Hierarchical geomorphological mapping in mountainous areas

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ABSTRACT
We present a method of digital geomorphological mapping of mountainous areas with a legend consisting of a three-tiered nested hierarchy using two case study areas from Vorarlberg, Austria. Users can easily visualize maps in a geographical information system (GIS) at the finest level with a legend of 33 morphogenetic domains. Reclassification of the morphogenetic classes in an automated GIS-workflow generates the medium and high levels of hierarchy, and each tier is accompanied by suggested scale ranges for visualization. A variety of high-resolution input data (LiDAR-derived data, geomorphological and geological raster maps) supports the mapping method, which also strongly benefits from field knowledge. The method facilitates analysis, interpretation, visualization and application of geomorphological data at a large range of scales and corresponding information densities within one database. The structure of the legend allows for inclusion of additional morphogenetic classes and for application and adaptation in other environments.

1. Introduction

Geomorphology can be broadly defined as the study of landforms and of the geological forces that produce them (Bauer, 2004; Fairbridge, 1968). Geomorphology combines form, material and genesis; form refers to the outer shape of landscapes and landscape elements; material to the substratum, i.e. rocks and unconsolidated deposits that underlie the surface of the landforms; and genesis to the past and present processes that have created the landforms (Seijmonsbergen et al., 2014). Maps and mapping are part and parcel of geomorphology in our view, in spite of the fact that many geomorphological studies lack a mapping component.

Geomorphological mapping has a long history and is subject to continual development, from classical maps to computer-generated digital maps (Griffiths et al., 2011). According to Seijmonsbergen (2013), classical geomorphological maps are representations in a single paper map of the spatial distribution of landforms, materials and the processes responsible for their formation. They contain a wealth of information that is usually documented with the aid of symbol and color legends. Uniformity amongst geomorphological legends does not exist, mainly because the traditional mapping ‘schools’ independently developed systems for use at different scales in a variety of landscapes. Technological advances have changed the preparation, data collection, analysis, storage and visualization of geomorphological maps. The computer-generated digital geomorphological map is the next step in the development. Seijmonsbergen (2013) describes it as a digital collection of georeferenced data which provides scale-independent information on the Earth’s surface geomorphometry/morphography, surface material distribution and processes, and is, in its most advanced form, accompanied by an accuracy assessment. Raw data and information are stored in a (geo-)database, which contains georeferenced raster, vector and tabular data. These data can be queried, analyzed and visualized in, commonly, a geographical information system (GIS). The terms ‘map’ and ‘mapping’ have become somewhat inappropriate for these databases and visualizations. For the sake of convenience, we still use them, although ‘digital geomorphological information layer’ and ‘building database’ would arguably be better terms.

A geomorphological map is more than just a way of presenting data (De Graaff et al., 1987; Gustavsson et al., 2006), it is also a synthesis of research: mapping reveals the geomorphological setting, i.e. the association of landforms, which is essential for the understanding of both individual landforms and landscapes (Campos et al., 2018; Chandler et al., 2018). An important aspect of the geomorphological map is that it can serve as a principal basis for further work. Derivative or thematic maps can be generated...

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highlighting certain geomorphological features or showing applied aspects of geomorphology, e.g. potential geoconservation maps (Seijmonsbergen et al., 2014) or hazard maps (Rupke & De Jong, 1983; Westen et al., 2000). Such applications greatly benefit from the development of detailed digital maps (Seijmonsbergen et al., 2014).

We present and discuss a method for multi-level geomorphological mapping with a three-tiered hierarchical legend in a digital environment. It was developed in the mountains of Vorarlberg, Austria, which straddle the boundary between the Eastern and Western Alps and are known for their diverse geology and geomorphology (Friebe, 2007). The need for information at varying levels of detail, i.e. scale or information density, as a function of mapping objective or application drove the development of the method, which we illustrate with two case studies (Figure 1). Moreover, comparison of geomorphology with other types of data require alignment of scales.

