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Development of a Detailed Geomorphological Mapping System and GIS Geodatabase in Sweden

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Abstract

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This thesis presents a method for detailed landscape presentation. The method incorporates both fieldwork-based comprehensive geomorphological description and digital data handling and thus contributes in filling the gap between traditional geomorphological mapping and modern geomorphological studies performed in Geographic Information Systems (GIS).

The main part of the thesis relates to development of a new detailed geomorphological mapping system, constructed to be easy to use and yet present a large amount of geomorphological information. The legend of the mapping system has successfully been applied to various types of landscapes, mapped at various scales between 1:5,000 and 1:50,000 without any modifications needed. The information presented in the map is based on simple descriptive criteria and thus the subjectivity is kept low, which enables a broad field of usage. In parallel with the mapping system a GIS-based geomorphological database has been developed. The structure and data presentation of the new mapping system allows for easy transformation of the data to form part of this database. The selected format of the GIS database is the ESRI ArcGIS®, Personal geodatabase.

In the development of the geomorphological mapping system four field areas have been mapped in central (Bonäs, Risa and Liden) and northern Sweden (Tarfala). In addition the new legend has been adapted to a field area situated in Vorarlberg, Austria (Upper Gamperdona valley).

In relation to the Tarfala field area an added issue of the project has been to give insights in the effects of physical and chemical weathering on various rock types to see if this can be detected in materials and landforms. The results from this study point at that resistance towards weathering vary among rocks even though they are of same rock type.

Keywords: Geomorphology, Geomorphological map, GIS, Sweden

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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

- I Gustavsson, M., Kolstrup, E., Seijmonsbergen, A.C., 2006. A new symbol- and GIS-based detailed geomorphological mapping system: renewal of a scientific discipline for understanding landscape development. *Geomorphology* 77, 90-111.
- II Gustavsson, M., Seijmonsbergen, A.C., Kolstrup, E. Structure and content of a new Geomorphological geodatabase linked to a Geomorphological map – with an example from Liden, central Sweden. Submitted.
- III Gustavsson, M., Kolstrup, E. New geomorphological mapping system used at different scales in a Swedish glaciated area. Submitted.
- IV Beylich, A.A., Gustavsson, M., Kolstrup, E., 2007. Experimental weathering of selected non-calcareous rock types under wet/moist conditions. *Zeitschrift für Geomorphologie*, In Press.
- V Gustavsson, M. Geomorphological mapping and weathering studies in the Tarfala valley, northern Sweden. Submitted.

My contributions to the co-authored papers are:

Paper I: By far most of the fieldwork in the Bonäs area and all map drawing of the Bonäs map. Also final map drawing of the Gamperdona map. Contributions to discussion and writing.

Paper II: All fieldwork, map drawing and data handling. Major contributions to discussion and writing.

Paper III: By far most of the fieldwork and all map drawing. Equal partner with discussion and writing.

Paper IV: Fieldwork in Tarfala and about half of the laboratory work. Contributions to discussion and writing.

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Introduction

The landscape that surrounds us is essential to our life and activity and thus understanding of its characteristics and processes is important for sustainable development. Formed through long ages by changing climatic conditions, topography and materials, the landscape is complex and includes both resources and hazards to our society. Therefore the study of landscape characteristics is important, not only for benefit but also for survival. The landscape also forms an archive in which information on past processes are recorded as landforms and materials. Reading this record correctly might give us understanding of past responses to changed conditions. Thus it forms the key to maybe also understand and predict future development.

Early scientific descriptions of landscapes were made in words, occasionally in combination with illustrations, but since the second half of the 20th century, geomorphological maps i.e. maps with a scientific description of the landscape have been used for the description of the landscape, both in scientific and practical purposes. Due to the amounts of data required to give a full description of the landscape, comprehensive geomorphological maps often present a complex legend and map sheets that are hard to read. However, since the development of computer based Geographic Information Systems (GIS) two decades before the new millennium, the discussion about how to present a detailed general description of the landscape and its development has faded away. This is surprising, since the data handling capacity in a GIS could be the tool needed to solve previous problems with large quantities of data. Since traditional comprehensive geomorphological maps often are documents containing broad descriptive information of the landscape characteristics, a transformation of these into modern GIS databases could result in a powerful tool for landscape analysis.

This thesis summarises a project aimed at connecting the past comprehensive landscape studies with the modern remote sensing and GIS techniques. The project is a methodological study with the aim to construct a comprehensive geomorphological mapping system using an easy-to-use legend. In addition the new mapping system is designed to be used in parallel with a geomorphological GIS database incorporating the same data.

In relation to the Tarfala area (see section 4.3) an added issue of the project also concerns weathering studies. The aim of these was to estimate or at least give insights into the importance of physical and chemical weathering

in cold environments and also to estimate their mutual importance in the formation of forms and materials in the Tarfala area.

The aims of this project can thus be summarised in:

1. To construct a detailed geomorphological legend and mapping system that is applicable for different types of landscapes
2. The legend should be easy to use and should be usable at different scales.
3. To enhance the usability of the geomorphological data the subjectivity should be kept low.
4. The system should primarily be constructed with Swedish landscapes in mind and be able to deal with phenomena occurring there (such as tills, highest Holocene shoreline, bedrock features, weathering etc.).
5. To construct a geomorphological database linked to the mapping system which enables easy data transformation from the original map.
6. The GIS database should be designed to be useful in both general and thematic applications.
7. To give insights about the effect of weathering and weathering resistance in various rock types on the development of landforms and materials.

1 Scientific background

Since one of the aims of this thesis is to build a bridge between traditional geomorphological mapping and GIS environment of today, it seems suitable to first present a short background to geomorphology and geomorphological mapping. To this it might also be good to define a few terms and concepts which will enhance further reading of this thesis.

Since this project mainly has been based on geomorphological studies in Sweden, this chapter will also give a small presentation on the history of geomorphological mapping in Sweden.

1.1 Geomorphology

In a dictionary, the term geomorphology is explained as the science of the forms of Earth's surface and the processes creating and reshaping them (Nationalencyklopedin, 1992). This incorporates parts of many different scientific genres (i.e. geophysics, sedimentology, geochemistry, hydrology, climatology, pedology, biology, and engineering) and thus geomorphology deals with the combination of these and their effect on the landscape configuration and development. Though the term geomorphology is a rather new term in science (1880's), thoughts and ideas about the landscape and the mechanisms creating it are very old and written sources in the subject are available from the age of Herodotus (5th C BC) and Aristotle (384-322 BC) (Summerfield, 1991).

