largely based on local background knowledge and experience is applied in the evaluation of slide hazard activity.

Collapse due to gypsum karst

A special hazard is formed by the collapse of material into sub-surface cavities created by the solution of gypsum. Ground subsidence and collapse is especially frequent in covered karsts, where cavities may be formed by natural erosion within the mantle of non-lithified sediments, and may collapse without warning (FOO=KES and VAUGHAN 1986). In certain areas this is a phenomenon that has to be taken into account. This type of hazard is judged from the geomorphological map. Areas with concentrations of collapse dolines have been picked out. It appears that two types and magnitudes of covered karst occur in the area. Both types have been indicated on the hazard zonation map by a suffix (k) and are combined with other codes. No special activity or endangering class has been annotated.

1) Collapse of bedrock overlying gypsum
2) Collapse of unconsolidated deposits overlying gypsum

The formation of large collapse dolines in bedrock is a rare and infrequent process and was discussed in more detail in chapter 2, map sheet Gampberg. The nature of the process prohibits an evaluation of the activity. Solution as an active process can be observed in the upper Gampbach valley, where active debris flows dump their material in dolines. The large collapses of bedrock (Kessiloch, Bärenloch, Schmalzberg, Neuwald, Schneeböden) probably predate the last glaciation, not only because glacial materials have been found inside. The volume of gypsum that has to be solved in the subsurface to create collapse depressions of 70 m deep and 100 m wide takes more than the postglacial period. CAMMERAAT et al. (1987) mention values of 10.4 m of lowering of the subsurface in 8000 years. Following these values, it would take approximately 55.000 years to arrive at the present dimensions. However, it may be assumed that during the last glaciation less water was available, meaning that the age can thus be far older. Still, other processes are activated. Rockfall and scree production along the inner slopes of the depressions, sometimes creating scree cones and in the case of Neuwald active sliding, occurs.

The collapse of unconsolidated deposits into the subsurface is a more widespread phenomena. The sudden nature makes them difficult to predict. Collapse dolines deeper than 10m are rare, usually the depth is in the order of 5-10m and inner slopes range between 50º and vertical, which was also observed by GÖTZINGER (1952, 1955). Careful comparison of the aerial photographs of 1956 and 1984, showed that there are no indications for newly formed collapse dolines during this time interval in the non-forested zones. When constructions are planned in these zones further detailed site investigation is recommended.

Remarks

As much as possible it was tried to integrate all relevant data in the hazard zonation map. All the necessary steps (from geomorphology to hazard zonation) were performed by the author to avoid major classification errors. As far as the reproducibility is concerned, this depends in the first place on the expertise of the mapper and less on the cartographic representation. The main terrain units and most sub-units will be delineated in a similar way. Objectivity in the judgment of the degree of endangering is more complex, since so many factors are involved that vary from place to place and the determining factor is not always the same. This would be a disadvantage of the use of checklists, since they are not sufficiently flexible in terrain where detailed data are necessary and available. This detailed information in the method described here is gathered during extensive field mapping surveys during which terrain units were not known yet. They became apparent after a complete picture of the area was obtained. After this step checklists would be of potential use in classifying degree of endangering (KIENHOLZ 1977), but they do not influence the delineation of the terrain mapping units. Moreover the subjective choices that were made in constructing checklists and the (numerical or experience-wise) weighting of the results may introduce inconsistencies in the classification process.

The situations of all maps reflect the terrain conditions of the summer of 1990. Natural changes and the impact of human interference may demand the need for updating and re-interpretation of danger zones. It must be remembered that the areas that have been classified as N (not endangered) will always be subject to a certain 'remaining' probability of a hazard to occur. This stems largely from the fact that according to human knowledge and observation no signs of hazard have been observed. In the dynamic alpine environment however some hazards may occur infrequently so that former relicts have been removed or covered by other deposits.
Samenvatting.