2. Methods
2.1. From classical field mapping to digital geomorphological mapping in Vorarlberg

We present here an innovative mapping method which is the latest development in a geomorphological mapping project initiated in the 1950s in the mountains of the state of Vorarlberg (Austria) and adjacent areas (Simons, 1985). The original, classical geomorphological map is a field-based, area-covering inventory of landscape elements and deposits, with emphasis on genesis. The paper map includes a legend which is a ‘box-of-bricks’ of lines, symbols and colors (De Graaff et al., 1987). The availability of paper-based contour maps at scale 1:10,000 in combination with the objective of generating detailed maps required for glacial-geological and slope-instability studies determined the standard mapping scale of 1:10,000.

The standard presentation scale was also 10,000 (Van Noord, 1996; Rupke & De Jong, 1983;
Seijmonsbergen, 1992), which departs from the usual analog-era practice of presenting final maps at a coarser scale than the surveying scale with the purpose of mitigating errors, e.g. in the position of boundaries and uncertainties of interpretation. The need for detail was the overriding reason.

The transition from our classical map to a computer-based one was first presented by Seijmonsbergen et al. (2009) and, subsequently, updated by Seijmonsbergen et al. (2014). The computer-generated map is polygon-based, and the legend, a morphogenetic classification scheme, consists of thirty-three morphogenetic domains (Table 1). Refer to Seijmonsbergen et al. (2014) for a detailed description of the legend classes; the conversion from a line & symbol map to a digital, polygonal map is illustrated in the example of Figures 7–10 in this publication (see also Figure 6 in Seijmonsbergen, 2013). The thirty-three classes comprise common geomorphological features in a mountain area; new classes can be added, if necessary. The legend is conceptually multi-level and hierarchical; mapping and visualization focus on the level of morphogenetic domains, which, generally speaking, corresponds with levels 7–9 of the hierarchical taxonomy of Dramis et al. (2011). The first computer-generated maps were conversions of the classical maps into digital versions: paper maps were scanned, then experts with knowledge of the area converted the content into polygons (vectors) by delineating (on-screen digitizing) units according to the morphogenetic classification scheme. New computer-generated maps are now made in a GIS by on-screen digitizing without the intermediate step of rasterizing paper-based maps.

Just as in other areas, important technical drivers behind this development in Vorarlberg are the availability of high-resolution large-survey digital data of the Earth’s surface (e.g. 50 cm resolution laser altimetry data (LiDAR), 10 and 25 cm resolution aerial photos), the rasterizing of a large variety of analog data (e.g. geological maps), and the increased data-processing capacity of computers and software (Anders, 2013). The creation and visualization of digital geomorphological inventories at a wide range of scales, from very detailed (<<1:10,000) to overview (>>1:50,000), using one database (Hengl, 2006) have become achievable. The technical innovations have paved the path to multi-level geomorphological mapping, and parallel mapping at varying scales, from fine to coarse, has become possible through the concurrent development of modern mapping methods in a GIS exploiting digital datasets.

### 2.2. Method of hierarchical geomorphological mapping

We have expanded the morphogenetic classification scheme of our computer-based mapping method to three levels, or tiers, arranged in a nested hierarchy

