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Geomorphometry and landform mapping: What is a landform?

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ABSTRACT

Starting from a concept of the land surface, its definition and subdivision from Digital Elevation Models (DEMs) is considered. High-resolution DEMs from active remote sensing form a new basis for geomorphological work, which is moving on from consideration of whether data are accurate enough to how the surface of interest can be defined from an overabundance of data. Discussion of the operational definition and delimitation of specific landforms of varying degrees of difficulty, from craters to mountains, is followed by the applicability of 'fuzzy' boundaries. Scaling, usually allometric, is shown to be compatible with the scale-specificity of many landforms: this is exemplified by glacial cirques and drumlins. Classification of a whole land surface is more difficult than extraction of specific landforms from it. Well-dissected fluvial landscapes pose great challenges for areal analyses. These are tackled by the delimitation of homogeneous elementary forms and/or land elements in which slope position is considered. The boundaries are mainly breaks in gradient or aspect, but may also be in some type of curvature: breaks in altitude are rare. Elementary forms or land elements are grouped together into functional regions (landforms) such as 'hill sheds'. It may often be useful to recognise fuzziness of membership, or core and periphery of a surface object.

Plains and etched or scoured surfaces defy most of these approaches, and general geomorphometry remains the most widely applicable technique. It has been applied mainly within arbitrary areas, and to some extent to drainage basins, but more experimentation with mountain ranges and other landforms or landform regions is needed. Geomorphological mapping is becoming more specialised, and its legends are being simplified. Its incorporation into geographical information systems (GIS) has required greater precision with definitions, and the separation of thematic layers, so that it is converging with specific geomorphometry and becoming more flexible and more applicable, with a broader range of visualisation techniques.

1. Introduction

> "A definition is useless unless the thing defined can be recognized in terms of the definition when it occurs." H. Jeffreys, 1961 p.8

Recent work has asked questions such as 'What (or where) is a mountain?' (Smith and Mark, 2003; Fisher et al., 2004), which raises perceptual and linguistic as well as geomorphological considerations. Here I tackle the question 'What is a landform?', and take a more strongly geomorphology-centred approach. Landforms are central to many definitions of geomorphology, e.g.:

> "Geomorphology, or the study of landforms…" (Lobeck, 1939 p.3)
> "Geomorphology is the study of landforms." (Pitty, 1971 p.1)
> "After about 1860 the study of landforms…was later also known as physiography or geomorphology." (Chorley et al., 1964 p. xi)
> "Geomorphology is the science that investigates the landforms of the earth." (Ahnert, 1998 p.1).

Others put it slightly differently:

> "Geomorphology is the study of the Earth surface." (Butzer, 1976 p.1)
> "Geomorphology is the scientific study of the geometric features of the Earth's surface." (Chorley et al., 1984 p.3)
> "Geomorphology is the science concerned with the form of the landsurface and the processes which create it." (Summerfield, 1991 p.3).

Recent research has concentrated on processes, materials and chronology, but the land surface itself remains central in geomorphology. Its analysis is essential in the verification or calibration of models (Dietrich et al., 2003). Thus, the specialised subject of geomorphometry (Pike, 2000; Hengl and Reuter, 2009) has grown tremendously in recent years as more and better DEMs (Digital Elevation Models) have become available.

An important distinction between 'landform' and 'land surface form' parallels the distinction between specific and general geomorphometry (Evans, 1972; Goudie, 1990). Land surface form is continuous and covers the whole globe (both subaerial and subaqueous), as well as other planets, moons and asteroids. General geomorphometry analyzes this

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continuous field. Landforms are bounded segments of a land surface and may be discontinuous: they need not cover the whole surface (Fig. 1). Specific geomorphometry analyzes the geometric and topological characteristics of landforms. The question of what to do with 'the bits left between' deserves consideration.

The definition of landforms of various sorts is an essential part of geomorphological mapping. Complete delimitation is a further necessity for specific geomorphometry: to measure their geomorphological characteristics, individual landforms must be separated from their surroundings. Characteristics such as area and mean slope gradient require a complete boundary: thus, it is not sufficient to map a cirque by a crescent (indicating the headwall crest in a generalised way) as on many traditional geomorphological maps. A prerequisite for specific geomorphometry is to draw a closed boundary: this is the procedure known as delimitation, marking the limits of the landform (Evans, 1987; 2010). The question whether these limits can be fuzzy, or must be precise, is considered below.