Deze studie behandelt de geomorfologische ontwikkeling van een 150 km² metend alpien gebied in het noordelijke Rätikon-gebergte en de zuidelijke Walgau in Vorarlberg, de meest westelijk gelegen bondsstaat van Oostenrijk. De geomorfologie is weergegeven in een serie A2-formaat kaarten op schaal 1:10.000, met behulp van een sterk enetisch/proces gerichte legenda die gestoeld is op het gebruik van vlak-, lijn- en puntsymbolen. De geomorfologische kaarten dienen als uitgangspunt om geotechnisch gezien, homogene eenheden te omgrenzen en een zonering van natuurgevaren te bepalen, evenals om tot een indeling in gevarenklassen te komen. Deze afgeleide kaarten zijn als transparante overlaykaarten bijgevoegd, zodat de eenheden zoveel mogelijk aan de originele gegevens gecorreleerd kunnen worden.

In het eerste hoofdstuk I wordt het doel van de studie uiteengezet en algemene geografische informatie gegeven over het studiegebied. Naast een kort overzicht van de voorhanden zijnde relevante, vooral glaciaal-geomorfologische georiënteerde literatuur, wordt op beknopte wijze ingegaan op de tektonisch-geologische opbouw van Vorarlberg en van het studiegebied in het bijzonder. De schubsgewijze (dekbladen) opbouw en het voorkomen van plooi- en georiënteerde literatuur, wordt op beknopte wijze ingegaan op de tektonisch-geologische opbouw van Vorarlberg en het studiegebied. Naast een kort overzicht van de voorhanden zijnde relevante, vooral glaciaal-geomorfologische

In het tweede hoofdstuk gaat gedetailleerd in op de geomorfologische ontwikkeling. Allereerst wordt de geomorfologische legenda-opbouw besproken. De morfometrie en morfografie vormen het frame van de kaarten en worden met lijnen weergegeven. Hierbinnen worden materialen d.m.v. raster-symboolen en de processen/genese met kleurgebruik aangeduid. Als regel bepaalt het laatste proces het kleurgebruik.

De totstandkoming van de geomorfologische kaarten valt uiteen in drie fases: een eerste 'pre-field' fase waarin van geselecteerde gebieden een eerste interpretatie gemaakt werd a.d.h.v. zowel zwart/wit panchromatische (schaal 1:18.000) als false-colour infrarood luchtfoto's (schaal 1:10.000). Tijdens de veldfase (drie zomers) werd gekaart door middel van drie methodes: transect-kaarting, areale kaarting en kaarteren 'op afstand'. In de derde (bureau)fase worden de terrein en fotokaart tot het uiteindelijke produkt uitgewerkt.

De huidige geomorfologie en de ruimtelijke verspreiding van niet-gelithifieerde materialen is in sterke mate te koppelen aan de opbouw en het uiteenvalLEN van het ijstroomnet tijdens ijstijden. Het voorkomen van kristallijn erratisch materiaal in de fluviaal bepaalde benedenlopen van zijdalen in de Rätikon is gerelateerd aan het binnendringen van de III- hoofdgletsjer in deze dalen tijdens vroeg-glaciale en laat-glaciale periodes. Tijdens het binnendringen wordt de uitgang en daarmee de drainage van een zijdal geblokkeerd, zodat afhankelijk van perioden (glaciale stuwmeervorming) kunnen onstaan. Typerende dalopvullings-sequenties, die hierdoor ontstaan zijn, worden sedimentologisch beschreven.

Vervolgens wordt per kaartblad ingegaan op de, voor de verwerking tot geotechnische en natuurgevarenkaarten, meest relevante geomorfologische onderwerpen, voornamelijk:

- reconstructie van de glaciale geschiedenis inclusief het voorkomen van fossiele blokgletsjers,
- het voorkomen van gipskarst en de invloed hiervan op hellinginstabiliteit.

Het hierdoor verworven en gedetailleerd weergegeven genetisch-tijd beeld maakt het mogelijk in korte tijd afgeleide kaarten te produceren zoals in hoofdstukken verder wordt besproken.

