ISSN 2047-0371

Geomorphological mapping

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ABSTRACT: Geomorphological mapping is regarded as a fundamental technique of the discipline producing valuable base data for geomorphological and environmental research and practice. Geomorphological maps can be considered graphical inventories of a landscape depicting landforms and surface as well as subsurface materials. Geomorphological mapping is a preliminary tool for land management and geomorphological risk management, also providing baseline data for other sectors of environmental research such as landscape ecology, forestry or soil science. The widespread distribution and extended graphical capabilities of GIS-software as well as the availability of high-resolution remote sensing data such as aerial and satellite imagery or digital elevation data has led to a rejuvenation of the method. This chapter outlines the history, creation and dissemination of geomorphological maps; it provides a brief overview of field and digital mapping techniques, as well as introductory information on cartographic principles applied to geomorphological mapping. Finally, there are a range of key references that can aid the reader by providing more in-depth information on selected topics.

KEYWORDS: map, GIS, cartography, DEM

Introduction

Geomorphological maps can be considered graphical inventories of a landscape depicting landforms and surface as well as subsurface materials. Sketches and maps of landscapes and landforms (e.g. Dykes, 2008) have been fundamental methods to analyse and visualise Earth surface features ever since early geomorphological research. The widespread distribution and extended graphical capabilities of geographic information systems (GIS) as well as the availability of high-resolution remote sensing data such as aerial and satellite imagery and digital elevation models (DEMs) has led to the recent rejuvenation of the method (Lee, 2001, Paron and Claessens, 2011, Smith et al., 2011). Geomorphological maps can act as a preliminary tool for land management and geomorphological and geological risk management, as well as providing baseline data for other applied sectors of environmental research such as landscape ecology, forestry or soil science (Cooke and Doornkamp, 1990, Dramis et al., 2011, Paron and Claessens, 2011).

Geomorphological maps can be categorised as *basic* or *analytical* and *derived* or *specialised*. Whilst basic maps represent the observed features of a landscape, derived maps are focused on a specific theme or application. One example of derived maps are geomorphological hazard maps that depict risk-causing phenomena and their magnitude and frequency (Dramis, et al., 2011). Basic geomorphological maps may either focus on selected landscape features, for example only depicting the morphology of active processes, or deliver a full view on the landscape composition and its evolution (Knight et al., 2011, Verstappen, 2011).

In contrast to other types of geoscientific maps, very little international standardisation exists for geomorphological mapping legends. In the second half of the 20th century different legend systems developed in various European countries (Barsch and Liedtke, 1980, Brunsden et al., 1975, Embleton and Verstappen, 1988, Evans, 1990, Klimaszewski, 1982, Pellegrini, 1993, Schoeneich et al., 1998, Tricart, 1965). The choice of mapping symbols (or legend system) is determined by the purpose of the map, the message to communicate and the targeted group of users. It is therefore important to analyse and plan these conditions before starting a mapping campaign. The application of complex symbols using GIS or graphic software may influence the selection of the legend system.

This chapter outlines the techniques for the creation and dissemination of geomorphological maps; it provides a brief overview of field and digital mapping techniques, as well as introductory information on cartographic principles applied to geomorphological mapping. Finally, there are a range of key references that can aid the reader by providing more in-depth information on selected topics.

Field Mapping

Despite the growing offer of high resolution digital information on the Earth's land surface the visual impression gained from direct observation in the field provides unprecedented detail and access. Field observation, and subsequent mapping, allows the most direct way to appreciate a landscape’s character and enables a basis for terrain assessment and geomorphological analysis. Though field mapping by its nature is subjective and affected by the skills (experience) of the mapper, it allows the mapper to become familiar with the landscape (Cooke and Doornkamp, 1990). This is a crucial aspect as it enables exploratory investigation through direct observation of surface morphologies and subsurface exposures; this allows the development of a "mental model" of the landscape which can be incorporated in to later interpretation and analysis.

The production of good and purposeful maps in the field requires a clear definition of the aims and objectives. The mapping procedure includes (i) pre-field preparatory steps, (ii) the actual field work and (iii) post mapping activities that result in the creation of a publishable final map (*Table **1***).