This paper moves from the definition and properties of specific landforms in relatively clear-cut cases, through more difficult situations, to consider finally the application of general geomorphometry and geomorphological mapping. First, the concept of the land surface is defined, and the DEMs from which it may be analysed for landform definition are considered. Cirques and drumlins are used as examples of clearly-bounded landforms: other landforms and terrains vary in the difficulty of delimiting forms. The objectives are to make connections, to review concepts and progress in defining and measuring landforms, and to illustrate landform allometry and scale-specificity. Such a concern with the essence of landforms relates to the philosophical field of ontology (Smith and Mark, 2003). Hierarchies and broader-scale divisions, such as land systems, landscape types and physiographic provinces, are not discussed here. The focus is on the geometry of landforms, not topology or relation to materials and processes, and on areal more than linear features.

2. The land surface concept: scale

Reflecting perhaps the influence of many years in a Geography Department, my concept of the land surface starts at the human scale:

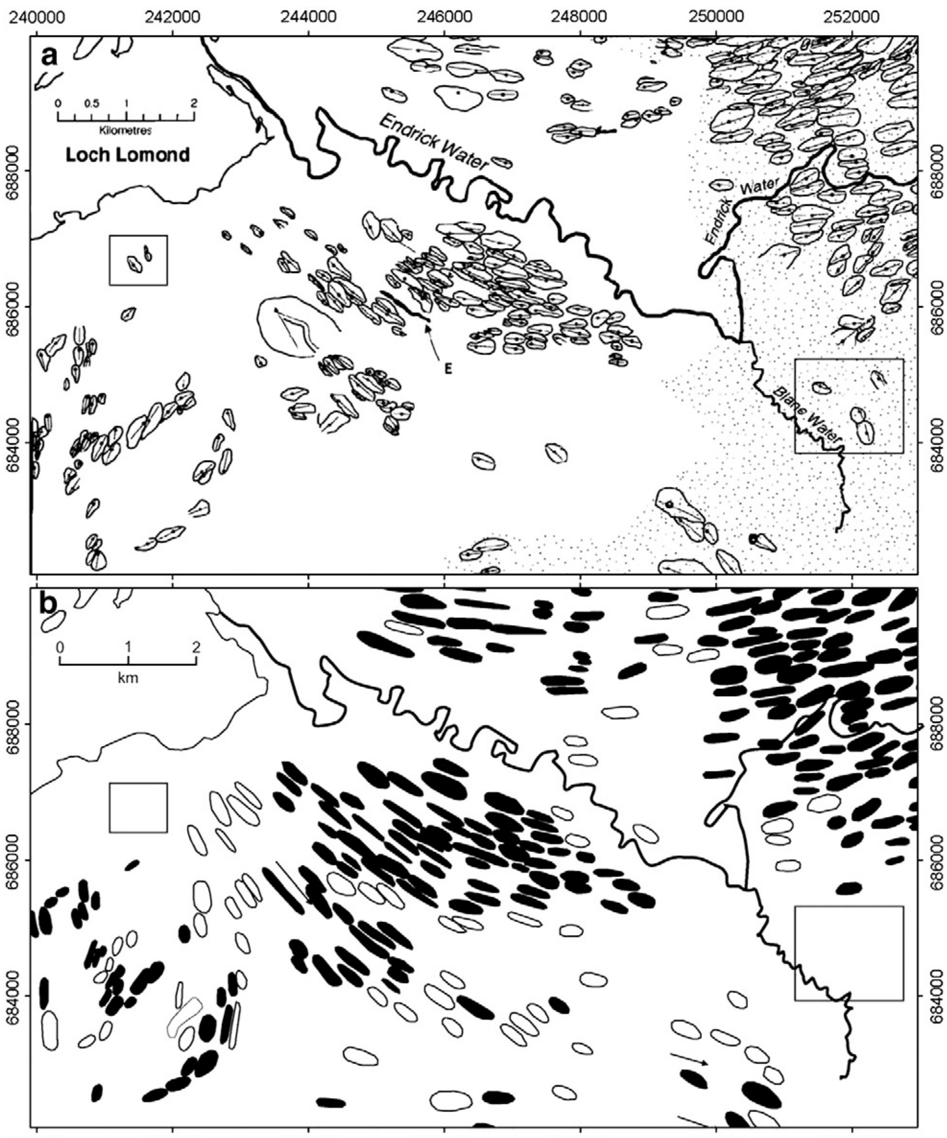

Fig. 1. Comparison of drumlins mapped for an area close to Loch Lomond in Scotland by (a) intensive field mapping by J. Rose. Drumlins, crestlines and summits are mapped. The esker (marked 'E') was erroneously mapped as two drumlins in (b), mapping from the NEXTMap 5 m DEM. In (b) solid black drumlins coincide with field mapping; black outlines are those found from the DEM but not in the field, and the boxes highlight areas where field mapping found examples that were not seen in the DEM.
From Clark et al. (2009).