In het derde hoofdstuk wordt een beoordeling van geotechnische eenheden gegeven. De methode omvat het herkennen en afgrenzen van, vanuit geotechnisch oogpunt gezien, homogene gebiedjes. De losse materiaaleenheden werden direct uit de geomorfologische kaarten afgeleid, de gesteente-eenheden worden uit bestaande geologische kaarten overgenomen en aangevuld met specifieke geomorfologische informatie. De losse materialen werden deltagegrupeerd en onderverdeeld volgens genese, proces en ontwikkeling in de tijd in totaal 30 klassen. Bij de onderverdeling van massabewegingsmaterialen werd het type beweging (vloei-, valbeweging) en de textuurklasse van het materiaal (bergstort, fijnklastisch hellingpuin) als belangrijk scheidend criterium gehanteerd.

Beter inzicht in de samenstelling en daarmee in het komst van sediments werd verkregen door het nemen van grindmonsters (fractie 4.8-8mm) uit randglaciale terrassen, moreneafzettingen en ijsscontact-afzettingen. Op grond hiervan konden o.a. de voormalige kontaktzones van de zij- en hoofdgletsjer nauwkeurig worden vastgesteld. Met behulp van een Schmidt-Hammer werd in het veld een indruk verkregen van de ongesteunde druksterkte van de diverse gesteente-formaties. Deze werden op basis hiervan formatie-gewijzigd ingedeeld in sterke, middelmatig sterke en zwakke gesteente. Tabelsgewijs zijn een aantal eigenschappen van los materiaal en gesteente in het veld bepaald en/of aan de literatuur ontnomen, die als indicatieve waardes moeten worden gehanteerd. De variabiliteit binnen de 'terrain mapping units' laat niet toe dat 'site' gegevens over het gehele gebied geëxtraheerd worden.

In een aantal geselecteerde gebiedjes werd gebruik gemaakt van geofysische technieken (electro-magnetische en geoelectrische methodes) om aanvullende gegevens te verzamelen over laterale verbreding, dieptebereik van massabewegingsmaterialen. In een aantal geselecteerde gebiedjes werd gebruik gemaakt van geofysische technieken (electro-magnetische en geoelectrische methodes) om aanvullende gegevens te verzamelen over laterale verbreding, dieptebereik van massabewegingsmaterialen. In een aantal geselecteerde gebiedjes werd gebruik gemaakt van geofysische technieken (electro-magnetische en geoelectrische methodes) om aanvullende gegevens te verzamelen over laterale verbreding, dieptebereik van massabewegingsmaterialen. In een aantal geselecteerde gebiedjes werd gebruik gemaakt van geofysische technieken (electro-magnetische en geoelectrische methodes) om aanvullende gegevens te verzamelen over laterale verbreding, dieptebereik van massabewegingsmaterialen. In een aantal geselecteerde gebiedjes werd gebruik gemaakt van geofysische technieken (electro-magnetische en geoelectrische methodes) om aanvullende gegevens te verzamelen over laterale verbreding, dieptebereik van massabewegingsmaterialen. In een aantal geselecteerde gebiedjes werd gebruik gemaakt van geofysische technieken (electro-magnetische en geoelectrische methodes) om aanvullende gegevens te verzamelen over laterale verbreding, dieptebereik van massabewegingsmaterialen.

In het vierde hoofdstuk staat de beoordeling van natuurgevaren en het weergeven ervan in gevarenklassen centraal. Allereerst wordt kort ingegaan op enige bestaande classificatiesystemen. Gezien de schaal, afmetingen van het gebied, beschikbare tijd, doel en beschikbare expertise werd hier gekozen voor een kwalitatieve 'hazard' analyse, volgens een
This study deals with the geomorphological evolution of an alpine area, measuring 150 km², in the northern Rätikon-mountains and the southern Walgau in Vorarlberg, the westernmost federal state of Austria. The geomorphology is depicted in a series of 1:10.000 scale maps (format A2), and is based on a legend that is based on the representation of processes/genesis and materials by using areal-, line- and point-symbols. The geomorphological maps form the basis for the delimitation of geotechnically homogeneous units and hazard zones, and a subdivision of these hazard zones into degrees of endangering. These derived maps have been enclosed as transparent overlays to allow correlation with the original geomorphological data as much as possible.

