Physical Landscapes

Mike J. Smith and James S. Griffiths

Abstract The scientific discipline of geomorphology is concerned with the processes that act upon and shape the Earth's surface to create physical landscapes. Maps have a very specific utility within this domain as they allow a spatial representation of shapes (or landforms), their material composition, age and the processes that formed them. From the creation of the very first geomorphological maps in the early 1900s, there has been continual development and increased sophistication in the representation of complex datasets. The implementation of geographical information systems, integrated with the widespread availability of satellite imagery and digital elevation models has enabled much greater application across a range of disciplines beyond geomorphology, notably in natural hazard evaluation, disaster response assessment, insurance, infrastructure planning, civil engineering and engineering geology. This chapter provides a brief outline of the development of cartographic techniques where the primary purpose is to provide maps of geomorphology that have met the requirements of different end-users. Initially this involved standard approaches of field mapping and drafting of hard-copy maps but has now developed into the use of much more sophisticated methods of digital data collection and management. This has resulted in significant growth in the use of geomorphological maps, and recognition of their wider societal significance. Whilst geomorphology, by definition, refers to mapping of the Earth's surface, there is increasing use of mapping techniques on planetary bodies across the solar system. The horizons for geomorphological mapping clearly continue to expand and this chapter concludes with a discussion on the future challenges and opportunities within the subject.

Keywords Digital elevation model (DEM) · Geomorphology · Terrain · Landscape · Legend · Symbol · Laser · Radar · Physical morphology

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S.D. Brunn and M. Dodge (eds.), *Mapping Across Academia*,
DOI 10.1007/978-94-024-1011-2_2

1 Introduction

This chapter is concerned with the role of mapping to understand physical landscapes and more specifically the scientific discipline of *geomorphology* and its application in real-world land management tasks. The study of geomorphology deals with the form of the Earth's surface and the processes that act upon and shape it, with mapping focused upon recording the location and distribution of different landforms of interest (often including details on material composition and age) either as a specific graphical output or as data input to subsequent numerical modelling. Landscape analysis in geomorphology is inherently science based and, given the complexity of natural systems, an inductive approach to the acquisition of knowledge has often been taken. The observation of physical systems is a key tenet and geomorphologists have often used this as the basis for classifying sample sets of the environment and then generalising this complexity into a standardised theory (Chorley et al. 1985).

In geomorphology it is apparent that maps are a natural outcome of the observational process and highlight the data-driven nature of much research. This mode of knowledge construction dates back to at least the 1800s (e.g. Close 1867), although it was not until the early twentieth century that early derivatives of what we would now consider geomorphological maps first appeared (see, for example, in the work of Passarge (1912) in Germany). As geomorphology developed as a subject, more sophisticated techniques in mapping landforms began in earnest in the 1950s (e.g. Klimaszewski 1956) and 1960s (see review by Rose and Smith 2008); maps were a natural counterpart to this process as they allowed the storage, display and analysis of complex information. This inevitably led to a large number of bespoke feature classifications, symbol sets and visual designs (or more simply, legend systems), contextualised by their sub-discipline, such as glacial or country. As a result there was considerable effort put into the development of standardised systems, particularly by the International Geographical Union (1968). The richness and interdisciplinarity of geomorphology is exemplified through the diversity of application areas and close cross-over into other related disciplines such as geology, soil and natural hazard mapping.

Unfortunately, by the time academic consensus had been reached in the use of legend systems, two major changes had occurred: (1) research methods in geomorphology had changed and (2) geographic information systems (GIS) had been implemented in academic research. During the 1970s research methods in physical geography underwent a quantitative revolution and moved more towards inductive approaches to understanding physical systems; this involved detailed measurements at finer and finer scales. In short, mapping was a solution to a problem that many were no longer interested in.

Prior to this point cartographers were concerned with all aspects of data management, presentation and analysis; maps were the technological solution to harnessing the power of spatial information. The introduction of GIS and, more specifically, digital data handling was a major technological disruptor that caused a division in the cartographic community between those focused on design/communication and those on data handling. We now think of the former as "cartography," whilst the latter has become geographic information science. It is interesting to note from textbooks of the time, such as Monkhouse and Wilkinson (1971), that cartography was portrayed as an all-encompassing discipline, fundamental to the study of subjects involving the integration of two-dimensional space. Data management and analysis is conspicuous by its absence in modern volumes, with Kraak and Ormeling's (2010) *Cartography*, subtitled Visualization of Spatial Data.

Yet we would argue in the last decade or so that geomorphological mapping has undergone a period of renaissance. This is evidenced through the proliferation of maps in both the grey literature and actively being published. The establishment of the *Journal of Maps* (http://www.journalofmaps.com) in 2004 demonstrates the relevance of mapped output with a significant number of geomorphological maps (e.g. Glasser and Jansson 2008). This is underlined by the formation of the *International Association for Geomorphology (IAG)* Working Group on Applied Geomorphic Mapping (Pain et al. 2008) and publication of a new technical handbook on the topic (Smith et al. 2011).

In the next section of this chapter we detail the primary purposes of geomorphological mapping. This is followed by discussion of data collection and management issues, before the principle end-users of geomorphological maps are outlined, highlighting the breadth of contemporary inter-disciplinary involvement. In combination these sections demonstrate why geomorphological mapping has seen such recent growth and assumed a role of societal significance. The purposes of geomorphological maps are triggered by the requirements of end-users, but this is also driven by the availability of data and what can be achieved in its use. As a consequence the concluding discussion examines the future of mapping in geomorphology.