| Tier 1: Environments | Tier 2: Process Groups | Tier 3: Morphogenetic Domains |
|----------------------|------------------------|-------------------------------|
| Name and GIS code    | Name and GIS code      | GIS code                      |
| Glacial 1000         | Glacial - Erosion       | glacially eroded bedrock      |
|                      |                       | glacially eroded Quaternary deposits |
|                      | Glacial - (Glacio)fluvial erosion 1200 | glacial fluvial erosion |
|                      |                       | subglacial lits               |
|                      |                       | ablation lits                 |
|                      |                       | (glacial)fluvial deposits     |
|                      | Glacial - Accumulation 1300 | lake deposits                  |
|                      |                       |                               |
| Fluvial 2000         | Fluviatile - Erosion    | incision, slope subject to strong fluvial erosion |
|                      |                       | (sub)recent streambed         |
|                      | Fluviatile - Accumulation 2200 | fluvial terrace (incl. small escarpment) |
|                      |                       | alluvial fan, debris fan (incl. terrace) |
|                      |                       | lake deposits                 |
|                      | Mass movement - Degradation 3100 | deep-seated mass movement     |
|                      |                       | shallow mass movement (degradation) |
|                      | Mass movement - Accumulation 3200 | talus deposits               |
|                      |                       | flow and/or slide deposits    |
|                      |                       | protalus rampart              |
| Periglacial 4000     | Periglacial - Disintegration 4100 | surface subject to disintegration |
|                      |                       | Periglacial - Accumulation 4200 | rock glacier                 |
| Organic 5000         | Organic 5000          |                               |
| Karst 6000           | Carbonate karst 6100   | surface strongly affected by carbonate (gypsum) karst |
|                      |                       | surface strongly affected by sulphate (gypsum) karst |
|                      | Sulphate karst 6200    | covered gypsum karst (glacial deposits) |
|                      |                       | covered gypsum karst (slope deposits) |
|                      |                       | collapse structure due to gypsum karst |
|                      |                       | breccia exposure             |
| Aeolian 7000         | Aeolian 7100           | aeolian deposits              |
|                      |                       | take and its fill            |
|                      |                       | wide river                   |
|                      |                       | reservoir and its fill       |
|                      |                       | glacier                      |
| Settlements and infrastructure 9000 | Settlements and infrastructure 9100 | graded or levelled land |
|                      |                       | pits and quarries            |

Table 1. Complete morphogenetic classification scheme used to construct Tier 1, 2 and 3 maps.
(Table 1 and Figure 2) similar to what has been used in soil science (Wielemaker et al., 2001; see also Dramis et al., 2011). In GIS, we used a LiDAR-derived digital elevation model (DEM, resolution 50 cm) and LiDAR-derived land-surface-parameter (LSP) rasters, geological maps and aerial imagery, and we also consulted scanned (rasterized) & georeferenced classical geomorphological symbol & color maps to on-screen digitize and interpret the polygonal units of the computer-assisted map of the Tier 3 morphogenetic domains (see Figure 6 in Seijmonsbergen, 2013). To the Tier 3 level, we added the tiers of geomorphic process groups (Tier 2, fifteen classes) and geomorphic agents or environments (Tier 1, nine classes) (Table 1). Our experience in the study area provides the basis for these groupings, taking into account genetic relationships of the Tier 3 units.

We created workflows (toolboxes) in ArcMap and ArcGIS Pro for adding Tier 2 and Tier 1. In a first step, a field for Tier 1 is added to the attribute table of the input Tier 3 shapefile, then Tier 1 codes and names are added to the newly created Tier 1 field for the individual polygons based on their Tier 3 geomorphological code (Table 1). In a second step, a Tier 2 field is added to the shapefile and Tier 2 codes and names are added to the Tier 2 field for the individual polygons based on their Tier 3 code. Tier 3 legend units are renamed to Tier 2 and Tier 1 units using field calculations and by applying if/else statements. For example, the Tier 3 units ‘fall deposits’ (code 3211), ‘flow and/or slide deposits’ (code 3212) and ‘protalus rampart’ (code 3213) are automatically renamed as ‘3200 – Mass movement – Accumulation’ in the Tier 2 field using if/else statements. Likewise, Tier 2 units ‘3100’ and ‘3200’ are renamed as ‘3000 – Mass movement’ in the Tier 1 field. As a final step, a Tier 3 field is added and populated with the Tier 3 geomorphological codes and descriptions, and the original Tier 3 field containing only the geomorphological codes is deleted from the file. After running the toolbox, the newly created Tier 3, Tier 2 and Tier 1 attributes are included as feature classes in the geodatabase. The corresponding maps and legends are visualized with predefined color palettes on user-defined scales. Map objectives, accuracy and legibility determine the scale range for each level, and users can easily tailor the scale ranges in a GIS. We recommend the following optimal scale ranges: 1:2,500–1:10,000 for Tier 3, 1:10,001–1:30,000 for Tier 2 and ≥1:30,001 for Tier 1.