The aim of the study is explained in chapter I. General geographical information is given and the available literature, mainly emphasizing glacial-geomorphological topics, is reviewed in short. The geological-tectonical structure of Vorarlberg and the study area in particular is outlined. The various nappes, the presence of folding and diapiric structures, especially occurring within the Arosa-Zone and Raibler Formations (acting as decollement zones), I is reflected in typical gypsum karst (collapse dolines) and mass movement.

Chapter two focusses on the geomorphological evolution. At first the geomorphological legend is explained. Morphometry and morphography are depicted by line symbols and constitute the framework of the maps. By means of raster-symbols materials are indicated, the processes/genesis are denoted by means of colours. As a general rule the last active process determines the use of colours.

The preparation of the geomorphological maps can be separated in three phases: a prefield phase in which a first interpretation from both black & white panchromatic (scale 1:18.000) and false-colour infrared (scale 1:10.000) aerial photographs of selected subareas was made. During a field phase covering three summers the mapping programme was executed by using three methods: mapping along transects, "aerial mapping" and mapping 'at distance'. The geomorphological maps were finalized during the third phase (desk).

The present morphology and the spatial distribution of non-lithified deposits is related to the growth and decay of the former glacienetwork. The occurrence of crystalline erratics in the lower sections of tributary valleys in the Rätikon is related to the penetration of the trunk Ill-glacier in these valleys during early- and late-glacial phases. A blockage of the normal drainage in the tributary valley is the result, causing the formation of ice-dammed lakes. Sedimentological sequences of characteristic valley fill deposits that are related to these situations have been documented.

Next, the most relevant geomorphological features for the individual map sheet areas are described, emphasizing on:
- reconstruction of the glacial history including the occurrence of fossil rock glaciers,
- the spatial distribution of non-lithified deposits,
- mass movement processes and forms,
- the occurrence of gypsum karst and its influence on slope stability.

The acquired and represented detailed genetical-time model allows a relatively rapid production of derived maps, as is discussed in chapters 3 and 4.

In the third chapter an appraisal of geotechnically homogeneous units is made. The method involves the recognition and delimitation of geotechnically homogeneous units. The non-lithified materials were directly delineated from the geomorphological map, the rock units were reproduced from the existing geological maps, supplemented with specific geomorphological information. The non-lithified materials were grouped and subdivided according to genesis, process and the development in time into a total of 30 classes. The type of process (flow, fall) and the textural class (rockfall, fine scree) are the major discriminating criteria, although of different level in the classification, in the subdivision of mass movement deposits.

A better judgment of the composition and therefore provenance area of the sediments was obtained through analyses of the fine-gravel fraction (4.8-8mm) taken from ice-marginal terraces, morainic and ice-contact deposits. The former contact-areas of trunk and tributary glaciers could be determined with great certainty. Using a Schmidt-Hammer device
in the field an impression was obtained of the Unconfined Compressive Strength (UCS) of the various rock formations. On the basis of these values a classification could be made into strong, moderately strong and weak/very weak Formations. A number of rock and loose material properties, determined in the field or obtained from literature have been presented in tabular form; these data should be used as indicative values only. The variability within the terrain mapping units does not allow these data to be extrapolated over the total area.

In selected sample areas geophysical techniques (electro-magnetic and geo-electric methods) were applied in order to obtain additional data about the lateral distribution and the depth range of deposits and the dimensions of mass movement areas.