2 Purpose of Geomorphological Maps

The purpose of geomorphological maps is to systematically record the shape (or morphology), landforms types, landscape-forming processes and geological materials that constitute the surface and near-surface of the Earth. Originally described as 'physiography maps' these have a substantial history of use and development by geographers, although the earliest applications were mainly in North America (e.g. Powell 1896; Fenneman 1928). Until around 1960 geomorphological maps were used as a means of describing the landscape in fairly simply terms and typically at quite small scales. For example Hammond (1954) produced a 'geomorphic study' of part of southern California at a scale of 1:560,000, and went on to subdivide the whole of North America on 7½-minute rectangles that classified the landscape into eight types: (1) nearly flat plains; (2) rolling and irregular plains; (3) plains with

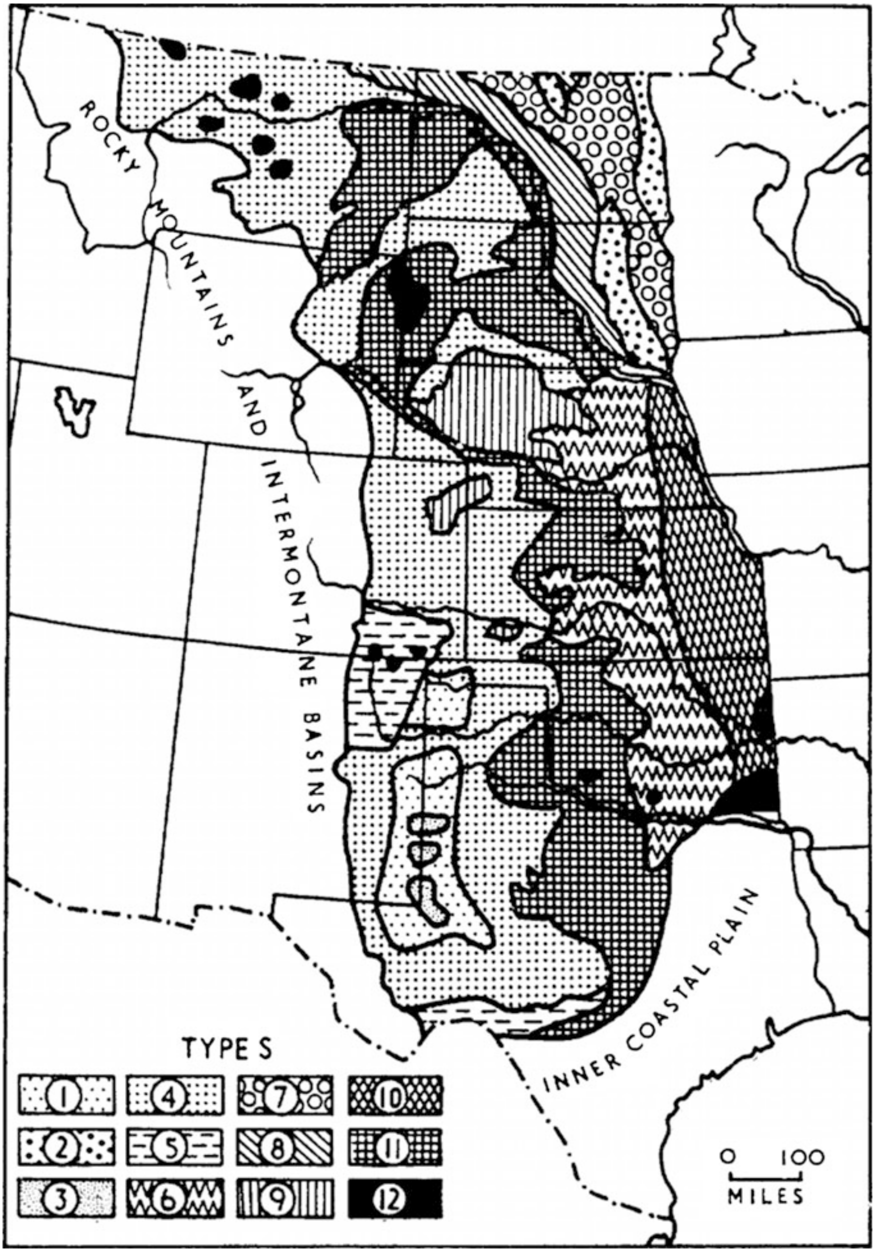

Fig. 1 Physiography of the American Great Plains (Lewis 1962)

widely spaced hills and mountains; (4) partially dissected tablelands; (5) hills; (6) low mountains; (7) high mountains; (8) ice-caps. An example of this type of map is presented in Fig. 1.

These small scale maps were useful for broad descriptions of the landscape and provided general background material but lacked the detail needed for a comprehensive understanding of the geomorphological history of an area. During the late 1950s and 60s there emerged, predominantly in Europe, an approach to geomorphological mapping that resulted in very detailed maps of the landscape and a standardised legend for this work was compiled by Demek (1972) and Demek and Embleton (1978). A summary of these developments are provided by Cooke and Doornkamp (1990) which also contains a more succinct collection of standard symbols for use in geomorphological maps. They suggested that such maps should be divided into four distinct types derived from data collected in a systematic manner using a system of morphological mapping devised by Savigear (1965):

1. Morphological maps—where the land surface is sub-divided into planar facets separated by gradual changes or sharp breaks in slope. On the maps the changes and breaks in slope are identified as either concave or convex in nature and recorded using decorated lines;
2. Morphographic maps—the distribution of a named suite of landforms and their material composition based on the boundaries shown on the morphological maps. Examples of the terms that might be used on this map are described by Griffiths and Stokes (2008);
3. Morphochronological maps—the age of formation of the landforms identified on the morphographic maps;
4. Morphogenetic maps—these show how geomorphological processes created the landforms and the overall landscape.

Otto et al. (2011) present the main symbol sets that have been developed and the contexts in which they should be used. It is important to note that geomorphological mapping seeks to capture the full complexity of the Earth's surface and represent it in a simplified form. Due to the complexity of the distinct map types noted above, symbol sets and the maps themselves can be visually complex, difficult to understand and therefore requiring considerable expertise to interpret. Much of the development and application resulted from work in Europe (Verstappen 2011) and Paron and Claessens (2011) outline the major "schools" of geomorphological mapping. Outside of Europe, it is only Australia and Brazil (e.g. DeOliveira and Vieira 2009) that have major traditions in national mapping, although the recent production of a national geomorphological atlas of China is noteworthy (Cheng et al. 2011).