1.5 m. It does not end there, but a long tradition in slope studies involves measuring over this slope length, notably with Pitty's (1971 pp. 402–404; Cox, 1990) slope pantometer. Finer-scale variation is described as microrelief, although its upper limit has rarely been clearly defined. Whatever the pros and cons of generalising to 1 or 2 m, it does give a common basis from which measurements can be compared.

Many geomorphologists have focused on the surface smoothed at a scale of a few metres. In slope profile survey, Young (1972 p. 146) recommended that "No measured length shall be more than 20 m or less than 2 m… for topography of normal scale". Gerrard and Robinson (1971) analysed gradients for fixed measured lengths from 1.5 m to 10 m, and discussed the effects of small protrusions and depressions (microrelief) that can give variations of a few degrees for measuring lengths of a few metres. Pitty (1971) advocated fixed lengths and used a frame giving a constant slope length of 1.5 m (previously 5 feet, i.e. 1.52 m) for gradient measurement: this 'human scale' relates to the practicality of one-person operation. Debate concerning fixed versus variable measuring lengths along profiles continued (Cox, 1990) and had some parallels with the debate about fixed grids, adaptive grids and irregular triangulations as bases for DEMs. In slope profiling the basic idea was to exclude individual particles (stones), minor bumps and depressions, and repeated microrelief such as earth hummocks (best analysed separately, by appropriate means of analysis, as are vertical cliffs, overhangs, pipes and caves). The influence of grain size was removed; boulders would generally be avoided. Buildings and vegetation were also excluded.

Boulders several metres long, for example in rockfall or glacial deposits, pose a problem. If they sit on the surface, they can be excluded from the concept of land surface in the same way as trees or buildings. If the boulders are close together or partly buried (and all degrees of burial exist), however, it is more appealing to pass a surface through the boulders, either averaged if the boulders are close together, or interpolated from the surrounding surface if this is relatively smooth. Thus, we reach a geomorphological concept of the (real) land surface, with a lower limiting scale of a metre or two, and relating to the ground, a continuous body or aggregate of material, rather than to individual particles. Wherever human modification is considerable, this is not the 'natural' land surface, which leads to difficulties discussed below. Exclusion of caves etc. is a necessary simplification to give a single-valued surface as a function of horizontal coordinates, permitting representation by a DEM. Here DEM is used in the narrower sense, as in Hengl and Reuter (2009): elevation (altitude) values for a gridded set of points in Cartesian coordinates. Technological progress has made DEMs an increasingly important basis for geomorphological research.

3. Defining the land surface on DEMs

Until recently, reliable measurements at 1 to 10 m scale required fieldwork. Early DEMs were coarse (with horizontal resolutions – grid mesh spacings – around 100 m) and mainly derived from contours manually digitised from medium scale maps (Tobler, 1969), e.g. at 1: 50,000 or 1: 25,000 — or even small-scale, 1: 250,000. Better quality was obtained by photogrammetry, e.g. the 10 m DEM used by Hancock et al. (2006), or at large scales for engineering works or from photos taken in the field (Lane, 1998), covering limited areas. It is well known that mean and standard deviation of slope gradient reduce rapidly as measured from coarser grids (Evans, 1972: Deng et al., 2007). Although altitude and regional variables may be insensitive to scale (Shary et al., 2005), curvatures are affected even more than gradients: an order-of-magnitude gap remained, between most DEM-based calculations and 1 m scale field measurements. Having rejected the fractal model in this context (Evans and McClean, 1995; McClean and Evans, 2000), it was clear that extrapolation was dangerous. In particular, gradients and curvatures from the coarse DEMs of the 1970s and 1980s (50 m or 100 m mesh: Evans, 1980) could hardly be compared with field-based measurements of slope profiles (Young, 1972; Parsons, 1988; Cox, 1990).

Sampling adequacy was also of great concern, together with the effects of errors in DEMs interpolated from contours (Wise, 2007). For example, as streams typically do not cooperate by passing through grid points, the related low points could often be missed, creating spurious pits upstream. Smoothing does not solve this problem, and filling the sink by raising levels up to the apparent outlet creates artefactual plains and falsifies data at many grid points. Rather than raising points over an area, it is better to lower points along a drainage line, as this is equivalent to displacing them (by less than one grid mesh) to the position of the presumed nearby channel, and fewer data points are modified. Pits can be removed by breaching (Martz and Garbrecht, 1999) or carving (Soille et al., 2003), yet it is dangerous to apply this automatically as even in fluvial topographies real depressions occur, becoming very common not only in karst areas but also in areas of eluviation of fines, or of deflation (Reuter et al., 2009; Li et al., 2011). A large body of literature grew up on 'drainage tracing' from DEMs (Gruber and Peckham, 2009), but the possibility remained of major mis-assignments of drainage direction because of channels missed between well-spaced grid points. These algorithms could not match the accuracy of drainage nets plotted directly from air photos.