In the fourth chapter the appraisal of natural hazards and its representation into hazard zones is emphasized. At first a short 'state of the art' review is given of several existing classification methods. As for scale, dimensions of the area, available time, purpose and available knowledge a qualitative hazard analysis was chosen, according to a direct mapping approach, relying on the 1:10.000 geomorphological inventory. The legend used is closely related to the already community-wise existing hazard zonation maps in Austria, which enhances possible use. In this study an appraisal of flooding, avalanche and mass slope instability hazard is made. The relative activity of slope instability and flooding hazards is especially based on geomorphological pattern analyses. The most important considerations leading to the appraisal of the activity have been formulated in specific questions for each legend unit. A restricted number of stereographical projections of discontinuity planes in the rocks were made for the evaluation of stability. Additional information on the occurrence and location of other hazards, such as avalanches, was obtained from avalanche records, hazard zonation plans and chronicles. A more complete picture was established by questioning of local inhabitants. The results have been presented in 1:10.000 scale transparent overlay maps covering the whole area.

Both derived maps should be regarded and used as general purpose maps on a medium scale and could, apart from their value as planning documents, serve as a basis for further specific site investigation.

References


BÄCHTIGER quoted in HANTKE, pp.118 (1980)


GEONICS (1980): TN-6, Electromagnetic terrain conductivity measurement at low induction numbers; 1745 Meyerside Drive Mississauga, Ontario, Canada L5T 1C6.


Annexe I
GEOMORPHOLOGICAL, GEOTECHNICAL AND NATURAL HAZARD MAPS OF THE NORTHWESTERN RÄTIKON MOUNTAINS AND SOUTHERN WALGAU (Vorarlberg, Austria) at scale 1:10.000 (Separate enclosure)

Annexe II
List with numbers of the aerial photographs used for the preparation of the geomorphological maps.

18 x 18 cm black and white panchromatic photographs at approximate scale 1:18.000 were flown in 1956 by order of the ‘Bundesamt für Eich- und Vermessungswesen’ in Vienna.

23 x 23 cm black and white panchromatic photographs at approximate scale 1:18.000, flown by the French allied forces in 1947.
Nos: 6302-6311 6333-6334 6264-6268 6350-6359 5343-5345 5053-5054

23 x 23 cm false colour infrared photographs at the approximate scale of 1:10.000 were flown in 1984 by order of the ‘Agrargemeinschaft Nenzing’ for the ‘Waldzustanderhebung 1984’.

23 x 23 cm black and white panchromatic photographs at approximate scale 1:20.000 were flown in 1983 by order of the ‘Bundesamt für Eich- und Vermessungswesen’ in Vienna.
Nos: 5301-5304 5286-5289
List of maps used for the preparation of the geomorphological and the derived geotechnical and hazard zonation maps:

GEOLOGICAL MAPS:

TOPOGRAPHICAL MAPS:
- 1:10,000 topographical base-maps produced in 1954 by the ‘Bundesamt für Eich und Vermessungswesen’ in Vienna.
  Nos.: 141/1-N 141/2-N 141/1-S 141/2-S 141/3-N 141/4-N
- 1:10,000 ortho-photomap Nenziger Himmel especially produced by the ‘Bundesamt für Eich- und Vermessungswesen’ in Vienna, by order of the Agrargemeinschaft Nenzing.
- Landeskarte der Schweiz 1:25,000, Blatt 1116 Feldkirch, Blatt 1136 Drei Schwestern, Blatt 1156 Schesaplana.
- 1:5,000 scale ortho-photomaps with contourlines and cadastral divisions produced by the ‘Bundesamt für Eich- und Vermessungswesen’ in Vienna.
  Nos: 1023-5100 1023-5101 1023-5102 1023-5103
  1023-5300 1023-5301 1023-5302 1023-5103
  1024-5303 1122-5000 1122-5001 1123-5000
  1123-5001 1123-5002 1123-5003 1123-5102
  1123-5200 1123-5201 1123-5202 1123-5203
  1123-5300

Annexe IIIA

Location of petrographical samples.