Figure 2 illustrates the application and development of approaches to geomorphological mapping, with Fig. 2a presenting a morphological map for a series of landslide features in Dorset. This simply presents the *shape* of the landscape; it is not until interpretation adds information on processes and chronology that the real explanatory and communicative power of geomorphological maps are exposed.

The next stage in the development of geomorphological mapping came from an unexpected direction; it was found to be an approach that lent itself very effectively to preliminary investigations and planning for civil engineering construction

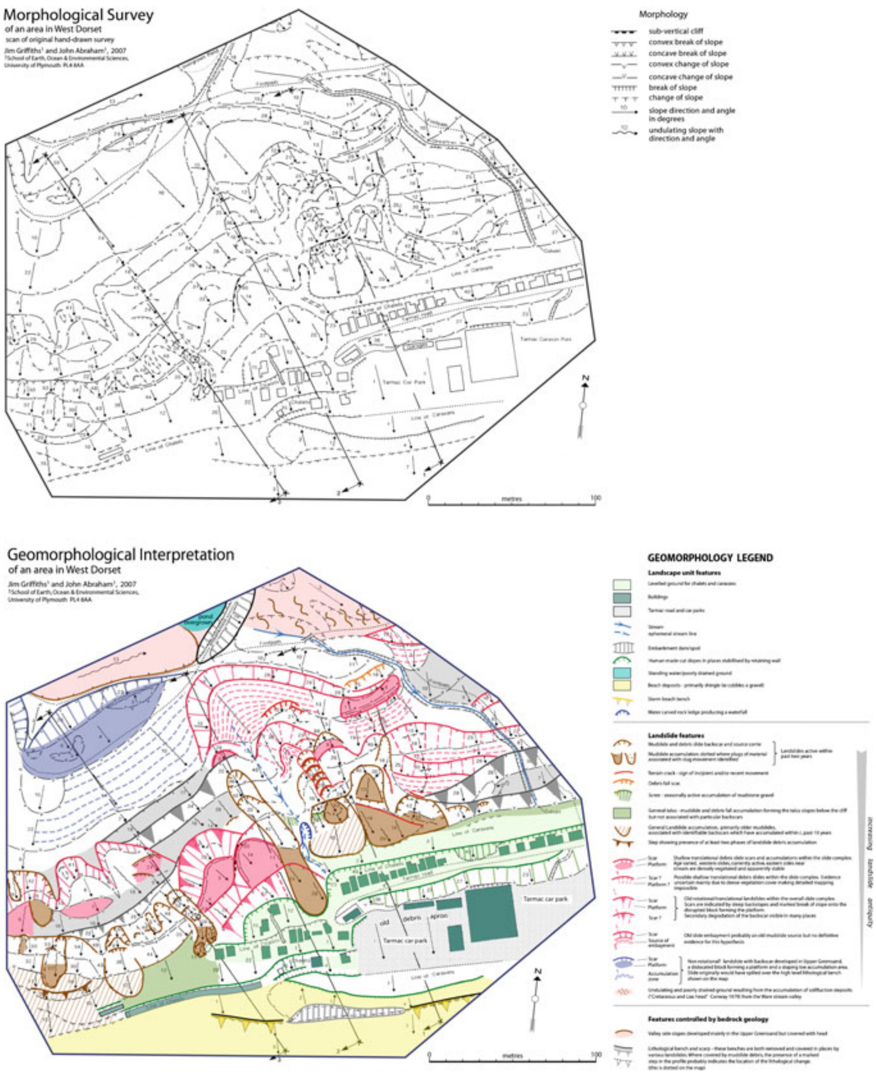

Fig. 2 Area in West Dorset, UK, illustrating active landslide features (*top*). Morphological map of the study site and (*bottom*) geomorphological map, incorporating process and chronological information (after Griffiths and Abraham 2008)

projects where an understanding of surface form, near-surface materials and surface processes is crucial. This was demonstrated by Brunsden et al. (1975) and Doornkamp et al. (1979) through a series of case studies in the UK, Nepal, and the Middle-East. As an example of this work, Fig. 3 presents the geomorphological map from the Suez New City master plan (Jones 2001). Geomorphological mapping became closely associated with developing techniques of engineering