Table 1. Workflow for undertaking geomorphological field mapping (modified from: Knight et al. 2011)

Activity
Pre-Mapping:
- Identify region of interest
- Identify purpose or goal of mapping
- Obtain remote sensing data
- Obtain geological and soils mapping information
- Design and create a GIS database
- Compose a field mapping protocol
- Map major morphological forms using remote sensing data
- Create draft map at a suitable scale for field mapping
- Prepare legend systems and symbols
- Obtain permission for access to the mapping region
- Conduct risk assessment for the planned activities
- Obtain weather forecast
During the field campaign:
- Conduct field mapping following the protocol, including walking the area
- Use hand-held GPS to mark tracks or waypoints
- Write notes and take photos, positioned using GPS
- Adhere to health and safety issues and/or update the risk assessment
Post-Mapping:
- Download and integrate GPS data with the existing GIS database
- Compare field and remote sensing mapping in order to validate remotely sensed observations
- Write up notes and integrate notes with photos
- Produce final geomorphological map in the GIS software
- Draw final map using analogue or digital cartographic symbols either using the GIS software, or graphic design software
- Write and present explanatory notes accompanying the map
- Publish the map

Typical preparation includes the gathering of additional information on the area (location, accessibility, history, and previous work), the choice of mapping scale and symbols, as well as planning the mapping campaign (Knight, et al., 2011). The analysis of aerial imagery or DEMs helps to familiarise the observer with the field area and should always be performed before mapping. This results in a draft map that includes major landforms mapped from the remote sensing data. The draft map is taken into the field for verification, addition of detail and delineation of exact boundaries. The creation of a field mapping protocol that details the steps of the mapping campaign is important as it allows the organised collection of additional information on landforms and the creation of a database for the data mapped in the field (Knight, et al., 2011).

The mapping scale used for data recording is usually larger than the scale of the final map in order to collect as many details in the field as possible. Typical detailed field maps are created at a mapping scale of 1:3000 to 1:25,000, whilst detailed geomorphological maps have scales between 1:5000 and 1:50,000. Consequently, map production requires generalisation of the field data. It is worth noting that medium and small scale geomorphological maps exist, ranging from 1:100,000 to > 1:1,000,000 (Dramis, et al., 2011).

Key equipment

Paper based (analogue) field mapping is usually performed using tracing paper, a topographic map of the area of interest, a clipboard and a pencil. The topographic map is used for orientation and location and should be enlarged to the mapping scale. Aerial photos and/or relief shaded (see below) images at the same scale are also useful. Other tools include a global positioning system (GPS) receiver for the collection of waypoints or the exact positioning of boundaries and objects. Additionally, binoculars are useful particularly in mountain areas to investigate inaccessible terrain. In order to have all the required symbols at hand, the legend system of the symbols should be printed out and taken into the field.

When using digital devices such as mobile field computers, mapping is generally performed using field mapping software. This allows for the digitisation of vector data directly onto the screen. The base data for mapping (topographic map, aerial photo, DEM) are stored on the field device. For exact positioning the field computer should be connected to a GPS. The application of a digital mapping device requires the preparation of the GIS data base structure prior to the field campaign (Figure 1).