<table>
<thead>
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<th>NR.</th>
<th>TYPE</th>
<th>MAP SHEET</th>
<th>SECTOR</th>
<th>HEIGHT</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>(fan) terrace deposit</td>
<td>SCHIFIS</td>
<td>A5</td>
<td>535 m</td>
</tr>
<tr>
<td>2</td>
<td>ablation deposit</td>
<td>N.-HIMMEL</td>
<td>E2</td>
<td>1305 m</td>
</tr>
<tr>
<td>3</td>
<td>(fan) terrace deposit</td>
<td>GURTIS</td>
<td>D5</td>
<td>850 m</td>
</tr>
<tr>
<td>4</td>
<td>lacustrine valley fill</td>
<td>GURTIS</td>
<td>D5</td>
<td>910 m</td>
</tr>
<tr>
<td>5</td>
<td>washed till deposit</td>
<td>GURTIS</td>
<td>D5</td>
<td>910 m</td>
</tr>
<tr>
<td>6</td>
<td>subglacial till</td>
<td>GAMPBERG</td>
<td>C2</td>
<td>1120 m</td>
</tr>
<tr>
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<td>lacustrine valley fill</td>
<td>FUNDL-K.</td>
<td>E1</td>
<td>1110 m</td>
</tr>
<tr>
<td>8</td>
<td>valley-fill deposits</td>
<td>FUNDL-K.</td>
<td>E1</td>
<td>1105 m</td>
</tr>
<tr>
<td>9</td>
<td>washed till deposit</td>
<td>FUNDL-K.</td>
<td>E1</td>
<td>1110 m</td>
</tr>
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</tr>
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<tr>
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<td>DUNZA-T.</td>
<td>A5</td>
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Annexe IIIb.

Petrographical composition of the fine gravel fraction (4.8-8 mm) for samples from the Gamperdonas, Gamp- and Galina-valleys and the southern Ill valleyslope between the Samina and Mengbach rivers.
The locations are indicated on the geotechnical overlay maps. A listing of sediment type, height and map sheet sectors is given in Annexe IIIA.

A = granite, gneiss, schist, quartzite
B = amphibolites, epidotes
C = quartzites
D = calcite
E = dark limestone
F = light coloured limestone
G = red limestone
H = red + green Sandstone
I = other sandstone
J = dolomite
K = shale
L = cemented fragments
M = rest
n = number of stones counted
I = A+B+C/100-(H+I+K+L+M)
II = D+E+F+G/100-(H+I+K+L+M)
III = J/100-(H+I+K+L+M)

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Annexe IV.

Description of the most widespread Formations. The data have been compiled from literature (RICHTER 1969, SEIJMONSBERGEN & VAN WESTEN 1986, LOCKER 1978 and own observations)

GHKe: Coches Rouges (Maastrichtian-Turonian).
The Coches Rouges Formation is a well bedded red to green limestone.
The Coches Rouges are morphologically expressed by vertical cliffs, large production of debris (scree cones), internal drainage and the development of vertical fissures in case of horizontal bedding.

GHKF: Plattenkalk (Rhätian-Norian). Well bedded limestone. The surface of bedding planes is often covered by a polished varnish. Thickness of layers: 1dm - 1m. Highly permeable, especially along joint systems. In the upper parts of the formation thin clayey fillings can be present in between layers. The Plattenkalk Formation is closely related to the Hauptdolomit Formation.

GHKg: Muschelkalk (Anisian). Darkgrey, 5-20cm thick limestone layers, separated by thin clayskins. Occasional flint concretions within the limestone layers. Intercalations of dolomitic layers and marls occur. Characteristic are: the high permeability and the open discontinuities.
The morphological expression: forms steep cliffs, is often associated with deep-reaching slope deformation, reflected by open fissures, in situ disintegration of the rock mass and related rockfall processes. The formation of solution rills (lapies) is a common phenomenon.

GHD: Hauptdolomit (Norian, Upper Triassic). Light to darkgrey, thinly to thickly well bedded strong dolomitic limestone. Highly fractured, narrowly spaced joints, causing rapid mechanical weathering producing very angular, small scree fragments. Locally tectonic disintegration led to sandy fine-grained fillings (mylonites). Internal drainage along discontinuities and bedding planes. Morphological expression: the Hauptdolomit F. dominates the waterdivides in the Ratikon and is always associated with huge scree cones.