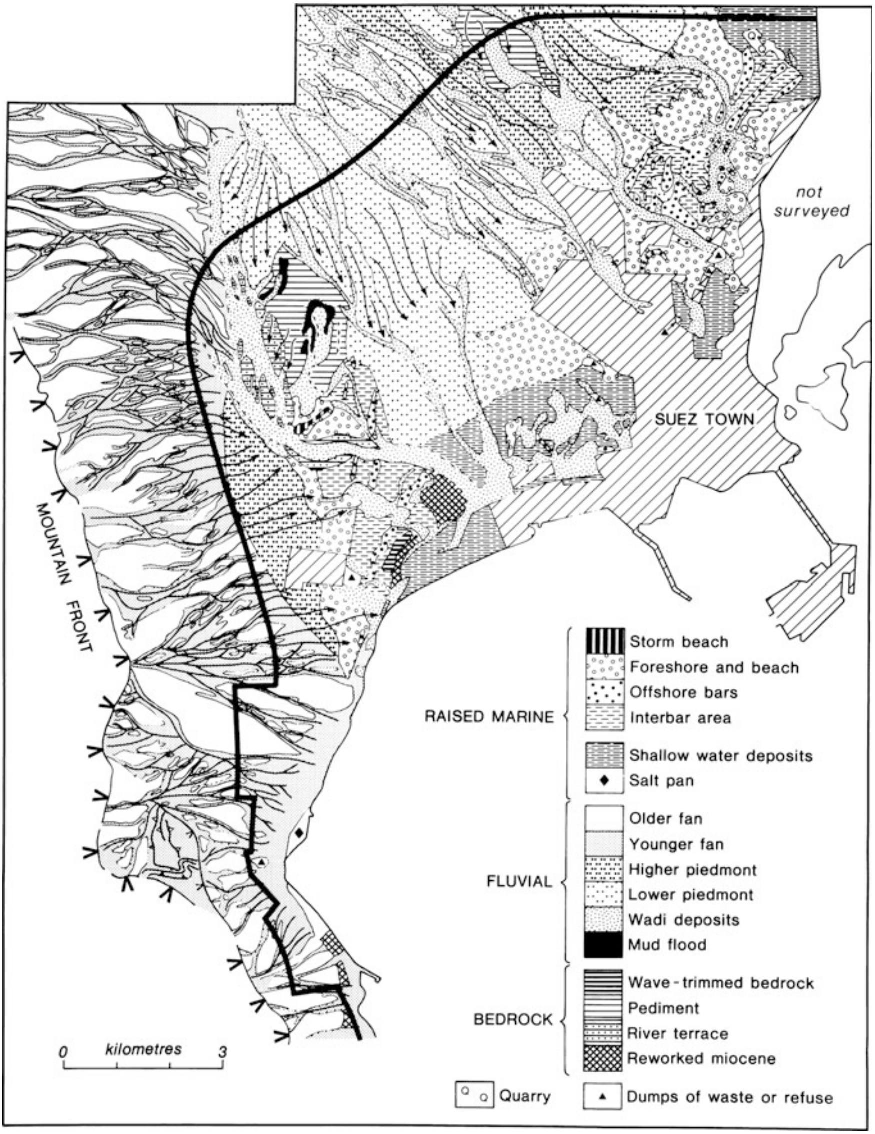

Fig. 3 Geomorphological map of Suez New City (Jones 2001). Reproduced with the kind permission of the Geological Society of London

geological mapping (Report by the Geological Society Engineering Group Working Party 1972; Dearman and Fookes 1974; International Association of Engineering Geology 1976) and in the UK recommendations were made in 1981 that both techniques should form part of future revisions to the code of practice for site investigation (BSI 1981; Griffiths and Marsh 1986). In connection with planning, it was apparent throughout many parts of the world that geomorphological data were central to more effective production of regional and local development plans (Doornkamp et al. 1987). The maps for planning that were produced were usually hybrids that incorporated a range of data including geology and geomorphology (such as the French planning maps ZERMOS; cf. Porcher and Guillope 1979), or part of a suite of maps that included specialist cartography on geomorphology (Smith and Ellison 1999; Burnett and Styles 1985, 1986; Styles et al. 1984).

By the late 1980s the on-going development of geomorphological mapping was no longer predominantly an academic pursuit but lay with applied geomorphologists and engineering geologists working in industry. In the UK examples of the application of geomorphological mapping include the Channel tunnel high speed rail link (Waller and Phipps 1996), associated with planning for the Ventnor landslide complex (Lee and Moore 1989), and as part of the Department of the Environment environmental geology mapping programme (Forster et al. 1987). In a review of these developments, Lee (2001) identified three distinct forms of geomorphological map which can still be identified in the published literature and all have distinct applications:

1. Regional surveys of terrain conditions, either for land use planning or in baseline studies for environmental impact assessment, for example the 1:25,000 scale maps of Torbay by Doornkamp (1988);
2. General assessments of resources or geohazards at scales between 1:50,000 and 1:10,000 (e.g. Bahrain Surface Materials Resources Survey; Doornkamp et al. 1980);
3. Specific-purpose large-scale surveys to delineate and characterise particular landforms (e.g. the 1:2500 scale investigations around the Parrot's Beak Ridge for the Ok Tedi copper mine in Papua New Guinea; Hearn and Blong 2001).

Whilst geomorphological mapping has now had significant resurgence as a means of data collection in academia, it still remains primarily an applied tool for engineering and planning purposes (Smith et al. 2011). An indication of the way geomorphological mapping is now part of mainstream engineering, particularly for more remote, undeveloped areas, is demonstrated by Hearn (2011) in his review of mountain road engineering. An example that illustrates an applied geomorphological map of the type recommended by Hearn (op. cit.) is presented in Fig. 4 (Griffiths 2001). This map shows a multiple rotational landslide with a distinctive backscar, a series of displaced benches, a double accumulation zone, and secondary degradational movements. The map formed the basis for subsequent ground investigations for the channel tunnel portal which was located in this landslide.