With the development of two types of active remote sensing, things are now very different (Nelson et al., 2009; Reuter et al., 2009; Smith and Pain, 2009). Radar-based products are available at various resolutions. Airborne Interferometric Synthetic Aperture Radar (IFSAR) can be flown at high altitudes and fast speeds, covering large areas with few problems from weather. Western Europe and the conterminous USA are covered by the 5 m resolution NEXTMap IFSAR DEM. For Britain this was provided in two versions, the initial product (digital surface model: DSM) showing forests, hedges and buildings, and a smoothed product (digital terrain model enhanced: DTME) where these had been filtered out. Livingstone et al. (2008) mapped drumlins, glacial lineations and other features in much of northern England, manually interpreting hill-shaded NEXTMap DEMs with two orthogonal illumination directions, as well as a slope gradient map. Interestingly, they worked mainly from the initial DSM product because it retained relevant detail lost in the filtering process. A number of workers using visual interpretation have preferred to use the unfiltered DSM, but it would be difficult to automate landform recognition without filtering out vegetation and buildings.

Laser scanning can give such dense point clouds that gridding at 1 m represents generalisation. Once we could process 'last returns' as well as 'first returns', the ground and not just the forest canopy could be mapped accurately from the air, and absolute vertical accuracies better than 0.3 m could be achieved (Pirotti and Tarolli, 2010). Under dense forest, however, the 'bare earth' DEM is interpolated from fewer points and is less accurate than elsewhere because only a small proportion of returns are from the ground (Norheim et al., 2002). Although airborne laser scanning (LiDAR: Light Detection and Ranging) is expensive, it is so promising, especially for hazard evaluation, that coverage of laser-based DEMs with 1 m resolution is rapidly increasing: for example, for the whole of Switzerland below 2000 m, and for entire Länder in Austria. Belgium, the Netherlands and Alberta are covered at 2 to 5 m resolution. Terrestrial laser scanning can provide even greater detail for individual landforms, and even for coarse-grained sediments (Hodge et al., 2009): in studying overland flow, (Smith et al., 2010) use a 2 mm resolution DEM. With fine-resolution LiDAR, many old problems fade, and new ones appear. Error assessment is changed radically (Fisher and Tate, 2006): technical errors have become rather small, but errors of definition remain and loom large.

Laser and radar returns produce data some of which is of geomorphological interest, and some not. We have to think even more carefully, exactly what is the land surface? What version of the surface is relevant to the problem in hand? We can agree that trees and bushes should be removed, but what about buildings? Here views may diverge between those attempting to explain the natural land surface, and those working on applications such as flood routing and slope stability. If buildings are solidly built of stone or brick, they will obstruct water flow — up to the point where the walls collapse. Cellars may extend below the natural ground surface, and the land around a building will often have been levelled leaving a steeper cut on one or more sides. This makes it difficult to interpolate through a building from the surrounding surface, and algorithms to remove buildings may often leave ghostly artefacts betraying building position. Working at 1 m resolution, or even 5 m, major road and rail cuts are clearly represented: removal is difficult and perhaps unreasonable. The anthropogenic nature of much of the modern-day land surface must be accepted. Rather than being removed, such features should be identified and delimited as specific landforms, analysed separately from the remaining surface.

The complexity of desirable filtering algorithms is formidable if we consider not only buildings and trees, but also vehicles, livestock and feeding troughs, and derelict parts of these. Producing a LiDAR DEM compatible with the above concept of land surface seems to require a full initial remote-sensing identification of all other objects in the data.

One implication of LiDAR is that the amount of data to be processed can be huge: fortunately, the relentless increase in computer power makes this acceptable. Although the distinction between point-based and pixel (area-based) raster data is important for analysis (Strobl, 2008), the generation of 1 m raster grids from LiDAR point clouds with several returns per m^2 does produce some convergence. Another implication of such highly detailed grids is that stream banks are often visible, and only the tiniest stream channels can be missed. Pirotti and Tarolli (2010) find it best to smooth or thin 1 m DEMs to map small channels and channel heads successfully, from points with curvature deviations exceeding 2 standard deviations. This means that gross errors in drainage tracing should not occur. But representation of the water surface means that results depend on the water level (stage) at the time of survey. As the true land surface includes the channel bed (also lake beds) rather than the fluctuating water surface, grid points falling on the surface should be coded as such: survey of the water bed requires different techniques and is not available unless bathymetric LiDAR is used (Hilldale and Raff, 2008).