GHS: 'Gault' (green) sandstone Formation (Aptian/Albian/Cenomanian, Middle Cretaceous). Green to greyish thickly bedded massive strong gneissite bearing sandstone, locally alternating with limestone/marl layers. Contains pyrite and phosphorite in varying amounts. Geomorphologically the resistance of the formation is expressed in the steep slopes with related scree accumulations.

GMS: Reiselsberger Sandstone Formation (Cenomanian-Turonian, Upper Cretaceous). Thickly bedded darkgrey to lightbrown mica-rich strong sandstone. Contains variable amounts of chlorite, quartz, calcite, feldspars and dolomite. Cementation by calcite and/or quartz. The Reiselsberger sandstone formation is known for its in situ disintegration along joint systems producing a very coarse mantle of coarse scree and blocks and its susceptibility to deep reaching slope deformation.

GMSb: Buntsandstein and Verrucano (Perm-Skyth). These rocks exist of red and green conglomerates and coarse sandstones and alternate with red, green and white quartzites and locally with red shales. Of subordinate importance in this area, found in Quaternary deposits.

GMVb: Flysch Formations, Planckner-Brücke Formation, Piesenkopf-Formation, Fanola-Formation (Cenomanian/Turonian/Coniacian/Santonian/Campanian/Maastrichtian, Late/Upper Cretaceous). Thiny bedded sequence of alternating dark grey strong limestone and/or silicous limestone, and/or brown to greyish moderately strong fine-grained to coarse-grained sandstone, and/or fine breccias intercalated with dark grey marl layers. Graded turbiditic series are commonly encountered. Micro-folding and faulting is characteristic. Due to the intercalations of marl the Flysch Formations are impermeable.
The Flysch forms the lower relief units in the area and is characterized by an extensive cover of glacial- and ice-marginal deposits.

GMVc: Arosa Zone Formations (Dogger to Turonian, most of the series are of Cenomanian age).
Main rocktypes are reddish, green and black marls and shales. They alternate with strong sandstones, sandy limestone, breccias and quartzitic layers. Isolated pockets of conglomerate have been found. These competent layers have often been disrupted by tectonic deformation. Therefore broken fragments are often found isolated within the matrix of marl series. In most cases these series can be regarded as impermeable to water. The geomorphological expression: builds gentle to steep slopes, often associated with (deep-seated) mass movement which is reflected by an undulating topography, ponding, the presence of slide units and a distorted drainage network.
GMVe: Raibler Schichten (Karnian). This formation consists of series of sandstones, dolomitic limestones, marls, rauhwickes, shales and the characteristic anhydrite and gypsum layers (see below). The limestone series consist of highly jointed layers, light to dark blueish-grey and can be 50 m thick. The Raibler Formation builds irregular undulating to steep slopes, is susceptible to weathering and erosion.

GMVF: Arlbergschichten (Ladinian). The Arlberg Formation is composed of an alternating sequence of light to dark-grey limestone and marl beds. The limestone beds are thickly layered and highly fractured. Dolomitic members are commonly found in the upper part of the formation, as well as transitional dolomitic beds. The limestone and dolomitic layers are waterbearing, the impermeable marls strongly oppose water movement perpendicular to the bedding planes. In general the Arlberg Formation builds relatively stable steep slopes.

GMVg: Partnachschichten (Ladinian). Within the formation alternations of thinly layered dark colored massive claysstones with thickly layered parts occur and it is commonly veined by thin calcite bands. Waterbearing parts are restricted to jointed zones. Together with the Arlberg Formation these series occur in steep slopes and is moderately susceptible to surficial mass movement (slides, scree production).

GGG: Gypsum of the Raibler Formation (Karnian).
Characteristic morphological expression: The presence of gypsum in the subsurface is morphologically expressed by numerous typical gypsum solution hollows and collapse depressions in covered karst areas. Cementation of unconsolidated sediments often occurs in relation to groundwater that has been in contact with gypsum/anhydrite beds. In positions were steep Hauptdolomit walls overlay gypsum bearing zones deep reaching rock-slope deformation can be expected.
Annexe V.

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