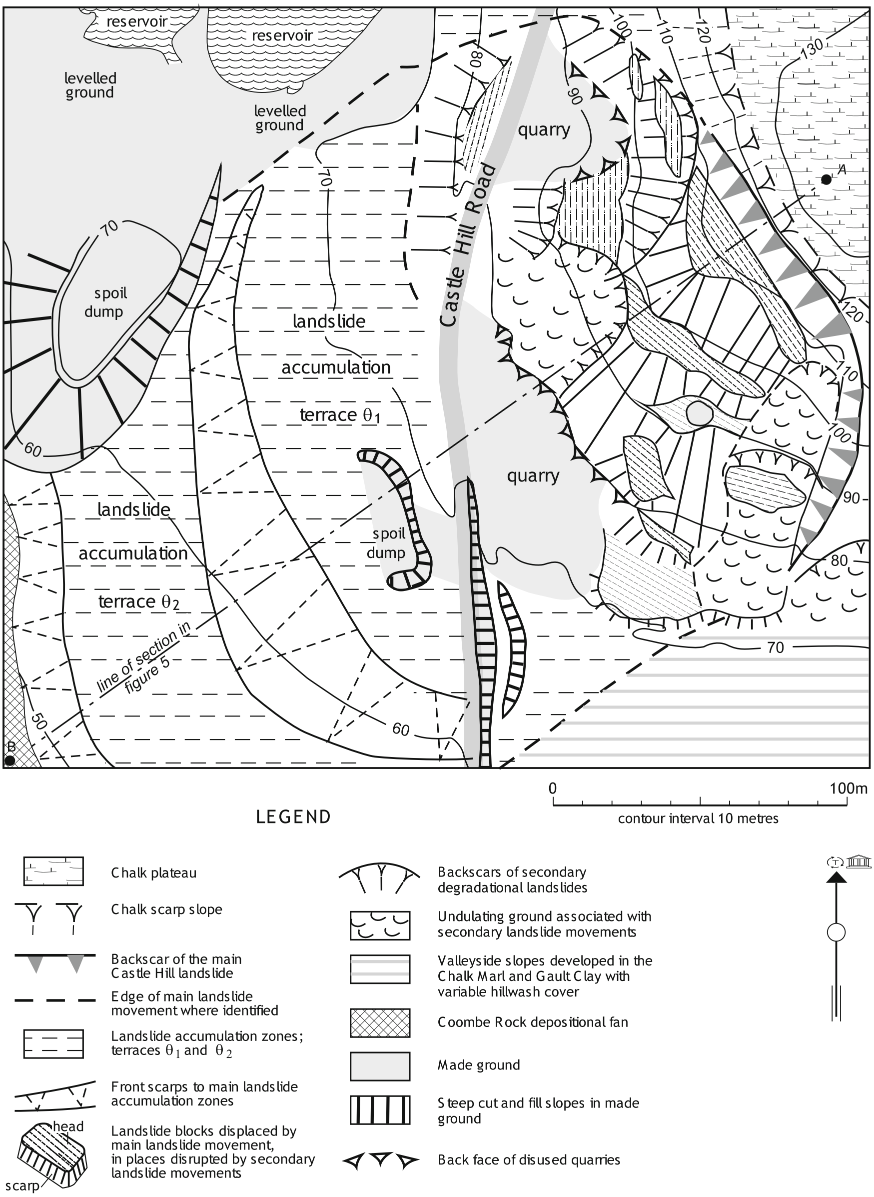

Fig. 4 Geomorphological map of the channel tunnel portal area, UK (Griffiths 2001). Reproduced with the kind permission of the Geological Society of London

3 Data Collection and Management

Cartography in its widest sense, has long been concerned with data collection, classification, management and representation. GIS is central to the future role cartography plays, however there is no need to labour its importance in the study of spatial phenomena given the extensive treatment in other chapters in this volume. It is enough to note the significance of data management in the physical sciences; the ability to reproduce the (layered) paper-based cartographic paradigm digitally through data storage, spatial analysis and map production allowed efficiency savings, the processing of very large volumes of data and the extent of analysis that had previously been impractical or impossible.

GIS therefore provides the organising framework through which geomorphological mapping takes place. As geomorphology is concerned with the form and acting processes of the Earth's surface, the spatial modelling of terrain is central to undertaking research work and effective mapping of landscapes. The digital elevation model (DEM) is a raster representation of the landscape, where each individual cell contains an elevation value. This basic framework was outlined early on (Miller and LaFlamme 1958) to allow computer processing of terrain (surface elevation), and led specifically to the development of algorithms and a theoretical underpinning through the sub-discipline of *geomorphometry* (Evans 1972; Hengl and Reuter 2008). Whilst any elevation value is inherently vector based (e.g. spot heights or contours), data processing has largely focused upon the manipulation of raster data due to the simplicity of the computation. However the relatively recent use of LiDAR (see below) has allowed the compilation of massive vector datasets that area increasingly processed and modelled within a vector framework.

Data collection is a key component in terrain modeling and visualisation and here we consider some of the important trends that have taken place. When working with historic data, conversion to a digital format is necessary. Spot heights and contours are the primary legacy datasets and these have been dealt with extensively (e.g. Gousie and Franklin 2005; Carrara et al. 1997) and are of significance because they allow the temporal analysis of landscapes. In terms of contemporary data collection, manual, field-based, techniques remain common place and are used extensively, particularly where detailed survey data is required for small areas. A theodolite with integrated distance measuring device (known as a Total Station) is often employed and will usually have a data logger allowing direct digital data capture. For many applications these have been largely replaced by global positioning system (GPS) receivers which are simpler and faster to use. Survey-grade GPS receivers allow millimetric accuracy measurements to be made. Perhaps the single greatest impact upon geomorphology over the last ten years has been the upsurge in the use of remotely sensed techniques to measure surface elevation (Smith and Pain 2009). This has allowed the collation of medium-resolution datasets over large areas thereby allowing regional-scale analyses. Three technologies have led these developments: Light Detection and Ranging (LiDAR), interferometric synthetic aperture radar (InSAR) and photogrammetry.

For terrain measurement, LiDAR typically utilises a laser pulse to calculate the distance (or range) from the scanner to the target based upon the travel time (Baltsavias 1999). With the horizontal and vertical angles of the pulse known, a three-dimensional position can be calculated; current systems can measure up to of 500,000 points per second creating a “point cloud” of data. Airborne laser scanning (ALS; e.g. Lohani and Mason 2001) has seen rapid development over this period. Output data provides a range to the *visible surface* meaning that it is often not possible to model the actual terrain surface, having to include “clutter” such as buildings and trees (although these are of significant interest for urban and ecological applications). One benefit of using laser ranging is that the pulse itself is narrow; as a result it is often able to penetrate through a tree canopy and reflect off the actual ground surface. Terrestrial laser scanners (TLS or ground-based; e.g. Hodge et al. 2009) have had far slower uptake principally due to the high unit cost and data management requirements. Heritage and Large (2009) outline the theory and application of laser scanning in the environmental sciences.