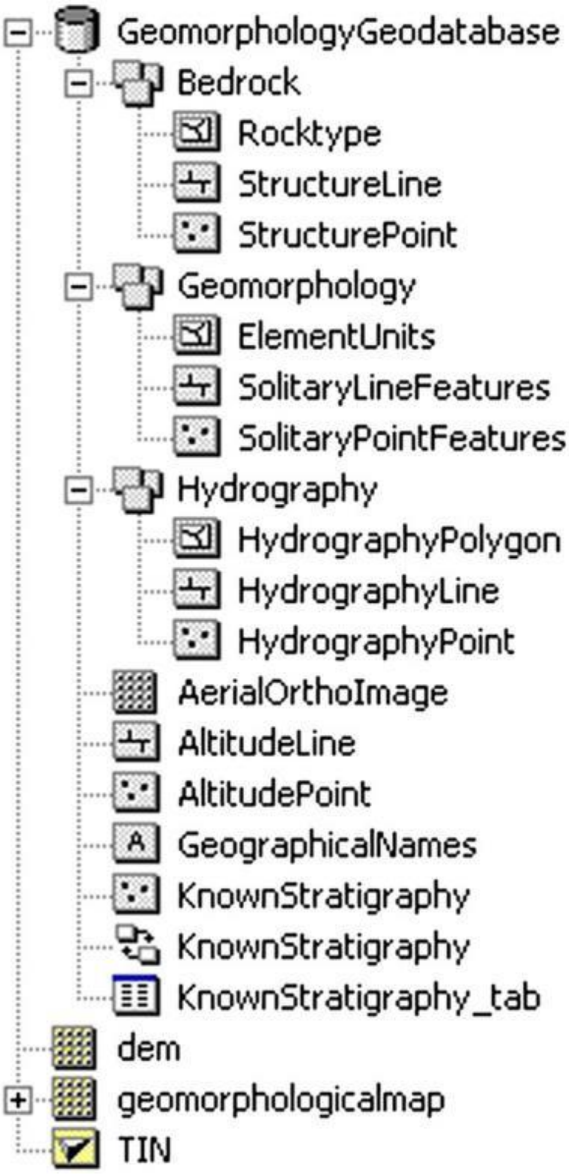

Figure 1. A typical GIS data base structure for a geomorphological mapping project (after Gustavsson et al., 2008).

Mapping procedure

A typical field mapping campaign starts with a 'walk through' to generate an overview of the area. This enables an estimate of the time for mapping and planning of the route through the study area in accordance with the field protocol. The mapping itself starts with the marking of breaks of slopes or a verification of the draft map contents. One method for avoiding overload of the field map sheets is to use separate sheets of tracing paper for each layer of information; for example morphology, process, and surface material. Mapping of processes usually requires interpretation from surface form and material composition since few active processes will be observed 'live' in the field. Mapping of surface and subsurface material is usually performed by visual interpretation or rapid field sampling. The goal of material mapping lies in the identification of material patterns rather than detailed sediment analysis (Dackombe and Gardiner, 1983).

Mapping speed depends upon the experience of the observer and the ground conditions. Even though mapping in mountainous regions may be more time consuming due to the rough terrain, mountains/hills often provide a better view of the landscape compared to flat terrain that needs to be walked through completely in order to see all features. An experienced mapper is able to map up to 2-3 km²/day, depending on local conditions and the complexity of terrain.

Digital Mapping

Where field mapping is not practical, it is common practice to utilise digital data sources (Smith and Clark, 2005, Smith and Pain, 2009, Oguchi et al., 2011, Smith, 2011) to compile mapping within the framework of a GIS. Primary data sources include aerial photography, satellite imagery and DEMs - care should be taken in the selection of data so that it is at an appropriate scale and provides sufficient coverage of the study area. The user then has two options for performing mapping: (1) manual and (2) automated or semi-automated.

Manual Mapping

Manual approaches rely on the experience and skill of an individual mapper using visual heuristics to identify landforms of interest (Colwell, 1983); accuracy is generally high, the method is simple and rapid to deploy, however this is at the expense of an objective and repeatable approach. The *representation* of a landform on an image is dependent upon: (i) the landform itself, (ii) the data source and (iii) the method used to process it (visualisation method).

For satellite imagery a range of standard image enhancement techniques can be applied; these include false colour composites, band ratios, convolution filtering and contrast stretches. However there are three main controls on landform representation (Smith and Wise, 2007): (i) relative size: the size of the landform relative to the spatial resolution, (ii) azimuth biasing: the orientation of the landform with respect to solar azimuth and (iii) landform signal strength: the tonal/textural differentiation of the landform. For any specific image used for mapping there is a minimum resolvable landform size and a range of landform orientations (which is more pronounced the greater the linearity) at which they can be represented. The definition of these landforms is then determined by their relative reflectance in comparison to surrounding features. Smith and Wise (2007) recommend acquisition of imagery with solar elevation angles <20º in order to enhance the topographic "signal" through shadowing.

For DEMs only the issue of relative size holds true and as a result they should offer more refined visualisations for mapping (Hillier and Smith, 2008, Smith and Clark, 2005, Smith et al., 2013). DEM processing is a subject area of itself known as geomorphometry (Hengl and Reuter, 2008), with land surface parameters (LSPs) the processed "derivatives" of the raw elevation data; these are used to present visualisations for manual mapping.