Scientific attempts to understand and document the landscape have since the late 19th century resulted in maps with emphasis on the geomorphology. To construct such a map the geomorphology first needs to be generalised into subparts of recordable data. One way to do this could be to separate geomorphology into all disciplines of science covered by the term, but then the connections and relations between the parts would be lost. A better method is to subdivide geomorphology into the descriptive parts: morphology, genesis, processes, lithology, chronology and hydrography.

Morphography, which is a combination of the Greek words *morphē* meaning form and *logia* meaning science (SOED, 1970) can be further subdivided into morphography and morphometry, where morphography is the scientific description of form (SOED, 1970) used for the descriptive, qualitative documentation of morphology while the term morphometry is used for

the measurable, quantitative documentation of the morphology (Tricart, 1965; Summerfield, 1991). Genesis is also a Greek word and means origin or creation. In geomorphology the term (also named morphogenesis) relates to the origin of a landform, in other words the process responsible for creation of the form. Process thus is defined as the mechanical or chemical process itself. The term lithology has been used since 1716 as “The science of the nature and composition of stones and rocks.” (SOED, 1970, p 1153). In this thesis the term is used in a wider sense, also including organic sediments. The Latin word chronology is the science of computing time or a chronological table and in geomorphology the term is used in the meaning of geological age. First used in 1559, the term hydrography is a scientific term used for the “...science which has for its object the description of the waters of the earth’s surface...” (SOED, 1970, p 939) and thus the hydrography in a map is the description of the surface hydrology.

1.2 Geomorphological maps

1.2.1 The development of geomorphological maps

As long as there have been maps, these have in one way or another described the landscape. Even though the early maps were not ment to be used for scientific purposes, but rather for easier orientation, military strategy or economical purposes, they nevertheless needed to depicture landforms seen in the landscape. The first maps produced by mapmakers in Babylon c. 4500 years ago used the mound method to describe the topography of landscape and this method together with symbols for vegetation and hydrography were then used for several thousands of years. Since the 18th century the topography has been described by the hachure method and since the 19th century by the contour lines method, sometimes combined with a shaded relief (Elvhage, 1983). Examples of these three methods are presented in Figure 2:1.

Through the study of topographical maps some landforms can be distinguished and some may also be interpreted genetically if the general context is known. Topographical maps however, do not present direct information about the genesis and distribution of the landforms. Nor do they inform about smaller and less pronounced forms, the age of landforms, their lithology or their relationship to the geologic settings. Thus it is impossible to reconstruct the landscape development from topographic maps alone. To better understand the environment and its development through time geomorphological studies and maps have been used for over 100 years. Early geomorphological investigations were published as verbal descriptions of landforms, sometimes also including some profiles, photographs and draw-

ings, but soon also thematic geomorphological maps were constructed (Klimaszewski, 1982; Elvhage, 1983).



Figure 2:1. Maps of various age using different methods for describing the topography. From left to right: Mound method (from Bureus, 1649); hachure method (from Sundqvist, 1937), and contour lines (from Forslund and Härjung, 1995). Reproduced by permission I 2006/1599 © Lantmäteriet, Gävle 2006.

The earliest geomorphological maps often showed distinctive features such as river valleys or terraces. Other maps showed some slope forms, karst landforms, land slides and rock falls or concentrated on groups of landforms created by selected processes such as fluvial or glacial features. Thus these early maps were thematic rather than comprehensive and often not even a detailed classification of the landforms was given (Rudberg, 1979; Klimaszewski, 1982; Elvhage, 1983; Klimaszewski, 1990). The concept of thematic geomorphological maps describing a limited amount of information is still common and used in for example morphogenetic maps commonly used in field studies of glacial features (Evans, 1990).

In the early 20th century the first attempts were made to construct comprehensive geomorphological maps that include all aspects of geomorphology. In 1912 H. Gehne produced a geomorphological map describing morphography, structure of the substratum and the morphogenesis (presenting the forms of the relief and their genesis), and two years later S. Passarge presented the first true detailed geomorphological map. This map was published in the form of a Morphological Atlas presenting the geomorphological information in eight separate map sheets (at 1:50,000 scale) describing topography/vegetation, slope gradients (in five classes), valley forms, stratigraphy, physical resistance, chemical resistance, petrography and relief development (Klimaszewski, 1982).

During the 1920's and 1930's several attempts and proposals of geomorphological maps were published. During the Second World War geomor-

phological surveys were used by several participators and thematic geomorphological maps were applied for planning and to guide troops, especially in connection to amphibious invasion operations (see e.g. Williams, 1947; Rose and Willig, 2004). It was however not until after this war that some attempts to reach an international standard were made.

During the 18th congress of the International Geographical Union (IGU) in Rio de Janeiro 1956, two concepts of geomorphological mapping were presented and this resulted in the creation of the IGU subcommission for geomorphological mapping. The tasks for this subcommission were to introduce the method of geomorphological mapping into geomorphology, to develop and adopt a uniform mapping system. The idea was that the geomorphological map together with other thematic maps should be used for economic planning on both local and regional scale. After several publications and meetings of the subcommission in the 1960's, common principles for a detailed geomorphological map were determined. In 1968 the IGU subcommission completed the development of a Unified Key mapping system for international detailed geomorphological mapping (see Unified Key, 1968; Demek et al., 1972), which was followed by a Unified Key for geomorphological mapping at medium scale (see Demek and Embleton, 1978).

Parallel to the work of the IGU subcommission, the International Institute for Aerial Survey and Earth Sciences (ITC) also developed and published a comprehensive geomorphological mapping system for international use (Verstappen and van Zuidam, 1968). From during the 1970-90 several both local and regional geomorphological mapping systems at scales between 1:10,000 and 1:100,000 were constructed all over the world, with a concentration in Europe.

Even though the development of geomorphological maps has continued for almost 100 years, there has been no universally accepted form, content or cartographic symbolisation to the present day which sometimes make maps hard to compare, even when covering the same area. Since common principles were determined by IGU, comparison between different detailed geomorphological maps have become easier since their content is about the same. There are however still large differences in the way information is presented (Barsch et al., 1987; Klimaszewski, 1990).

Since the last decades before 2000 geomorphological surveys and mapping have emerged from mainly two different approaches. The first approach is the analytical, which base the map content on descriptive information on genesis, morphography, morphometry and chronology, while the second approach is the synthetic, where the geomorphological data is presented combined with non-geomorphological parameters such as soils, vegetation and hydrology. Apart from these two comprehensive approaches, a third approach is also the pragmatic approach, where only limited geomorphological information concerning a specific purpose is collected (Ten Cate, 1990).