4. Delimiting landforms

Landforms are one type of geomorphological (or geomorphometric) object (Schmidt and Dikau, 1999: MacMillan and Shary, 2009). Other types are linear features: ridge lines, slope lines, course (valley) lines and break lines, and special points: peaks, passes and pits. Landforms in this narrower sense are areal objects on a DEM, and in general they have a third dimension — they are volumetric. Mark and Smith (2004 Table 3.1) define 25 broad specific landform types, with many subsets. Some features have multiple identities: all large volcanoes are mountains, and some volcanoes are islands, but many islands and mountains are not volcanoes. In geomorphometry and geomorphological mapping, the more precise term ‘volcano’ is usually adopted, rather than the broader terms. Full classifications recognise nested hierarchies of terms: for example, barchan dunes are a type of transverse dune, a subset of aeolian dunes. Other processes also produce dunes, which are a mobile type of bedform, and bedforms are a major type of landform.

Evans (1987) specified nine stages in a specific geomorphometric study, starting with conceptualisation and operational definition of the landform type. Further operations can now be performed on-screen or by computer calculation: delimitation, measurement, derivation of ratios, assessment of frequency distributions, interrelation and mapping. Finally comes the more subjective procedure of interpretation in relation to genesis and chronology. Concern here is especially with conceptualisation, operational definition and delimitation. As yet, delimitation of specific forms is mainly manual, using visual identification: automation of the process remains a research frontier, with acceptable success rates somewhat elusive. Progress is being made with both supervised and unsupervised classification of DEMs (Seijmonsbergen et al., in press).

Islands and lakes form special cases that can be delimited precisely by the water level at a given time, although this does vary a few m even within a year, and much more over the long term. Nunataks are likewise limited by the ice surface, which also varies over the years. On the other hand it could be argued that the true landform of an island or nunatak extends below the water or ice, for example giving the true height of Mauna Loa, Hawaii (over the Pacific Ocean floor) as 10,099 m. The more clearly a landform can be defined, the more likely is it to be the subject of a morphometric study, i.e. of specific geomorphometry (Goudie, 1990; Evans, 2010). In glacial geomorphology, this has meant drumlins, lake basins and cirques, but studies have been extended to ribbed moraine, megascale glacial lineations, and troughs.

Drumlins and many other depositional or mobile forms have limited vertical dimension and are, thus, poorly portrayed on standard contour maps. Fieldwork and air photo interpretation have been essential in achieving accurate mapping (Rose and Smith, 2008). Although drumlins are clearly defined, multi-convex landforms, Smith and Wise (2007) showed that the number identified increased considerably as satellite image resolution increased (from 30 m to 15 m). Probably the same applies to increasing DEM resolution. Smith et al. (2006) used visual interpretation of LiDAR data gridded at 2 m both to check and to improve on field-based mapping of drumlins. Differences occurred in both directions, but the LiDAR data permit subtle hummocks and lineations to be noticed that were missed in the field. Bedrock distribution, however, is less clear on the LiDAR images than in the field. DEMs from digitised contours on 1: 50,000 and 1: 10,000 maps were inadequate for drumlin delimitation, and satellite radar data at both 90 m and 25 m horizontal resolution provided no useful data (Smith et al., 2006 Fig. 4).

Unfortunately the LiDAR data were available for only a small area and both this and later British studies made extensive use of NEXTMap airborne radar-based DEMs at 5 m resolution. Fig. 1 compares the delimitations of this set of landforms, showing both superiority to field data and some omissions (Clark et al., 2009). While not as detailed as LiDAR data, NEXTMap has proved a very useful source for the manual identification of glacial depositional forms and has shown patterns which had not been recognised in the field or from air photos. The identification of drumlins requires high-quality data, but once recognised they should be relatively easy to delimit (either manually or automatically).

Smith et al. (2009) have developed a ‘cookie cutter’ tool for first approximations to the volume of convex (or concave) landforms in relation to a horizontal plane. They used it to calculate the volumes of drumlins by superimposing digitised outlines onto the 5 m DEM. The outlines are delimited manually, so the technique is described as ‘semi-automated’.