3. Results: Au West and Dunza-Tschengla case study areas

We selected two case study areas to generate geomorphological maps that demonstrate the mapping method. The two case study areas together offer a representative sampling of the variety of geomorphological features in the state of Vorarlberg, based on our long-
term experience conducting research in the area. The Au West area is the primary example; refer to the supplement for the main map. The map covers a larger area than the version presented by Seijmonsbergen et al. (2018), the earlier one being extended to the south and east. The map of the Dunza-Tschengla area is a digital conversion from classical maps presented by Seijmonsbergen (1992) and Van Noord (1996).

We also created an online storymap (https://arcg.is/Xjvy4) of all three tiers for both areas, which scales automatically as the user zooms in and out between scales to show how the data are dynamically visualized in a GIS.

3.1. Geomorphology of Au West

The Au West case study area is located in the catchment of the Argenbach, a tributary of the river Bregenzerache. The geological substratum is formed by rocks of the Helvetic Säntis Nappe, consisting predominantly of limestones, marls and shaley marls of Juro-Cretaceous age (Friebe, 2007).

The northwestern part of the area is a structurally controlled, east–west running saddle, to the south of the Kanisfluh mountain (2044m) with its impressive southern dip slope and to the north of the Klippern (2066m) mountain range, with steep north-facing slopes (Figure 3(A)). The broad-scale morphology of this area is glacial-erosive (Tier 3 GIS code 1111, see Table 1 for corresponding names and descriptions). Subglacial and ablation tills (1311 and 1312, respectively; Figure 3(E)) cover the central-lower areas. Rock-fall and debris-flow processes (3211 and 3212, respectively) modify the original glacial shape of the niche (Figure 3(B)).
Cirque-like niches with south aspect are to the south-southwest of the Korbschrofen-Klippern mountain range, in the southwestern corner of the map area. Shallow mass movements (3112, 3212) mildly modify the original glacial morphology. Rare carbonate karst features (i.e. karren) are observed (6111).

Central and eastern parts of the study area are dominated by erosion and mass movement, completely altering the original glacial landscape, creating an irregular slope down to the Argenbach (Figure 3(A, C, D)). Scree is actively produced (3211) and debris flows (3212) take place on and at the foot of the steep Korbschrofen cliff. Downslope accumulations of blocky debris are evidence of massive rock-fall events. The irregular topography of niches and lobate features further downslope is indicative of sub-recent mass movement, in which degradation and temporary accumulation (3112 and 3212, respectively) have interacted – and are continuing to interact on a small scale – in a spasmodic way. Large slump-like features, now modified by surficial mass movement, are indicative of past deep-seated instability (3111).

Sub-recent fluvial terraces (2212) occur along the Argenbach in the southeastern corner of the map area. The flanks of the incisions (2111) of small tributaries to the Argenbach are mostly altered by shallow mass movement (3112). Small alluvial fans (2213) occur at the mouth of these tributaries (Figures 4–6).

3.2. Geomorphology of Dunza-Tschengla

The Dunza-Tschengla case study area is in the catchment of the river III, which joins the river Rhine near...
Figure 5. Tier 2 geomorphological process groups of the complete Au West study area. Refer to Figure 4 for geographical features not shown on this map, such as roads and rivers.