1.2.2 Geomorphological maps in Sweden

The geomorphological maps produced in Sweden have mainly focused on inventory of landforms and geologically remarkable areas and their developments are linked to the development of geological nature conservation. This development can be traced back to a discussion raised by R. Sernander during a Geologiska föreningen (GF) meeting in Stockholm in February 1905 (Sernander, 1905). Owing to the at that time ongoing discussion about the creation of nature conservation areas in Sweden (for biological, mostly botanical reasons), Sernander pointed out the need of protecting areas also for geological reasons. He also pointed out the need of inventory and documentation of such areas. At this stage it was suggested that the people of Sweden would be requested to send documentation of local geologically remarkable features to GF or the Swedish geological survey (SGU) (Sernander, 1905). After this meeting however, no real inventories, except from local surveys, were made until the 1960's when the discussion of nature conservation of geologically interesting areas came up to discussion once again (Soyez, 1971).

In the late 1960's the Swedish Environmental Protection Agency (SNV) started a project for inventory of areas for nature conservation. The aim of the project was to map medium-sized landforms above the highest Holocene shoreline in the Swedish part of the Caledonians, an area of approximately 70,000 km². With these guidelines a geomorphological mapping system was developed under the supervision by G. Hoppe resulting in a test map covering the north-western part of Dalarna, Sweden (Soyez, 1971). During the 1970's and early 1980's a series of 24 maps based on aerial photograph interpretation and limited field controls were published at 1:250,000 scale. Included in the map descriptions were also environmental value assessments and detailed thematic maps of areas of special interest (Borgström, 1983). After the publication of these maps a methodological study for further production of geomorphological maps covering other parts of Sweden at the scales 1:50,000 or 1:100,000 was made. This study resulted in six 1:50,000 geomorphological map sheets covering the Siljan-area in Dalarna before the project was discontinued (Ulfstedt and Yrgård, 1982-83; Yrgård, 1980).

In 1979 S. Rudberg published an attempt to use the IGU Unified Key to map Swedish areas of different characteristics at different scales. Rudberg realised that this mapping system had to be complemented with symbols for the many hard rock features found in Sweden and small changes in use of colour were also suggested (Rudberg, 1979).

Except from these attempts of broad landscape descriptions, geomorphological mapping in Sweden has been concentrated to experimental or thematic maps ordered for local or regional planning (e.g. Elvhage, 1983; Mattsson and Swantesson, 1987) or simple maps for specific scientific surveys (e.g. Rudberg et al., 1976; Rubensdotter, 2002).

1.3 The design of a geomorphological map

Paper I in this thesis includes a detailed discussion about the content of a geomorphological map and how this information should preferably be expressed through the legend, but nevertheless it seems proper to present a short introduction to the basic concepts.

To get a full picture of the landscape, its development and the processes reworking its surface a comprehensive geomorphological map that presents information on morphography, morphometry, lithology, structure, hydrography, geological age, processes and genesis is needed.

The report on detailed geomorphological mapping published by the IGU (Demek et al., 1972) states that a geomorphological map should describe the interaction in the boundary between the lithosphere and the atmosphere/hydrosphere and in the report on medium-scale geomorphological mapping (Demek and Embleton, 1978) the content of geomorphological maps is extended to describe the surface of Earth's crust and its contact with the hydrosphere, the atmosphere, the pedosphere and the biosphere. Hence even though most geomorphological maps produced are products of surveys dealing with the land surface at different locations in the world, geomorphological maps should also describe the bottom of lakes and oceans.

Thanks to the work of the IGU subcommission for geomorphological mapping the general content of a detailed geomorphological map is agreed upon. A detailed geomorphological map must be a result of mapping in the field; the scale should be between 1:10,000 and 1:100,000; the map should give a full picture of the landscape presenting morphography, morphometry, genesis and age; coloured symbols should be used to present the geomorphology at scale; lithology should be marked with special symbols; and the legend should be arranged in genetic-chronological order (Klimaszewski, 1982). There are however still different opinions of the importance and details of the different datasets included, and how this information should be presented, i.e. in how the legend should be constructed.

“The essential component of a geomorphological map is its legend.” (St-Onge, 1981: p. 313). Even though landscapes might seem complex there is often an underlying order (Brunsden, 2003) and it is the classification of this which forms the basis for the legend. In the construction of a geomorphological map legend it is important to separate the descriptive and interpretative information, which makes it possible for the map reader to draw different conclusions than the map author. If this is not done the map will purely be a document of the map author's opinion. In the best case the map legend will not only make it possible to describe and explain individual landforms based on morphogenesis, but also explain their relation to other landforms and various processes in their surroundings (St-Onge, 1981). Verstappen (1970) states that the mapping system should be flexible, allowing the user to adopt the symbols most appropriate for the area concerned and that

the system should be applicable for mapping at all scales. Another important statement by Verstappen (1970) is that the maps should be as simple as possible to counteract cartographic problems, i.e. enhance the readability.

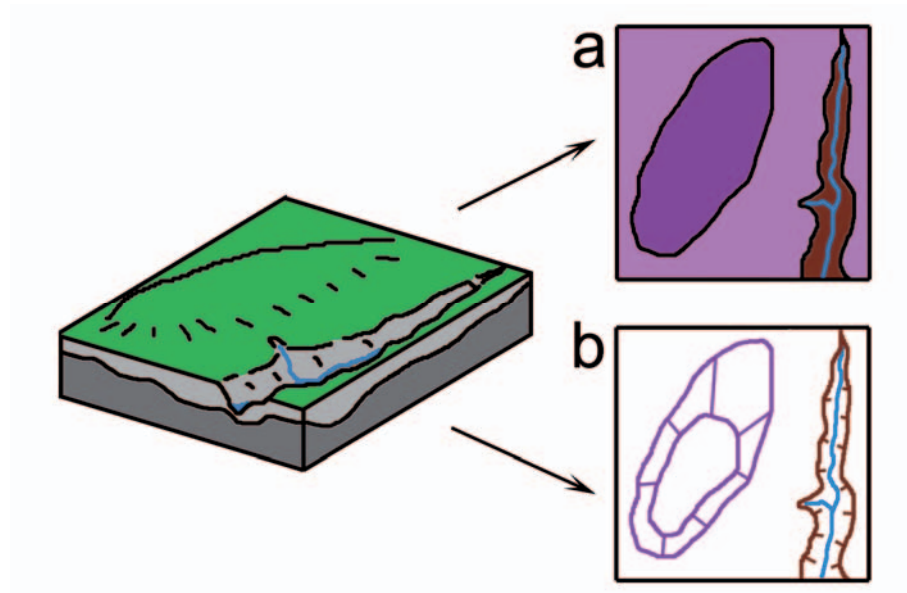


Figure 2:2 The figure illustrate two different models of landscape description. In the Landform Pattern Model (a), this hypothetical landscape is described as three main objects: a hill, a ravine (with a stream) and a plain. In the Landform Element Model (b) the hill is divided into a crest surrounded by slopes and the ravine is described by a stream in between two escarpments or slopes. The plain in this case gives a similar description to that of the Landform Pattern Model.