The most common method is *relief shading* which mimics a satellite image by placing an artificial sun in the sky and calculating the shadowing (Figure 2a). It is intuitive to view and highlights subtle topographic features, however it reintroduces the above controls on representation, particularly azimuth biasing. It is therefore desirable to utilise methods that are free from azimuth biasing, however these may not improve identification rates of landforms (Smith and Clark, 2005); in addition, if interpreters are not familiar with the output from these techniques, then they may find landform identification more difficult.

Gradient is perhaps the most common method (Figure 2b) and measures the steepness of slope (rate of change of elevation); as landforms often have steep sides they can be readily identified. The rate of change of gradient is *curvature* and is comprised of three components (Schmidt et al., 2003): profile, planform and tangential.

Profile curvature is particularly pertinent as it measures downslope curvature, helping identify breaks-of-slope. Two other common methods include *local contrast stretch (LCS)* and *residual relief separation (RRS)*. LCS (Smith and Clark, 2005) uses the concept of relative elevation and that a landform is spatially distinct from neighbouring features - a standard linear contrast stretch is applied to a region of a specified size, thereby providing a localised increase in contrast. RRS (Hillier and Smith, 2008) takes a different approach and begins with the conceptual understanding that landscapes are comprised of different elevation elements that are "stacked" on top of one another - these often occur at different width-scales and if the regional-scale relief is removed, then the small-scale "remainder" (or residual) can be extracted. These residuals ideally only contain features of interest, however as this is a scale-based technique it will contain *all features* at that scale and this can include anthropogenic features.

Semi-Automated Mapping

Given the benefits of objective and repeatable methods, automated and semi-automated techniques are highly desirable. They utilise algorithms to quantitatively process input data in order to identify landforms, however the complexity of the process often results in low or moderate levels of accuracy when compared to manual methods - as a result this remains an active topic of research that is evolving rapidly (Seijmonsbergen et al., 2011). The area borrows heavily from the classification of