Figure 6. Tier 1 geomorphological environments map of the complete Au West study area. Refer to Figure 4 for geographical features not shown on this map, such as roads and rivers.
Feldkirch (Figure 1; https://arcg.is/Xjvy4). The south–north oriented mountain range of Schillerkopf (2006m) and Mondspitze (1967m) dominates the western part with east- and west-exposed cirques. The central and eastern parts consist of a plateau hanging above the broad valley of the Ill in the northeast, with an overall relatively gentle slope from 1600 to 1000 m.

The Dunza-Tschengla area is within the tectonic unit of the Northern Calcareous Alps, with a substratum of the Hauptdolomit formation, Raibler Schichten formation and Arlberg-Formation (Friebe, 2007; Oberhauser, 1998, 2007). The Hauptdolomit formation consists of dolomites and forms the backbone of the Schillerkopf-Mondspitze divide (Figure 7(A)). Steep cirque walls (Tier 3 classes 1111 and 3112; see Table 1) with large scree accumulations (3211) are characteristic landscape elements. Moraines and rock-glacier deposits (1312 and 4211, respectively) cover the bottom of the cirques. The Raibler Schichten formation is heterogenic with clastic and calcareous beds and, notably, gypsum layers. Sulfate karst (6211, 6212 and 6213) has a large impact on the landscape formation, both in the divide – where it underlies the Hauptdolomit formation – and on the plateau, where it is at or immediately below the surface in many places (Figure 7(B)). Surface dissolution leads to the formation of often deep and steep sinkholes and irregular topography. Subsurface dissolution contributes to mass movements (3111, 3112 and 3212) and to the formation of large collapse sinkholes due to the disintegration of the Hauptdolomit cap rock (6214) (Figure 7(A)). Large parts of the plateau show an intricate pattern of ice-marginal features consisting of moraines (1311 and 1312), dry valleys (1211) and waterlaid deposits (1313) (Figure 7(C)). The limestones of the Arlberg-Formation form the glacially eroded (1111) edge of the plateau in the northeastern part of the study area. The Arosa-Zone tectonic unit, largely consisting of shales and marls, underlies the Lech Nappe. It forms the substratum of the southern-central part of the study area (Oberhauser, 2007). Glacial erosion (1111) and mass movement (3112) have formed the present-day landscape (Figure 8).

Figure 7. Landscapes and landscape elements of the Dunza-Tschengla case study area. (A) View to the south towards the Schillerkopf summit, in the westernmost part of the area. Active subsurface gypsum dissolution in combination with collapse of the overlying bedrock and scree production creates a very irregular mountain slope. Morainic ridges and fossil rock glaciers (with a cover of trees and bushes) are situated in front of the talus (photo from Seijmonsbergen et al., 2014). (B) View to the southeast of the central part of the area. An overall gentle slope formed by glacial erosion shows surface rugosity due to the combined effect of shallow mass movement of tills & slope debris and sulfate karst in the shallow subsurface. The mountains in the background are outside the study area. (C) View to the northwest of an ice-marginal fluvial terrace – or: shallow valley with flat bottom – in the central-northeastern part of the area. Flow was away from the photographer parallel to the former ice margin, which was on the right side outside the photo. Note the large erratics, which have in part been moved locally by man. The peak in the upper left of the photo is Mondspitze.
4. Discussion and conclusions

The basic unit of our computer-based mapping method is polygonal, whereas lines and symbols are the basic elements of our mapping method of the analog era. An important advantage of the polygonal legend & map is that, in GIS, calculations can be made, e.g. the areal extent of geomorphic classes. In addition, intersections with other polygon datasets such as biotope data can be made and assessed (Seijmonsbergen et al., 2018). Moreover, aggregating (reclassifying) polygonal units – the essence of hierarchy – has become a relatively simple procedure.