Finally when designing a new geomorphological mapping system it is worthwhile to consider how the landscape information should be treated, both regarding the descriptive and interpretative information and it is here appropriate to clarify the difference between two different basic models in the description of landforms (also discussed in Paper I). The first is the Landform Pattern Model which is the more interpretative of the two and in this the landforms are outlined and described as repeatable, easily definable forms (e.g. hills, ridges and channels) (Figure 2:2a), not necessarily drawn at scale. The second is the Landform Element Model which is more descriptive and here the landscape is instead separated into geometric elements (e.g. slopes and plains) (Figure 2:2b) (Speight, 1974). To be able to separate the descriptive and interpretative information as suggested by St-Onge (1981) the second model is preferable, but depending on scale this model often has to be complemented with the first model in various degree.

1.4 The use of geomorphological maps

The broad information in comprehensive geomorphological maps make them useful in several both academic and practical applications. The original intention of geomorphological maps was to be a tool to illustrate or to help explain the distribution of individual landforms in the landscape. As the maps in time have become broader in their descriptions of forms and processes they serve as comprehensive inventories of the mapped areas, often also presenting the interpreted landscape development. These scientific inventories are important for the understanding of the landscape and form a good basis for where to perform more detailed studies of for example processes. St-Onge (1981) states that the geomorphological map is as important to the process geomorphologist as the bedrock map is to the petrographer.

During the 1960-70 the concepts in geomorphology changed from being an extension of historical geology towards a discipline focused on studying process mechanisms and rate (Brunsden, 2003). As geomorphological mapping follows the trends in the whole discipline of geomorphology, the maps changed from being pure academic inventories towards getting more focus on processes and changes of the landscape. This change also caused applied geomorphology to become increasingly important (Goudie, 2001).

The concept of applied geomorphology is explained by the use of geomorphology to solve various problems. Today this is commonly related to development of resources or estimation and prevention of natural hazards (Goudie, 2001), an area which is becoming increasingly important with changing climatic conditions and rising sea level (Ten Cate, 1990). Mapping of natural resources and natural hazards as well as assessment of land surface resistance to denudation are important in guiding planning and may be very useful for example in developing countries or areas with expansion of population and infrastructure. Maps giving this information are especially important in densely populated high mountain regions, where relief and geomorphological processes control or have influence upon nearly all natural and anthropogenic features, such as slope stability, vegetation, glacial processes, hydrography as well as settlement and communication patterns (Barsch et al., 1987; Petley, 1998). Other areas where this use of geomorphological mapping can prove useful are in low lying areas close to rivers or close to the sea, or areas with frequent seismic or volcanic activity.

The results from detailed geomorphological surveys together with geotechnical data has proved very successful in stability analysis and future computer modelling of these results together with hydrological data would be a powerful tool for prediction (Brunsden, 2001). Even though it may not be possible to prevent them, the detailed recording of past processes offered by geomorphological mapping can be a useful tool for the estimation of effects during catastrophic events.

“Fortunately we have a formidable army of analytical and descriptive techniques by which to estimate the effects and likely occurrence of the events. In addition we can gain a good idea of the maximum effects, which are usually outside the experience of the measured record, because the diagnostic land-forms of the formative events remain in the landscape as a guide. If we can ‘read’ the landscape in event terms then we have a typology of what could happen in the future.” (Brunsden, 1996: p.286)

Detailed geomorphological maps also can be of practical use to many other branches of the society of today. In engineering projects the use of geomorphological mapping at the reconnaissance stage can give much information and save enormous resources. On administrative level geomorphological information is useful as a tool for planning purposes and in engineering projects the information is a good complement to engineering geological maps. The information presented in the maps is also of interest in planning for agriculture, settlements, communications, tourism, recreation and management of resources (Evans, 1990; Brunsden, 2003).

The introduction of GIS and the large quantity of digital remote sensing data available today have open possibilities of exploring and processing spatial data and this both increase and broaden the possibilities for geomorphological research (Butler and Walsh, 1998). Since the GIS is an excellent tool for handling large quantities of spatial data it should offer solutions to many of the problems run into in the development of comprehensive geomorphological maps. The use of GIS has however so far focused on solving specific problems (e.g. natural hazard assessment and risk analysis) and thus the possibilities of forming comprehensive geomorphological databases have not yet been fully explored.

2 Methods and techniques

2.1 Geomorphological map and geodatabase

The aim of this study lies in the development of a method for landscape description and therefore much of the methodological description and discussion are imbedded in the results and thus this chapter will only present the basic methods and techniques used during the project.

The first step in the development of the new geomorphological mapping system was to select field areas where the mapping system could be tested and developed. An important aim for the new geomorphological mapping system was that it should be applicable to areas of different landscapes characteristics and therefore four different field areas that showed a large diversity in landforms, materials and processes were chosen in Sweden (see chapter 4). Availability and previously published background material in forms of surveys and maps was also a criteria that affected the choice of field areas. Since this project is made in cooperation with the Alpine Geomorphology Research Group (AGRG) at the University of Amsterdam it was also decided to test the new map in a field area in the European Alps, which would offer yet another type of landscape (see section 4.4). Since the 1960's the AGRG has cooperated with local Austrian authorities in Vorarlberg, the westernmost federal state of Austria, bordering Liechtenstein and Switzerland. The main aim of this cooperation has been natural hazard zonation, based on detailed geomorphological maps, usually at 1:10,000 scale.

The next step was to study previously developed systems. Earlier published geomorphological maps made in various areas and for various purposes were carefully studied and this resulted in a first test legend that was used during the fieldwork. During the fieldwork however, new experiences and problems occurred, which caused modifications to the legend.

In total the fieldwork comprises approximately 6 months of mapping in the various field areas during the summers of 2001-2005. The field maps used in the Bonäs, Risa and Liden field areas were various copied topographical maps at scales 1:10,000 and 1:50,000. For the Tarfala field area a thematic 1:10,000 map by Holmlund and Schytt (1987) was used. Before leaving for fieldwork, the maps were prepared and general geomorphological features were sketched based on interpretation of aerial photographs,

orthographic aerial images, available maps (topographic, bedrock, quaternary deposits), and previously performed surveys in the areas.

In field the base map was used together with a handheld GPS (Garmin 76) which proved useful for collecting waypoints in difficult terrain. Since the field maps used in the Bonäs, Risa and Liden field areas were printed in the 1970's some features, such as roads and houses, were not updated and during following map drawing these things were corrected by use of newer orthographic aerial images and collected GPS data. At some places contour lines were corrected as well. The age of the base maps were however helpful in explaining some anthropogenic features now forgotten and overgrown. Useful information was added during the fieldwork based on information provided from people living and working in the mapped areas.