Visual interpretation of elongate features from a hill-shaded model is biased by the direction of illumination used (Smith and Clark, 2005; Smith and Wise, 2007). It is necessary to use multiple directions – I suggest at least four, as does Smith – and to combine interpretations from the different models. This can be cumbersome, and it would be desirable to automate boundary delimitation by direct processing of the DEM. A map of slope gradient is equivalent to a vertically illuminated model (with contrast enhancement), and it eliminates bias. The outer boundaries of drumlins are essentially concave breaks in slope, whether they are surrounded by lower areas or contiguous with other drumlins. Slope gradient steepens away from the summit: if this profile convexity is followed by a basal concavity, postglacial redistribution of material by wash or creep is suspected. It is usually assumed that postglacial modification has been slight, except where rivers or former meltwater channels have cut into drumlins and left obviously anomalous steep bluffs. The main complications are where younger drumlins are superimposed on larger ones that have been only partially remoulded, and where long streamlined tails merge into a hillside. Many drumlins contain some bedrock, but Clark et al. (2009) exclude those which are entirely bedrock and focus on drumlins formed in deformable materials.

Most bedforms are mobile and should, therefore, be categorised as neither depositional nor erosional. Fluvial and aeolian bedforms (such as dunes and bars of various types) have more in common with each other than either class has with glacial bedforms. They also evolve faster and are more accessible to study, so that the growth and decay of individuals can be studied over time, unlike most bedrock erosional forms. Dunes vary from the easily delimited barchan, where mobile material is sparse, to the complicated coalescent patterns of aklé and compound dunes.

Volcanic and meteoritic craters are the most easily defined erosional features, because of sharp convexities often separating opposing slopes. Yardangs and whalebacks are fairly well delimited. Another easily delimited form is a lake basin, but if we are interested in the rock surface underlying its sedimentary fill, expensive geophysical survey is required. Pingos usually have a sharp basal concave break in slope that clearly delimits them. Volcanoes are rather more difficult because broad pediments of lava or lahar deposits may merge

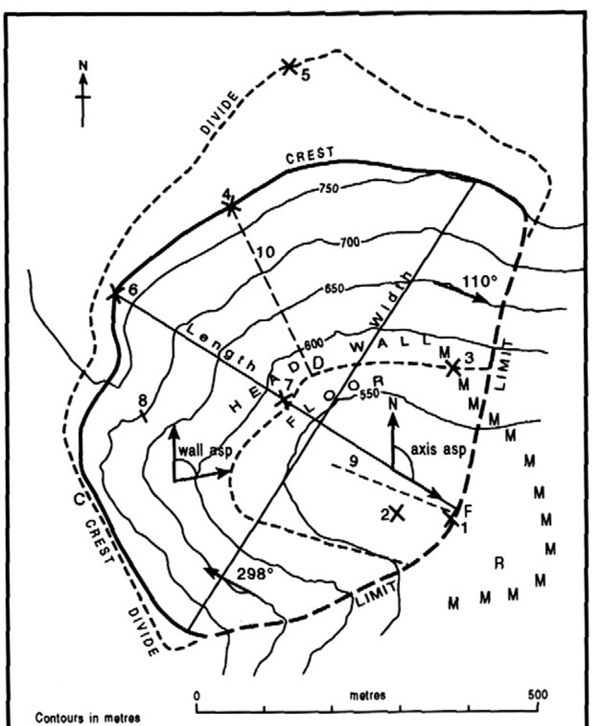

Fig. 2. Sale Pot, (2°51′E,54°30′N) in the High Street Range above Hawes Water, Northern England, is a well-defined-valley-head cirque with a minor bog and a clear threshold; it is eroded into mixed Borrowdale Volcanic rocks. Its drainage divide (dashed), crest (solid line), downvalley limit and floor: headwall boundary (dashed) are indicated. Contours are shown every 50 m. F: Cirque focus, middle of threshold. The median axis is drawn from 'F' so that area on left = area on right. It intersects the crest at 6. Length (of axis) = 590 m; width (normal to axis) = 790 m. Axis aspect = 121°; wall aspect = 085° (steeper wall faces north and east). Altitudes: 1. lowest, 520 m; 2. floor modal, 525 m; 3. max floor 582 m; 4. max crest 772 m; 5. max above 792 m; 6. median crest 752 m. 7. Grid reference, middle of axis: 3443 east, 5123 north. 8. 30 m fall in 18 m: max gradient = 59°; 9. 10 m fall in 195 m: min gradient = 2.9°. 10. Wall height = 770-570 = 200 m (max along any slope line). C: the col here cuts two 10 m contours, but 20 m this is below the minimum depth requirement (30 m), hence 'col' = 0. M-M-M Terminal moraine. planclos = (360-298) + 110 = 172° (measured over 100 m lengths, the mid-height contour, at 650 m, heads toward 298°, turns clockwise through north, and reaches 110°).