Like LiDAR, InSAR is an active remote sensing technique (Palmann et al. 2008) that has been used extensively for the collection of terrain data (Smith 2002). This operates at much longer wavelengths of “light” and, rather than using travel time, makes uses of the recorded *phase*; that is the incomplete proportion of a single wavelength received at the sensor. When the *difference* in phase between two images of the same area is calculated, the remainder is directly related to the elevation of the terrain surface; this can be extracted through a process known as *phase unwrapping*. InSAR is operated from both airborne and spaceborne platforms either in a single-pass or repeat-pass mode. In single-pass mode, *two* sensors on a single platform capture images at exactly the same moment. This produces the best terrain data, but is a more costly solution.

The final data collection technique is that of photogrammetry, which is now a fully digital process. This is concerned with quantitative measurements from photos which, when applied to landscapes, can be used to measure surface elevation (Mitchell 2007). If the exact position and orientation of a single camera is known, then it is possible to model a vector from the lens to an object of interest. If the exact position and orientation of a second camera is known for an *overlapping* photo, then trigonometry is applied to calculate the three-dimensional position of an object. When this is performed digitally, it is possible to iteratively calculate millions of points and generate point clouds in a fashion similar to laser scanners.

Traditionally photogrammetry would have used analogue (film) photography from bespoke aerial (metric) cameras acquired during dedicated surveys. However digital processing now enables a greater flexibility in approach allowing the use of off-the-shelf prosumer cameras (e.g. Chandler et al. 2005) and oblique imagery (Maas et al. 2006). The ability to mathematically model greater amounts of distortion allows the application of photogrammetry, and acquisition of surface elevation measurements, to new areas. One powerful application has been the use of historic aerial imagery (e.g. Barrand et al. 2009) to open-up this important environmental archive. A second area is *close range* imaging (within $\sim$200 m of the Earth’s surface). This scale of data collection has been relatively expensive to acquire and therefore under-utilised. However, the ability to use prosumer cameras, coupled with novel airborne platforms, is transforming the collection of imagery. Unmanned aerial vehicles (UAVs; Laliberte et al. 2010), blimps (Boike and Yoshikawa 2003) and kites (Smith et al. 2009) have all been successfully used to collect aerial imagery and subsequently processed photogrammetrically. Ultimately geomorphological mapping is reliant upon data on the form of the landscape, collected either through field-based assessment or from remotely sensed data. Where remotely sensed, there are considerable benefits to be gained from low cost, accessibility, reconnaissance and areal coverage, allowing greater utilisation of geomorphological information and therefore advancing the role of mapping in the decision making process.

4 Map Users

Robinson and Spieker (1978), researchers working at the United States Geological Survey published the book *Nature to be Commanded* which demonstrated the use and value of a range of Earth science maps including those depicting geomorphology. They make the claim that the purpose of Earth science maps is to:

> inform planners, decision makers or owners so that they can forestall or relocate new developments in areas where lives and property might be imperilled, propose appropriate design precautions in developments that cannot be placed elsewhere and/or alert inhabitants of imperilled developments to seek protection through engineering or insurance. (Robinson and Spieker 1978: 2)

On the reasonable assumption that Earth science maps will be of little value if they do not illustrate geomorphology, Table 1 identifies all the potential users of applied geomorphological maps.

In addition to geomorphological maps being used in applied settings, there will be a significant academic role by geomorphologists, geologists, environmental scientists, pedologists, foresters, cartographers, and physical geographers carrying out investigations of the landforms and processes in an area. There will also be non-specialist users, such as ramblers and farmers.

For example, Doornkamp et al. (1987) present an international review of environmental geological maps in relation to planning which demonstrates that throughout the USA and Europe geomorphological mapping is a fundamental requirement in the compilation of data. Styles et al. (1984) make a similar claim for Hong Kong in connection to the far-sighted Geotechnical Area Studies Programme and Land Use Planning. For the construction of low cost roads in mountainous regions, Hearn (1997) emphasizes the importance of understanding the geomorphology and working with the terrain for design and planning which will require the compilation of geomorphological maps. Finally, Fookes (1997) in the first Glossop Lecture makes it clear that understanding the geomorphology is fundamental to the

Table 1 Potential list of users of applied geomorphological maps

User	Application
Planners	Those responsible for local and regional development plans and also who will grant planning permission for new developments to take place
Decision makers	Local (or national) authority civil servants or politicians who have to agree to a development taking place
Owners	The clients who are paying for a development or own an existing development, whether it is a residential home, a sea wall, bridge, quarry, waste dump, tunnel, sea outfall, nuclear power station, sea defences or reservoir with a 100 m high dam
Architects	Who will design any new development
Engineers	Who will investigate sites, design and build new developments or remediate existing developments that are "imperilled"
Resource exploitation	Water authorities, exploration companies or national geological surveys seeking resources
Insurers	Those responsible for insuring or reinsuring existing, planned, under-construction or built developments
Banks	Who provide the financial package that allows a development to proceed
Disaster response	Those who will prepare disaster response plans for 'imperilled' areas (e.g. areas of flooding, landsliding, earthquake, tsunami, or volcanic hazard), including NGOs

creation of a ground model necessary for the safe and economic design of all engineering works.

Whilst the references cited above mainly refer to traditionally compiled two-dimensional maps, GIS has allowed the development of three-dimensional (surface and sub-surface) and four-dimensional (temporal) geomorphological maps which will only increase their importance and value to end-users.

5 Planetary Geomorphological Mapping

Whilst the importance of mapping terrestrial landscapes is well-established, new opportunities for scientific investigation by geomorphologists were identified in the physical landscapes of other planets in the solar system (Sharp 1967). Realistically this is limited to the Moon and Mars, where the solid surface can be clearly seen and analogues with terrestrial processes can be established, plus more speculative work on asteroids, comets and some of the larger moons, notably those orbiting the gas giants Jupiter and Saturn, Mercury and Venus.