The final map drawing was done using Adobe Photoshop® 7.0. An image of contour lines, waypoints (from the GPS) draped over a composite image of an orthographic aerial image and an image of a topographical map, exported from ESRI ArcGIS® 9, was used as a backdrop image.

For the development of the GIS geodatabase the final map images were saved as georectified .tif-images and imported into ESRI ArcGIS® 9 where the map sheets were digitalised on screen. Early attempts in the development of the geomorphological geodatabase were also performed using ArcView® 3.3 in combination with scanned and georectified map sheets.

2.2 Weathering studies

For the weathering studies a freeze room laboratory was used to simulate freeze-thaw cycles for rock samples collected during the fieldwork. The procedure for this is described in detail in Paper IV. The results from the freeze room laboratory were compared with both rock samples experiencing natural temperature changes and rock samples situated in room temperature. Both physical disintegration and chemical solution of the rocks were measured. These measurements were also compared with surface water samples collected in the field areas. Also N-type Schmidt Hammer tests and documentation of joint patterns were recorded in the Tarfala field area (Paper V).

3 Field areas

3.1 The Bonäs and Risa field areas

The Bonäs and Risa field areas (Paper I and Paper III) are both situated a few kilometers north of Mora (61°00'N, 14°30'E) in Dalarna, Sweden (Figure 4:1). The region is dominated by forest but farming occurs in the sandy areas surrounding the lakes Orsasjön and Siljan. Also several sand and rock quarries are located in the region. A reason for choosing these field areas was that the two areas are situated close to each other and yet offers two very different types of landscapes. The region has drawn scientific attention for a long time (e.g. Hedström, 1893; de Geer, 1908: 1914; Högbom, 1913; Halden, 1933; von Post, 1934; Nordell, 1984). In 1910 the excursion connected to the International congress on geology was held there (Nordenskjöld and de Geer, 1910). There are also two earlier published geomorphological maps made in the region (Soyez, 1971 and Ulfstedt and Yrgård, 1982-83).

During the fieldwork approximately 20 km² were mapped in the Bonäs area and 12 km² in the Risa area at 1:5,000 and 1:25,000. In addition to this c. 75 km² were mapped at 1:50,000, covering both the Bonäs and Risa areas.

3.1.1 The Bonäs field area

The small village of Bonäs is situated on the western shore of the lake Orsasjön, just north of Mora. The field area is situated between approximately 160 and 200 m asl, which is just below the local highest Holocene shoreline (situated at c. 220 m asl) formed in a long bay reaching the area from the Baltic sea basin along the river Dalälven valley (Nordell, 1984). During the deglaciation following the LGM, a c. 10 x 20 km large glaciofluvial delta was built up here and due to the isostatic uplift of land, the delta surface has during the Holocene been modified by aeolian and fluvial processes together with wave action (Figure 4:2a) (Lundqvist, 1951). Thus this field area offers fossil sand dunes, shorelines, lacustrine sediments, meanders, and human influences

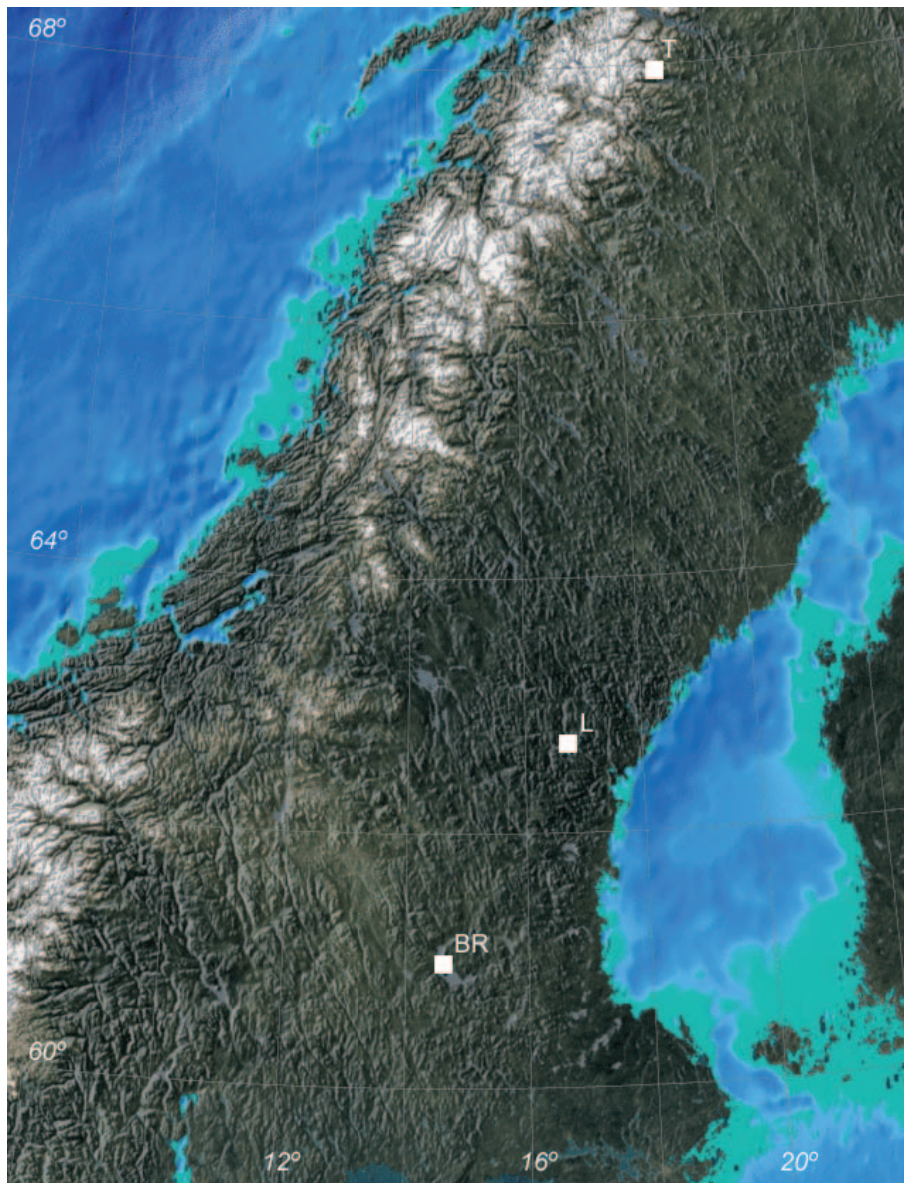


Figure 4:1 The map presents the locations of the Swedish field areas used in this study. BR: Bonäs and Risa field areas, L: Liden area, and T: Tarfala field area. Background image used by kind permission by UNAVCO (<http://jules.unavco.org>).