gradually with surrounding gentle slopes. Craters, volcanoes, pingos, dolines and salt domes are unusual in tending to radial symmetry, whereas most bedforms, plus cirques and slope forms such as landslides, tend to bilateral symmetry about the downstream/downslope direction. Among karst features, poljes are more irregular and difficult to delimit than dolines and tower karst (mogotes): likewise alas depressions in thermokarst (on permafrost) are not so easy to delimit. Landslide scars are delimited by sharp convexities; landslide deposits, by concavities which are initially sharp unless the material is so fluid that the lower boundary is unclear. Landslides have clear geomorphometric signatures (Pike, 1988).

Cirques (Fig. 2) are easily defined around the crestal convexities, which are sharp unless modified by overriding ice. The aim is to recognise simple, double-concave (plan and profile) features (Fig. 3: Rasemann et al., 2004). The down-valley limits are no problem for cirques with clear thresholds (convex breaks in slope below the floor) but difficult for some valley-head cirques without clear lateral convex slope changes (buttresses). Sometimes more than one down-valley limit is feasible — not so much a 'fuzzy' boundary (see below) as two or three alternative boundaries. But in most cases a decision can be made such that the headwall curves around the floor, and every cirque (including nested ones) has its own floor and a distinct section of headwall (Evans and Cox, 1995). The main problems arise from cirque coalescence around a valley-head ('splitters' and 'lumpers' may differ on the number of cirques recognised — on the prominence of the buttress required to recognise two instead of one) and from cirque-in-cirque forms (each lower cirque must have its own section(s) of headwall as well as a distinct floor).

Two topographical terms used for steep-sided valleys in northeast England are 'dene' and 'gill'. Inspection of their use in proper names on maps of East Durham shows that application is consistent. "Denes start around 100 m altitude and their channels slope at 14 to 30 m km^{-1}: their active development continues, eroding into both glacial deposits and Permian dolomite bedrock. … Valley-side slopes are generally steeper than 14 degrees. Similar valleys shorter than 700 m are known as gills." (Evans, 1999 p. 57). Sharp convexities at the crests of these valleys delimit them clearly. Gullies representing a change in process, such as the onset of soil erosion, are similarly delimitable. Likewise glacial meltwater channels have steep bluffs with upper convexities and rather flat floors.

Returning to 'What is a mountain?', the philosopher W.V. Quine proposed an interesting if compound definition. He advocated keeping the absolute term but resolving its vagueness by arbitrary stipulations:

"we may define a mountain as any region…such that

a) the boundary is of uniform altitude.
b) the highest point, or one of them, is at an inclination of at least ten degrees above every boundary point and twenty degrees above some, and is at least a thousand feet above them, and
c) the region is part of no other region fulfilling (a) and (b)." (Quine 1981 p. 33).

The vagueness Quine considered is of three types: of acceptable altitude, of basal boundary, and of indecision whether two summits count as two mountains or one (cf. the distinction between Munro's 'separate mountains' and 'tops': currently 283 Scottish mountains are recognised as being 'separate' and over 914.4 m altitude). Separateness may be based on distance as well as altitude change along a connecting ridge but, following J. R. Corbett, Dawson (1992) has used a rise of 152.4 m in all directions (rounded to 150 m) to list 1542 separate hill and mountain summits in Great Britain, regardless of altitude. He includes 205 mountains over 914.4 m altitude in Scotland. Dawson mentions others who have listed hills or mountains with summit magnitudes (rise in all directions) variously exceeding 10, 15,