Our three-tiered geomorphological mapping method follows a bottom-up approach (Dramis et al., 2011; Wielemaker et al., 2001) in which Tier 3 to Tier 2 to Tier 1 reclassification is done in an automated GIS-workflow. In a GIS, the end user can dynamically zoom in from coarse to fine map scales, with concurrent display of more detailed geomorphological

Figure 8. Three-dimensional stacking of tiered geomorphological maps in Dunza-Tschengla case study area, illustrating the reduction of information density from Tier 3 to Tier 2 to Tier 1. The GIS-based mapping method used a GIS database of classic geomorphological and geological maps, aerial photographs and LiDAR-derived data and allows users to easily select the optimal scale of information density depending on the user’s objective.
information, and vice versa. The automated generation of the Tier 2 and Tier 1 legends, via a scheme of nested hierarchy, is determined by expert-based interpretation of the genesis of landscape elements and deposits in the terrain.

The information density of the Tier 3 data is high which encourages visualization at fine scales, 1:10,000 scale being a recommended upper limit. Visualization of Tier 3 at a coarser scale will lead to overcrowding of information, reduce legibility and adversely affect application. We recommend visualization of information at the Tier 2 level at moderate scales, and at much coarser scales, e.g. >1:30,001, users should consider visualization at the Tier 1 level. Needless to say that these recommended scale ranges can be easily adjusted by the user in a GIS according to preferences or needs.

The Tier 3 maps are highly detailed and suitable for application on a local scale, e.g. in municipalities. The Tier 2 maps show the distribution of the process groups and offer sufficiently detailed information for application on a regional scale, e.g. provinces. The Tier 1 maps by their very nature offer only a first impression of the predominance of the processes and landforms of the glacial and mass-movement environments; the information has a ‘signal function’ on a supra-regional scale.

Aggregating through nested hierarchy, however, means that not all potentially relevant geomorphological information may be included in the mapping or the database. The theory of polygenetic landscapes (Fairbridge, 1968) says that successive periods of cold and warm or wet and dry climate, including the transitions, have left their imprint on the landscape. Landforms inherited from prior eras may exist beside landscape units formed by contemporary processes, or new landforms or landscape elements may be partly or completely superimposed on old landforms to produce palimpsest landscapes (Bauer, 2004). This very much applies to mountainous areas that were ice-covered in glacial periods and are largely free of ice in interglacial periods. Also on a shorter time-scale, i.e. within one climatic period, landscapes can be polygenetic. Geomorphological processes may not be active continuously but intermittently; they may alternate with other processes, and vary in intensity and size. The implication is that one may want to map (interpret) and/or display different characteristics of a geomorphological feature at different scales, thereby following aggregation or de-aggregation rules which are not hierarchically nested according to genesis as in our system. Scale-dependent mapping (interpretation) (e.g. Wielmaker et al., 2001) is an elegant, but potentially very-time-consuming way to address this issue. Alternatively, researchers can apply GIS techniques for aggregation using polygon properties (outline, area, neighboring polygons) as a technically simple solution, but possibly not satisfactory in terms of interpretation accuracy.

Our method allows for the inclusion of additional morphogenetic classes of the mountainous environment and for application in other geomorphic environments and other mountains than those of Vorarlberg (Seijmonsbergen et al., 2010). Application beyond geomorphology also becomes possible in a relatively straightforward manner: assessment of geoconservation potential of morphogenetic domains, input to biodiversity assessment, and comparison with biotope inventories (Gray, 2013; Seijmonsbergen et al., 2018).

Even more so than in the past days of analog mapping, the choice of the objective, content, mapping scale and presentation scale needs to be thought through when undertaking a mapping project in the digital environment with its almost unlimited possibilities – which may be a double-edged sword.

Software
We used ESRI ArcMap and ArcScene version 10.6.1 to collect and analyze all datasets. ESRI ArcGIS Pro version 2.6.3 and ESRI ArcGIS StoryMaps were used to prepare the final visualizations. A collection of ESRI ArcMap and ESRI ArcGIS Pro shapefiles, models, symbology files and map packages is available via https://doi.org/10.21942/uva.c.5290546.

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