3.1.2 The Risa field area

The Risa field area stretches from the small village Näset situated c. 165 m asl at the eastern shore of Orsasjön in the west, to the crest of Risaberget



Figure 4:2 Views from the Bonäs, and Risa field areas: a) shows a fossil dune field on top of the glaciofluvial delta west of Bonäs; and b) shows a lateral glaciofluvial channel cut into a till covered slope between Risa and Näset.

situated at c. 350 m asl in the east (Figure 4:1). This side of the lake is covered by a thinner coat of Quaternary sediments than the Bonäs area across the lake which makes it possible to occasionally find bedrock exposures at the surface. The thinner regolith also enables the influence of the bedrock structure to be detected in the surface morphology. The bedrock in this area is a mix of sedimentary rocks in the lower parts with porphyrites and granites dominating the higher areas, towards the east (Kresten et al., 1991). The Quaternary landforms are dominated by lacustrine sediments and wave action in the lower parts, while fossil lateral glaciofluvial channels cut into till and bedrock dominate the parts above the highest Holocene shoreline (Figure 4:2b). In between, along the highest shoreline, several glaciofluvial terraces are present (Lundqvist, 1951; Nordell, 1984).

3.2 The Liden field area

Liden (62°43'N, 16°48'E) is a village located in the valley along the river Indalsälven in central Sweden (Figure 4:1). In this field area c. 24 km² have been mapped at 1:5,000 stretching in an east-west direction across the valley by the village of Liden (Paper II). The altitude varies from 23 m asl by the river, to 379 m asl in the highest area. The area has a long tradition in hunting, fishing and forest industry but smaller areas along the valley floor have been cultivated.

The field area surrounding Liden was chosen to represent areas typical for the larger river valleys in the northern part of Sweden (Figure 4:3a). These usually have areas dominated by glacial activity and forms controlled by bedrock structure while their valley floors beneath the highest Holocene shoreline are filled with a sequence of glaciofluvial, lacustrine, and fluvial sediments. Together this forms a landscape with a wide variety in forms, processes and lithology. The compositions of the tills vary from tills composed of only large boulders, to tills with few boulders or clayey tills. Along and below the highest Holocene shoreline (at places clearly marked by shoreline erosion and beach deposits), the tills at many places have a wave washed surface (Lundqvist, 1987). At places glacially sculptured roches moutonnées and flyggbergs are found. The amount of striations found in the Liden area is however very low due to the weathered surface of the coarse crystalline and metamorphic bedrock (Lundqvist et al., 1990).

The isostatic uplift during Holocene eventually caused the Indalsälven to subsequently cut itself into the thick complex sediment sequences in the valley bottom thus leaving several terraces from older and higher river plains. During this incision, mass movement has also taken place along the steep banks along the river, causing bank collapses and creating several ravine systems in the silty sediments. In 1955 a water power plant was established at Bergforsen further downstream. The water level of Indalsälven was then raised and the river now forms part of a water reservoir with a rather stable water level at 23 m asl (Blomqvist, 1970).

3.3 The Tarfala field area

The c. 20 km² mapped at 1:10,000 in the Tarfala valley (67°55'N, 18°35'E) (Figure 4:1) in the northern part of Lapland, Sweden, represents an alpine sub arctic valley (Figure 4:3b) (Paper V). The valley is situated at approximately 900–2100 m asl and presents a variety of forms created by glacial, periglacial, fluvial, glaciofluvial as well as mass movement processes. The vegetation is sparse and is dominated by lichens, mosses and some ferns. While some forms seem to be actively created other forms appear to be relict.



Figure 4:3 a) View of the village Liden from the south. At the bottom of the picture the river Indalsälven can be seen and above this slopes and terraces with meadows formed in silty/sandy materials. The village is situated in the break between this valley fill and the till covered slopes above. The highest Holocene shoreline is situated in the forest halfway up the valley side. b) The Tarfala field area viewed from northwest. The photograph is taken at c. 1400 m asl next to the Kebnepakteglaciären, above the lake Tarfalasjön. The terminal moraines from the Isfallsglaciären can be seen at the lake outlet and to the left debris cones situated beneath chutes carved into the rockwall can be seen. c) View from the Upper Gamperdona valley, Vorarlberg. Photo (c) by A.C. Seijmonsbergen.

The bedrock in the area is part of the Seve nappes of the Scandinavian Caledonides and dips 20-40° towards the northwest (Andréasson and Gee, 1989). The lower parts of the Tarfala field area are strongly influenced by glacial processes with several large moraine ridges, roche moutonnées, flutes, and of glaciofluvial activity. In sloping areas the coarse debris of the regolith has often been reworked by mass movement and lobes or terraces caused by soil creep are commonly found. Along the sides of the U-shaped valley various forms of debris accumulations are found, often beneath chutes incised in steep rock surfaces. Higher situated smoothed plateaus surround the valley and these are strongly influenced by weathering and periglacial phenomena. Indications of periglacial processes, such as patterned ground and stripes can be found in all parts of the field area and the permafrost depth has been estimated to c. 300 m at a permafrost monitoring station situated at 1540 m asl (Holmlund and Jansson, 2003). The well developed patterned ground in the higher parts of the mapped area may be part of a relict surfaces left unaltered under the Fennoscandian ice sheet during the Weichsel (Hättestrand and Stroeven, 2002). At present six small glaciers (ELA, Storglaciären c. 1450 m

asl) (Holmlund and Jansson, 2003) are present along the west and north valley sides but probably the whole valley was ice free in the early Holocene.

3.4 The Gamperdona field area

In addition to the four field areas selected in Sweden the mapping system has been tested on an area situated in Vorarlberg, Austria (Figure 4:4). The Upper Gamperdona valley (47°05'N, 9°39'E), is located in the Rätikon Mountains, western Vorarlberg (Figure 4:3c) (see also Sejmonsbergen, 1992). This area situated at 1000–2100 m asl is dominated by mass movement activities with influences on morphology and materials by past glacial activity and bedrock structure. This area was mapped by A.C. Sejmonsbergen.