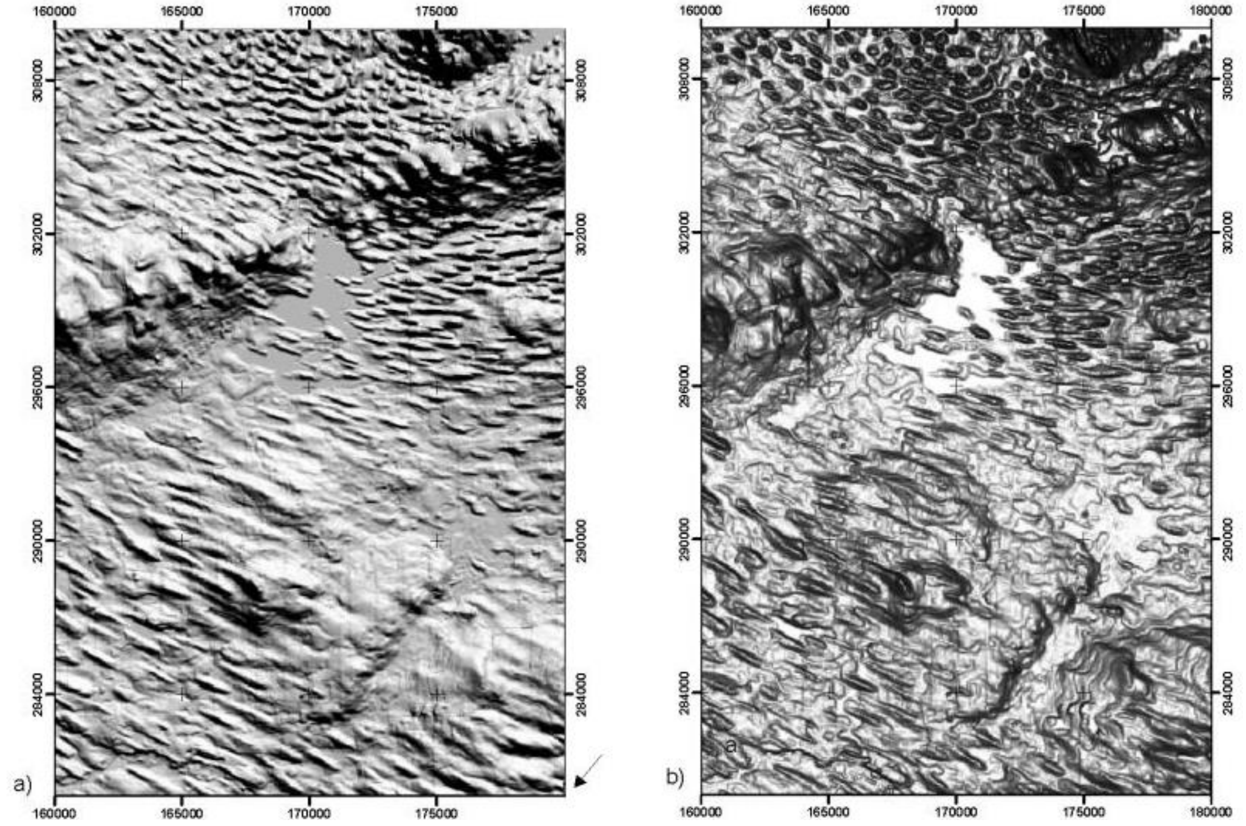

Figure 2 Illustrating the effect of relief shading (a) and gradient (b; darker tones are steep slopes) on the detectability of drumlins from high resolution DEMs of the same area

satellite imagery (Mather, 2004) where feature extraction techniques are used to identify surface features using reflectance at different wavelengths. For mapping, different wavelength inputs are replaced with different LSPs and then processed using either *supervised* or *unsupervised* techniques (Lillesand et al., 2008). Supervised techniques require interaction with a mapper and include methods such as rule-based object classification, cluster analysis (e.g. maximum likelihood) and regression analyses. Unsupervised techniques involve unsupervised object based classification, clustering (e.g. k-means), and machine learning. Perhaps the most promising approach is rule-based object classification (Blaschke, 2010), more commonly termed object-based image analysis (OBIA). Unlike more "traditional" remote sensing based classification techniques that operate on a pixel-by-pixel approach, OBIA operates on the fundamental principle that landforms are conglomerations of pixels. The two-stage process begins by using input LSPs to segment the image in to clusters of pixels using a multi-scale algorithm; once complete a set of classification rules is then applied to the objects The segmentation is controlled by parameters restricting the size and shape of clusters, with the size particularly important for landforms - recent developments have seen automated techniques for optimising the scale parameter for landform extraction (Anders et al., 2011, Dragut et al., 2010).

It is worth noting that testing mapping techniques is a difficult task as it requires a pre-existent knowledge of landforms to determine if an identification of individual features is successful. A higher spatial resolution dataset or manual mapping under "controlled" conditions are often used. Hillier and Smith (2012) take a different approach and place synthetic landforms in a real landscape allowing *a priori* knowledge of the landforms present. This can allow unequivocal testing of the landform mapping method.

Digital Output

Geomorphological maps are a specific kind of thematic map that use complex and illustrative symbolisation. The challenge of mapping is to portray a three-dimensional landscape with all its elements on a two-dimensional sheet of paper. To deliver this complex information, geomorphological maps make full use of a variety of elements of cartographic design. Different kinds of symbols and colours need to be arranged and composed carefully in order to generate a readable map that clearly expresses the content and message of the project.

Before starting the process of map design it is necessary to review the following questions (Otto et al., 2011):

- What is the purpose, message, and central theme of the map?
- Who has commissioned the map?
- Who will be using the map?
- How will the reader use the map (office, field)?

Applications of geomorphological maps range from simple descriptions of a field site, for example accompanying a journal publication or construction site report, to specialised land system analyses, for example for land management or natural hazard assessment. It is equally important to consider the production process and dissemination of the final product. Is it a paper map? Is the map produced in colour or black and white? Is the map accompanying a journal publication? Will it be published online? These issues strongly influence how to compile and arrange the data, which symbols are used, how the various map items are composed and whether colour can be used or not (Otto, et al., 2011).

Communication with maps differs significantly from other types of human communication. Maps are visual media and evoke visual stimuli that cause different reactions in people than books or conversations. Graphic communication, like maps, delivers all information at once. That means information is not perceived sequentially, but instantaneously with respect to the location and relative position on the map sheet or screen. Thus, the appearance and composition of graphical elements need to be considered thoughtfully. On a map, all information is spatially related and should be considered holistically. The composition of map items determines if and how the reader understands the message, with perception and understanding occurring subconsciously. To allow map-users to understand the meaning of the map, a visual link to the symbols and their attributes that correspond to the intention of the cartographer needs to be assigned (Robinson et al., 1995).