The International Association for Geomorphology has a working group (IAG PGWG) investigating planetary geomorphology (http://planetarygeomorphology.wordpress.com). Their work has identified a range of active and relict geomorphological activities including meteorite impact cratering, volcanism, plus processes identified as aeolian, fluvial, lacustrine, deltaic, mass wasting, rock disintegration, glacial and periglacial. The IAG PGWG notes that "Whilst the landforms appear similar to those on Earth, there are issues of equifinality in addition to important differences in denudation rates, landform scale and indeed geomorphic processes." The IAG PGWG web site hosts a collection of images displaying some of these landforms coupled with a description of the features, comparisons with possible terrestrial equivalents and further reading.

With the exception of meteorites landing on Earth and samples collected from the Moon landings 40 years ago, all the mapping and interpretation of the geomorphology is based on terrestrial telescope observations and remote sensing data. Whilst the Moon is dominated by impact craters (Ronca 1972), the Martian landscape presents a much more complex geomorphological picture (Balme et al. 2011). Craddock and Howard (2002) make the case for rainfall on a warm, wet early Mars and it is now accepted that flowing water has created many landforms on the Martian surface (Carr 1983), with Towner et al. (2011) suggesting there is evidence of water flow as recent as 100 Ma. Nekum et al. (2004) suggest there is evidence for recent volcanic (within the past 2 million years) and glacial activity (within the past 4 million years) on the planet. Studies such as these coupled with work notably at NASA (i.e. http://marsoweb.nas.nasa.gov/globalData/) have led to the creation of maps of many facets of the physical landscape of Mars which are now available interactively through Google Maps (http://www.google.com/mars/).

6 Future Challenges

It is perhaps strange in a book about mapping to spend so much time on data acquisition and management. Yet representing terrain is fundamental to understanding the environment and the recent renaissance in geomorphological mapping has been driven by the development of new techniques for data collection. Data are now available for larger areas, in greater detail and over short time periods. There has now been nearly 20 years of topographic data collection from space and this has been transformative for geomorphology and the physical sciences more widely. Whilst geomorphologists are concerned with terrain morphology and surface/subsurface material properties, it was really only surface material properties that were available prior to using remote sensing. The complementary addition of elevation datasets has greatly extended the capability of geomorphological investigation and provided the context for the expansion in mapping. This has been an evolutionary period for the discipline, yet the outputs and outcomes from research that have benefited from these data has been truly revolutionary. The scope and capability of such work has been significantly extended and this is explored by Smith and Pain (2009) where they show the temporal/spatial resolution constraints on current work (Fig. 5). In particular, there is a growing trend for more detailed imagery available over shorter timescales; this considerably expands the scope and scale of geomorphological investigation open to researchers. Whilst the technology, data and applications are available, not all researchers will have the knowledge or skills to take best advantage of them and one key challenge will be the

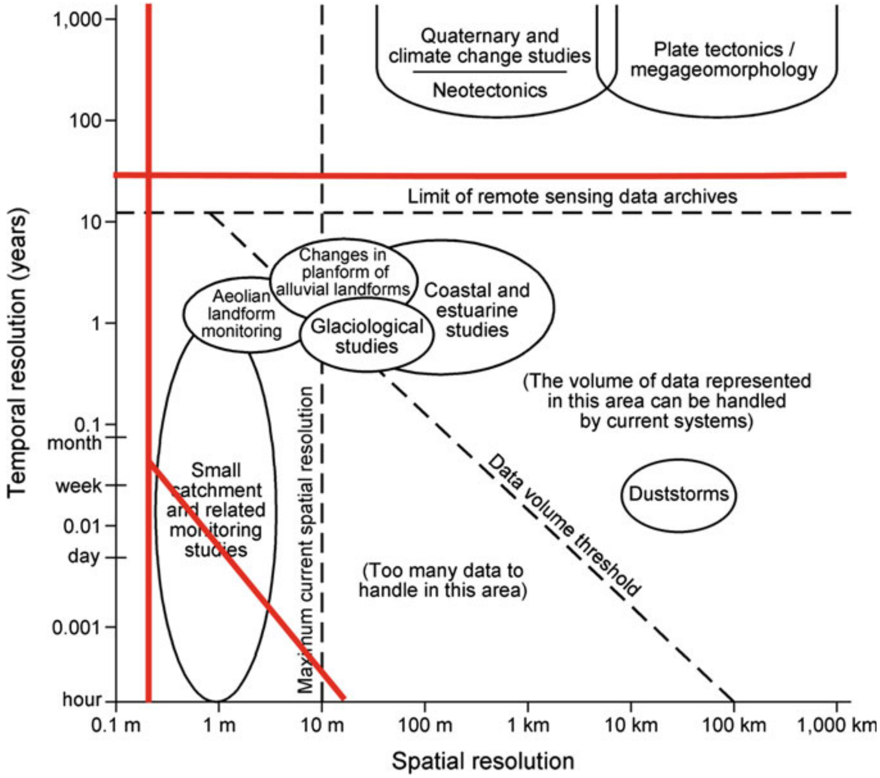

Fig. 5 Temporal and spatial resolution constraints of satellite sensors on geomorphological research (Smith and Pain 2009: 569)

dissemination of best practise. In this sense academics are self-regulating and the growth in published outputs such as the *Journal of Maps* and key textbooks including Smith et al. (2011) and Hengl and Reuter (2008) play their part.