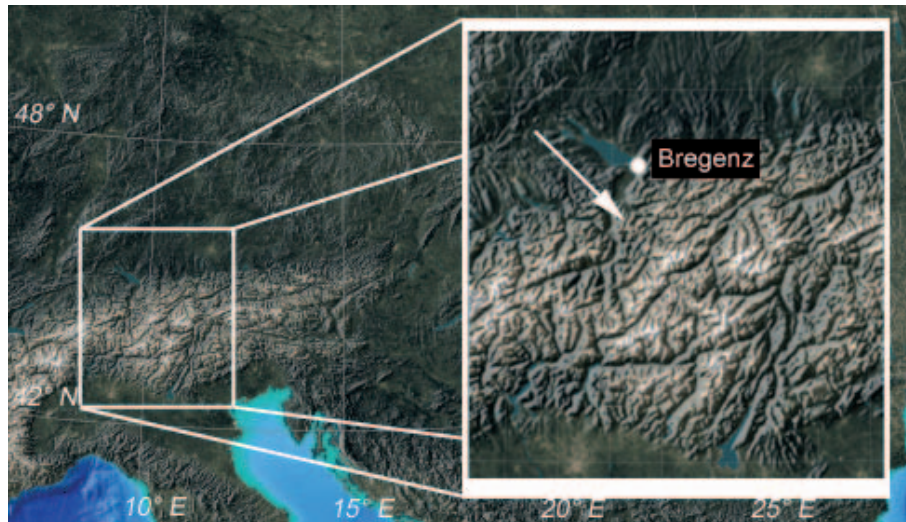


Figure 4:4 The location of the Gamperdona valley field area, Vorarlberg Austria. Background image used by kind permission by UNAVCO (<http://jules.unavco.org>).

4 Results and discussion

4.1 The new geomorphological mapping system

The ideal comprehensive geomorphological map should include information on morphometry, morphology, hydrography, lithology, structure, age, processes and genesis. A limiting factor for the readability and thus also the usability of a map is however the amount of data presented in one map sheet. One solution to construct an easy-to-read map is to limit the information presented or to print the information on several map sheets. For a geomorphological map this solution might produce thematic maps even useful to non-geomorphologists but the restricted information in such a map limits the area of usage. For this project it was thus chosen to construct a comprehensive mapping system to be used by geomorphologists.

The geomorphological mapping system developed (Paper I and Paper V) is not as detailed and precise in the information as other universal geomorphological legends (e.g. Verstappen and van Zuidam, 1968; Demek et al., 1972). Instead the strength lies in the simple structure where the information is based on the combination of individual descriptive data which results in an easy-to-use legend that yet makes it possible to describe complex landscapes. This structure also separates the descriptive and interpretative information which gives the map reader the possibility to interpret the landscape beyond the interpretation given by the map author (cf. St-Onge., 1981).

The legend is also a result of the graphical layout of the mapping system. A limiting factor in the usability of comprehensive geomorphological maps has been low readability due to the saturated combination of several layers of symbols (especially shaders) in various colours (e.g. Barsch and Liedtke, 1980). To enhance the readability of the new mapping system it was chosen to avoid filling shaders and this gives the map an open structure where point and line symbols can be clearly presented. The emphasis in the mapping system is on genesis and thus this is presented in colour. Even though the genesis is given the highest priority, it does not prevent the other information to be clearly presented (Paper I). The first impression of the maps might be that they are too complex, but once the reader gets familiar with the system a lot of information can be read out. The maps however have a relatively high readability in comparison with other geomorphological mapping systems

presenting the same information (see e.g. Barsch and Liedtke, 1980). During the project two minor modifications were done to the original legend (Paper I): To enhance the readability the colour for periglacial processes was changed and an additional symbol was added to describe the hydrography (Paper V).

The new legend (Paper I and Paper V) should not be seen as a final product but rather as the basic tools needed to present the geomorphology. The few symbols and open structure thus leave the legend open for additions and improvement according to the needs of the user.

4.2 Geomorphological information at different scales

Even though geomorphological maps have been produced at various scales it was decided to develop the new system to be used at a detailed scale (for scales larger than 1:50,000, cf. Demek et al., 1972). The reasons for this were that large scales are needed to be able to present geomorphological complex areas (such as an alpine landscape), and that large scales are also needed for successful practical applications.

The test usability of the new mapping system at different scales (1:5,000, 1:25,000 and 1:50,000) (Paper III) proved successful and no modifications were needed to the legend even though the change of scale might sometimes cause the change of symbol in the legend. The change in scale naturally caused a change in the details of the information technically possible to present. The results from Paper III however also point at that there might be a large difference in the geomorphological information presented for an area depending on the scale at which the information is collected. It was shown that the importance of interpretation increases (at the cost of description) with decreasing scale. Information on small-scale human impact, hydrography and surficial processes seem to suffer most, which is notable as details in this information are important for e.g. slope stability.

Awareness of this is not only important in the study and interpretation of traditional geomorphological maps but is maybe more important in the handling of digital data (Paper II and Paper III), and the conclusions in Paper III point at three cases where the scale can be of major importance: 1) In the choice of a proper scale for a specific purpose, 2) In the reliability of end results that are based on different sources, and 3) During the generalisation and extrapolation of data. In the huge amount of free or cheap GIS data available today these points are worth considering.

4.3 The geomorphological GIS geodatabase

The geomorphological geodatabase developed in parallel with the mapping system (Paper II) is an attempt to connect the “traditional” geomorphological mapping with the modern GIS environment. The clear separation of descriptive and interpretative data in the new mapping system (Paper I and Paper V) enables an easy transformation from the geomorphological map to an object based geomorphological geodatabase. Even though some information in the original map proved hard to translate into useful digital information (other than inventory), the geodatabase forms a comprehensive collection of detailed geomorphological data separated in several datasets and stored as attribute data. Throughout the transformation an important task has been to keep the data as basic as possible, which increases the usability of the data.

An advantage of the geodatabase is the possibility to easy processing or combination of the data with other spatial or non-spatial data. It also enables easy export of various types of thematic maps, presenting processed data or only a limited part of the database.

It is likely that the procedure for transformation of the map sheet into the geodatabase presented in Paper II also might work for other “traditional” mapping systems and thus the information in these systems could be “saved” and processed within a modern GIS environment. This would probably be of benefit for areas with a large coverage of geomorphological maps. A condition for easy conversion of a “traditional” mapping system is though that it is based on a clear separation of descriptive and interpretative data.

4.4 Weathering of different rock types

The simple weathering studies performed in parallel with the development of the mapping system (Paper IV and Paper V) did not yet produce any clear results but points at some trends and difficulties in the estimation of the effect of weathering in cold environments.

In the Tarfala valley the mylonitic gneiss appears to be the rock type most susceptible to both chemical and physical weathering while the dolerite is the least (Paper V). The amphibolite however seems to have a variable susceptibility (Paper V) and consists of both resistant and weak rocks.

In Paper IV it is shown that physical and chemical weathering occur together and probably enhance each other which can explain intensive chemical weathering even in cold environments. The mutual importance of the two seems to be related more to rock type than to climatic conditions. Together with Paper V, the results of Paper IV also indicate that there occasionally is a large difference in resistance to weathering among rocks bearing the same name. Due to small-scale differences in rock mineralogy, this difference can also be found in the same rock formation or even in the same rock outcrop

(Paper V). In the Tarfala valley these changes make comparison between laboratory rock studies and field measurements at sub-catchment scale difficult. Another complicated circumstance is that probably a major part of the weathering takes place in the regolith which is composed of several rock types in various percentages. Thus it would in future studies be better to also compare field measurements with laboratory studies of regolith samples.