The basis for most geomorphological maps is a topographic base map presenting contour lines and the general layout of the hydrography and infrastructure. The basic representations of objects on maps are the symbol primitives: point, line, and area (also referred to as marker, line and polygon symbols) (Robinson et al., 1995). Whether a linear feature in nature is represented by a line symbol on the map is primarily a question of scale. For example, a river could be depicted by a blue line. On larger maps (with increasing size of the map items) the river would be depicted using an area symbol of the river shoreline. The map scale also determines if a landform is depicted by a point symbol, or if it is split into its morphological components. Rock glaciers for example could be represented by a single point symbol on small scale maps, or by the assemblage of line and area symbols that differentiate the step height of the rock glacier front, furrows and ridges and the accumulation of boulders and blocks on top of the rock glacier, if the map scale increases (Otto et al., 2011).

Line and pattern symbols (or shading) are commonly used for illustrating gradient and morphology. Some guidelines for the creation of geomorphological maps have been established by the International Geographical Union (IGU) Subcommission of Geomorphological Survey and Mapping (Gilewska, 1968).

Geomorphological legend systems

A large number of symbols and legends have been developed since the onset of geomorphological mapping in the early 20th century (Passarge, 1914). The impressive diversity of concepts and cartographic conventions created in different scientific communities throughout Europe and the US is related to the terrain configuration of the surveyed region and the scientific focus and aim of the map. The more complex the terrain, for example mountain areas, the greater the diversity of symbols and colours required (Verstappen, 2011).

In general geomorphological maps and their legend systems can be differentiated into maps showing a single aspect of geomorphology, most commonly morphology, and analytical maps that encompass the full information of a landscape including processes, morphogenesis and even lithology (Knight et al., 2011, Verstappen, 2011). An overview of different legend systems is provided by Otto et al. (2011), in part highlighting how different countries have developed their own systems, either formally or informally, to suit their own cultural needs.

In Britain most geomorphological maps focus on the representation of form producing morphological maps (Cooke and Doornkamp, 1990, Evans, 1990) with significant breaks in slope the most dominant information. The purely morphometric information can be extended by morphogenetic and material information to complete the geomorphological representation of landscapes.

Most maps are generated using GIS or graphic design software, but only a few symbols sets exist that have been developed for digital application. Many legend symbols are so complex that automated drawing by GIS/graphic design software is not possible. Among the few exemptions are the "Mapping Symbols for High Mountains" (Otto, 2008, Otto and Dikau, 2004) and the legend for geomorphological mapping developed by the Institute de Géographie de l'Université de Lausanne (IGUL) (Maillard et al., 2011, Schoeneich et al., 1998) which can be used with Esri ArcGIS. Figure 3 shows a geomorphological map of a high alpine valley (Käfertal, Austria) produced in ArcGIS using the symbol set of Otto (2008).

Online maps

Digitally produced geomorphological maps hold the potential for online publication. The possibilities range from simple publication of raster maps or single vector layers as overlays for Google Earth to the generation of a genuine webGIS application containing each single layer of information of the geomorphological map. While the former is