Future technological changes in geomorphology can best be seen in current *airborne* technology, as sensor development and deployment is commensurately shorter than for space. Passive systems, such as radiometrics (composition of the upper 50 cm of the surface) and aeromagnetics (imaging subsurface features), and active systems, such as airborne electromagnetics (three-dimensional detail on conductivity down to 100 m), have great utility and are beginning to allow the development of a true three-dimensional understanding of surface and near-surface landforms and their material properties. An area currently in transition is that of hyperspectral remote sensing; rather than collecting images at single wavelengths, these sensors collect images at tens or hundreds of different wavelengths. This provides a far richer 'data cube' that enables more sophisticated investigation. At the opposite end of the spectrum, developments in close-range remote sensing will drive the acquisition of low-cost field-scale data. Already remotely controlled model aircraft or quad-copters can be pre-programmed to a set flight plan to acquire imagery using a prosumer camera. Subsequent imagery can then be processed photogrammetrically or as a series of mosaics. Costs will be driven down in this area, particularly with the use of *Arduino* (http://www.arduino.cc/), an open source prototyping hardware platform (e.g. http://ardupilot.org). Also expect to see far greater interest in the development of multispectral prosumer cameras that can be used on these platforms. These technological developments do not necessarily expand upon current capabilities, but significantly reduce the cost to implement meaning that the collection and application of these data will become widespread and ubiquitous, transforming the spatial and temporal scales that geomorphologists can investigate landforms and the processes that act upon them.

Not surprisingly the wealth of data is becoming overwhelming to manage, whilst finding relevant information appropriate to the task at hand is increasingly difficult. Data management has become a vital component in any project and GIS is ideally suited to fill this role, yet the increasing requirements for large datasets makes this problematic and current storage and processing paradigms lag behind the needs of the end user. In early 1980s ‘cutting edge’ remotely sensed data volumes involved the manipulation of ~240 Mb per dataset, while current systems can easily produce ~1.2 Gb of data for *one tenth* of the area. Ynnerman (2010) describes data explosion in the medical sciences where volumes from computed tomography (CT) scanners have dramatically increased; a single scan now generates 24,000 images and ~20 Gb of data. The whole area of spatial data visualisation and analysis requires a step-change in capabilities moving towards immersive three-dimensional environments, making use of multi-modal applications and greater leveraging of haptic interaction (Lundin et al. 2008). Much of the current investment and development is coming from the computer games industry (e.g. Microsoft Kinect) and the following years should see greater penetration into scientific visualisation.

Searching for data is an increasingly difficult problem and the development of data warehouses, such as the *Global Land Cover Facility* (http://glcf.umd.edu), are an attempt to solve this. It remains a fragmented area, however, with warehouses segregated between governments, research agencies, universities, subject specialisms, commercial aggregators, professional bodies and industry sectors. A key aspect is the provision and utilisation of metadata; often simple elements such as the producer, owner, copyright and spatial extent are missing. Details such as processing algorithms, precision, accuracy and currency are limited, particularly where secondary data is concerned. Many academic and research funding bodies now require the submission of data upon the completion of projects and, with the mandating of metadata, this is helping to improve their downstream discovery and use.

Access, use and re-use of some of the data highlighted above is mixed. Federally collected data in the US remains in the public domain and therefore entirely free from restriction. Yet much of the wealth in data and development of new applications come from recent commercial initiatives (e.g. high spatial resolution satellites such as *GeoEye-1*). These fall under copyright and their use protected.

Access to other datasets is often variable; professional bodies, funding agencies and universities may require some kind of affiliation before they grant access (although the data will remain under copyright). Governments are increasingly seeing the benefit and power of releasing data and there has been a movement to place these in the public domain or under a Creative Commons license (http://creativecommons.org/). Discoverability and reuse is of fundamental importance to researchers; geomorphological information can often be limited and it is therefore important that it is easy to find, access and reuse.

With all this technological change, another aspect that continually needs revising is that of *communication*. Researchers are increasingly aware of requirements by funding agencies to disseminate their work, maximise the impacts upon society and make their outputs widely available. Yet communication is often limited to conferences and papers, with spatial outputs ignored. Maps are a key part of this strategy, yet effective visual communication is often limited. With a renaissance in mapping comes a requirement to better communicate; dissemination of cartographic best practise is an important part of this. Likewise, researchers are finding new ways to communicate and disseminate; digital globes such as *Google Earth* and *NASA Worldwind* provide a platform through which they can provide online interaction with the general public. Likewise, the value and need for open spatial data standards are paramount and the support and traction gained by the Open Geospatial Consortium (http://www.opengeospatial.org) is of significance in easing this process.

Finally, given the wealth of digital data that can now be collected, collated and compiled, there remains the question of how to produce an actual accurate 'map' of the physical landscape. The ability to interpret the information to provide a genuine appreciation of the landforms and processes is dependent of the skill and experience of the geomorphologist. Such skills and experience can only be gained in the field and no matter how accurately the data can be represented on a map or in a GIS there will always be the requirement for the end product to be 'ground-truthed.'

7 Conclusions

Geomorphological mapping has a long history in the use of applied cartography. A range of specialised maps have been a fundamental 'enabler' in studying the landscape as both a method for visualisation and a paradigm through which data storage and analysis could be performed. The move of physical geography (and geomorphology) to quantitative, field-scale, approaches of study in the 1970s limited the application of maps. And, ironically, GIS led to the demise of maps in the published scholarly literature with almost a generation of spatial outputs largely absent from this permanent archive (Smith 2005). Yet the mantle of mapping was taken up in the 1980s by engineering geologists who saw the power of integrating morphology with an understanding of surface and subsurface materials and processes. Geomorphology represents one of the key linkages in understanding and managing the environment and can therefore be seen as a societal necessity. The real power of geomorphological mapping is unleashed through this interdisciplinary approach, between practitioners in, for example, engineering, geology, geomorphology, planning and land management. The full utility of this realisation has become apparent through a move in physical geography to combine process level understanding at the landscape scale; changes in data availability have now made such studies technologically feasible. Maps and mapping are an important part of this process and new demands are being placed upon visualisation and dissemination. Techniques for the automated production of maps directly from GIS, the presentation of complex multi-dimensional variables and the integration into electronic workflows are important and remain a developing area. It is with this backdrop that geomorphological mapping can look forward to the next decade with anticipation.

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http://www.springer.com/978-94-024-1009-9

Mapping Across Academia
Brunn, S.D.; Dodge, M. (Eds.)
2017, X, 394 p. 128 illus., 77 illus. in color., Hardcover
ISBN: 978-94-024-1009-9