5 Conclusions

The main aim of this study was to develop a method for detailed comprehensive geomorphological mapping adapted for the GIS environment of today and this was achieved using a combination of both “traditional” and new techniques.

- A detailed geomorphological mapping system was constructed. The legend presents information on morphometry, morphology, hydrography, lithology, structure, age, processes and genesis as separated layers of information.
- The legend of the new mapping system is an easy-to-use legend that results in maps with a relatively high readability. The legend is also left open for additions and improvement according to the needs of the user.
- The constructed mapping system was successfully applied to five field areas, all with different landscape characteristics.
- The new geomorphological legend was also successfully applied to a Swedish glaciated area at the scales 1:5,000, 1:25,000 and 1:50,000 without any modifications needed.
- A geomorphological GIS geodatabase was constructed using the ESRI ArcGIS® Personal geodatabase format. The geodatabase stores the information from the geomorphological map as separated datasets which easily can be processed or combined with other spatially related data.
- For geomorphological data, the details in information and the interpretation of the landscape as a whole are dependant on the scale used for data collection.

The weathering study of this paper did not produce any clear results but some conclusions could be drawn nevertheless.

- Due to minor differences in mineralogy and structure rocks might show very different resistance to weathering, even though bearing the same name.

6 Acknowledgements

Apart from all rocks, plants and animals (biting flies excluded) I have confronted in my field areas during this project there are also some people that I would like to thank for giving me support along the long road to this thesis.

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7 Summary in Swedish

Utveckling av ett detaljerat geomorfologiskt karteringssystem med tillhörande GIS-databas i Sverige

Denna avhandling presenterar utvecklandet av ett geomorfologiskt karteringssystem med tillhörande databas. Geomorfologi är vetenskapen om landskapets ytformer och de processer som skapar eller bryter ner dem. Landskapet är under ständig förändring vilket kan resultera i både resurser och faror för samhället. Genom att studera landskapet kan man skaffa sig en uppfattning om hur det har bildats och hur det har påverkats av olika processer under tidernas gång. Först när man har denna kunskap kan man försöka bilda sig en uppfattning om hur landskapet kommer att reagera på framtida förändringar av t ex klimat eller markanvändning.

Geomorfologiska kartor är kartor specialiserade på att presentera information om landskapets former, dess material och de processer som påverkar dem. Kartorna presenterar också landformernas ursprung, utveckling och ibland även deras ålder. Användningsområdena för geomorfologiska kartor har visat sig vara många och sträcker sig från vetenskapliga studier och riskbedömningar till att utgöra underlag för resursplanering och projektering för t ex skogsbruk och vägkonstruktion.

Projektet har resulterat i ett nytt geomorfologiskt karteringssystem som inte bara kan beskriva olika typer av landskap utan även kan användas för kartor i olika skalor (1:5,000–1:50,000) utan modifikationer av legenden. Systemet baseras på en användarvänlig legend (teckenförklaring) där landskapet presenteras som en kombination av olika beskrivande data. Tillsammans ger dessa pusselbitar en helhetssyn av landformerna, deras material och de processer som har skapat eller påverkar dem. Även om tolkningen av landformernas ursprung (genes) är en viktig del i kartans presentation, presenteras den övriga informationen så att kartans läsare kan se vad kartritans tolkning är baserad på och eventuellt också kan göra en egen tolkning.

De nya geomorfologiska kartorna presenterar information om form och storlek av landskapselementen, materialens kornstorlekssammansättning, ursprung av form och material, modifierande processer och ytlig dränering (hydrografi). Dessutom presenteras den ytliga berggrundens bergarter, ålder och relation till landskapets former, något som sällan framkommer i andra karteringssystem. En nyhet i det nya karteringssystemet är dess presentation av vittring. I tidigare karteringssystem har endast vittring relaterat till Karst-

fenomen (dvs kemisk vittring av kalkhaltiga bergarter) presenterats, men det nya systemet presenterar former och material relaterade till vittring i alla material. Karteringssystemet visar sig också vara användbart för att presentera både relikta och aktiva processer samt gör det möjligt att beskriva det sammansatta ursprunget hos former och material skapade av flera samverkande processer.

Under arbetets gång har fyra fältområden med olika landskapstyper karterats i Sverige. Bonäs och Risa är belägna på västra respektive östra sidan av Orsasjön i Dalarna medan Liden är beläget i Indalsälvens dalgång i Medelpad. Det fjärde svenska området är Tarfaladalen som ligger i Kebnekaisemassivet i norra Lappland. För att testa legendens förmåga att beskriva olika landskapstyper har legenden även applicerats på ett område i Vorarlberg, Österrike.

Även om inga modifikationer av legenden var nödvändiga vid kartering i olika skalor visade resultaten från denna kartering att inte bara detaljer utan även kartans helhetsintyck och innehåll ändrades avsevärt av skalförändringen. Detta visar att innehållet i geomorfologisk information är beroende av den skala vid vilken den är insamlad, oavsett om det gäller kartblad eller GIS-baserade data. Resultatet belyser också problemet med att extrapolera resultat mellan olika skalor.

Parallellt med det nya karteringssystemet har det även utvecklats en geomorfologisk GIS-databas. Databasen sammankopplar den breda helhetssyn på landskapet som finns i traditionella geomorfologiska kartor med moderna verktyg för analys och presentation av data. Formatet för databasen är ESRI's ArcGIS® Personal geodatabase. Det nya karteringssystemets konstruktion gör att informationen i kartbladen enkelt kan överföras till den geomorfologiska GIS-databasen där den lagras som separata dataset som sedan kan användas i beräkningar eller kombineras med andra GIS-baserade data.

Under utvecklingen av karteringssystemet föddes också ett sidoprojekt. Under fältarbetet i Tarfala observerades många tecken på intensiv vittring och därför beslöts att göra en vittringsstudie där både kemisk och fysisk vittring undersöktes parallellt i syfte att testa om vittringsbenägenheten hade inverkan på landformerna. Olika bergartsprover samlades in och placerades i lådor med vatten. Dessa utsattes sedan för frostcykler i ett frysrum och efter experimentets avslutande jämfördes provernas mängder av frostsprängt material och deras vattenkemi. Vidare jämförelser gjordes också med bergartsprover som fått uppleva naturliga temperaturförändringar och vattenprover från fältområden. Resultaten från vittringsstudien pekar på att det kan finnas stora skillnader i vittringsbenägenhet hos stenprover av samma bergart, men visar samtidigt att det finns ett visst samband mellan bergartarnas vittringsbenägenhet och landformerna.

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