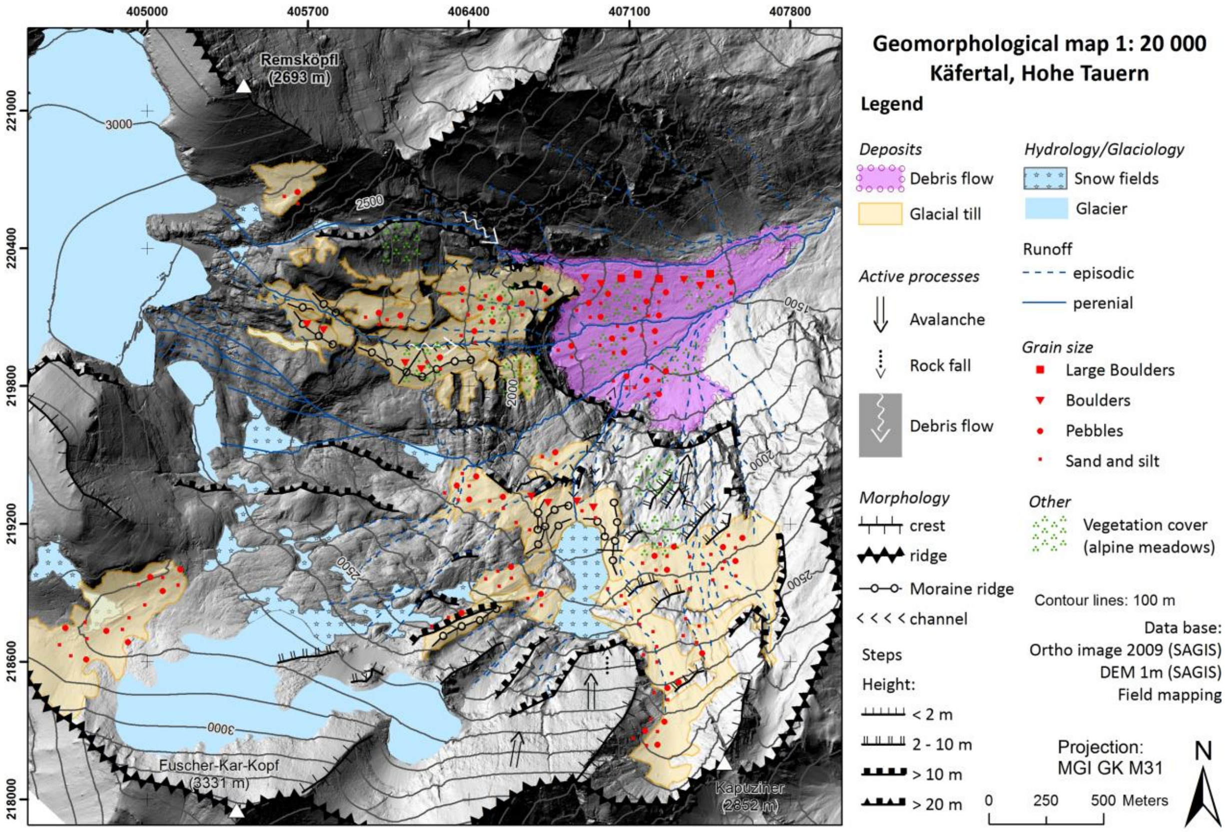

Figure 3: Geomorphological map of the Kafertal, Hohe Tauern, Austrian Alps using the "Mapping Symbols for High Mountains" (Otto, 2008, Otto and Dikau, 2004).

easily performed by export of maps or data layers into the standardised KML/KMZ format, the latter requires a web server application (webGIS software) for the dissemination of the map online. Otto, et al. (2011) and Smith, et al. (2013) provide an introduction to these methods for online publication.

Recently, the standard PDF (Portable Document Format) has been extended into a GeoPDF for display and dissemination of referenced map data. Geospatial functionality of a GeoPDF includes scalable map display, layer visibility control, access to attribute data, coordinate queries, and spatial measurements. Some geospatial data providers such as the United States Geological Survey (USGS; http://store.usgs.gov) and the Australian Hydrographic Service (AHS; http://www.hydro.gov.au/) currently publish interactive maps using the GeoPDF format.

Conclusions

Geomorphological mapping is undergoing a renaissance - with geomorphology proving to be a cross-cutting discipline, integrating academic and professional applications, the positive impacts upon society are large. Knowing *where* a landform is, *why* it is there, *what* it is made of and *how* it has changed is an incredibly powerful position from which to manage society's interaction with surface (and near-surface) features.

The re-emergence of geomorphological mapping as the pre-eminent paradigm for such studies is a direct result of the proliferation of spatial data (aerial and satellite imagery, DEMs) and IT systems to manage them (GIS). A clear framework for geomorphological spatial data management has been established. Whilst the 1960s and 1970s saw initial academic development, application was limited and as geomorphology as a discipline shifted to field-based studies interest declined. Indeed the mantle of geomorphological mapping shifted to engineering geology during the 1980s and

1990s as the benefits for direct application were recognised. The forefront of geomorphology has seen the integration of process-level understanding with regional scale modelling. GIS provides the underlying framework; maps and mapping are an integral part of this process and the skills, knowledge and understanding of the methods for data collection, processing and output are a key element. Geomorphological mapping is the underpinning domain as geomorphology moves centre-stage.

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