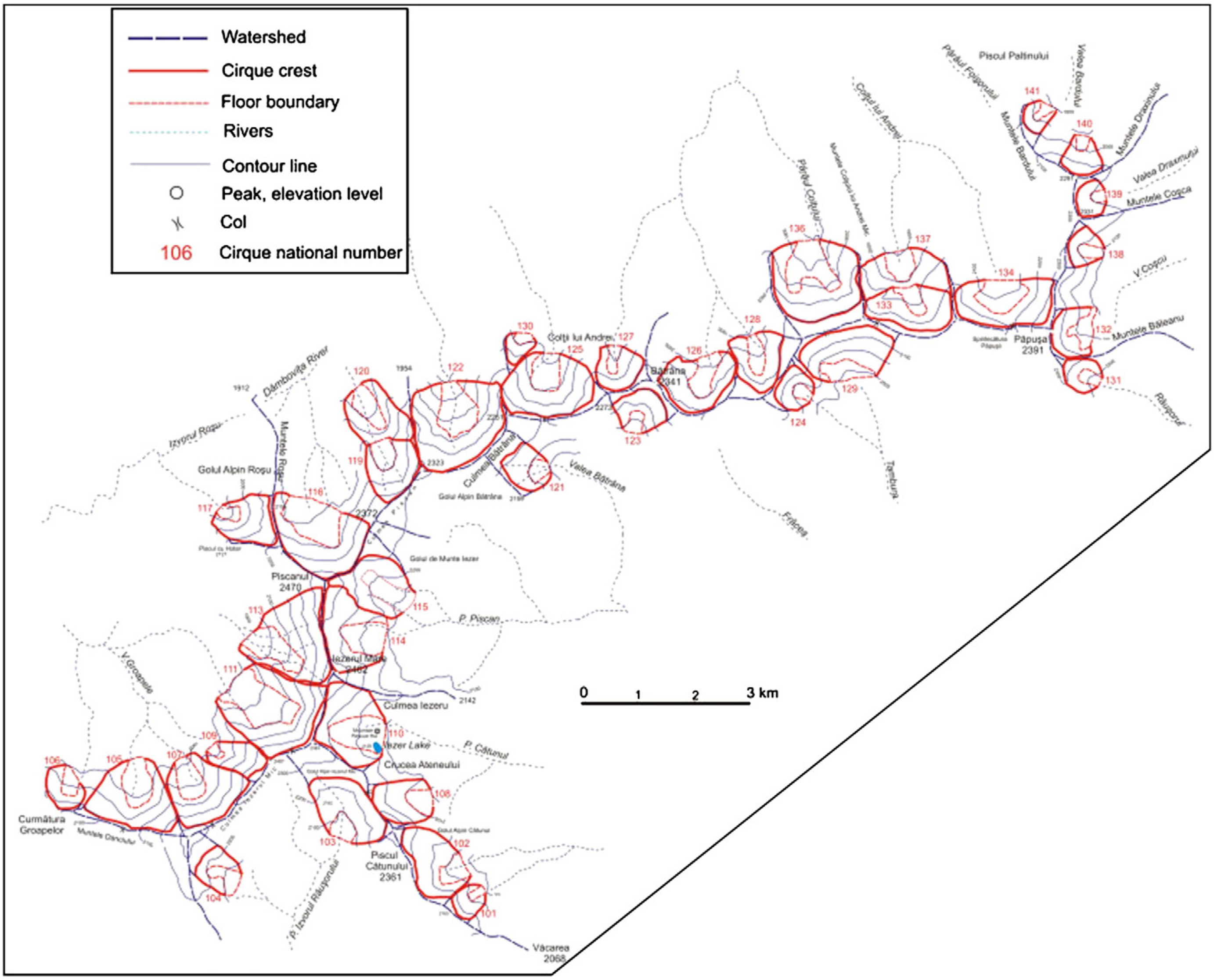

Fig. 3. Definition of cirques and cirque floors in the Iezer Range, Romania. From Cirque definition map of Iezer Mountains. North is at top. From Mîndrescu et al. (2010).

30, 100 and 150 m. This concept of height above the lowest closed contour within which a peak is the highest point – prominence or summit magnitude – is now widely used by mountaineers (http://www.peaklist.org/WWlists/WorldTop50.html). It permits nested mountains, contrary to Quine's point (c).

Quine concluded with a theorem:

> "the boundary of a mountain is the outermost contour line that lies wholly within ten degrees of steepness from the summit and partly within twenty."

We may argue with the arbitrary summit magnitude thresholds, with Quine's arbitrary (10°, 20°, 1000 feet) thresholds, or with the need for a contour as the boundary. Macmillan (personal communication 2010) prefers a boundary inclined down-valley. This is relevant to a binary distinction between 'mountain' and 'valley'. Those starting from supposedly equivalent terms to 'mountain' in other languages are very likely to propose different thresholds (Mark and Smith, 2004). But unless our definition includes some such arbitrary criteria, it is unlikely to be operational — that is, to be applicable consistently in practice. The most fundamental property of the type 'mountain' is being convex (Mark and Smith, 2004) — and large/high: each of these can be measured quantitatively and can, thus, be the basis of a definition if international scientists can agree, whatever the variations in common speech. It must be accepted, however, that 'mountain' is a vaguer term than cirque, drumlin, crater or landslide, and different definitions may be useful in different contexts.

At the least, each geomorphological study should state specifically the landform definitions it is attempting to employ. Terms such as small, short, light or weak are usefully kept relative, not absolute, but landforms should not be defined in a relative (contextual) way if they are to be mapped or measured. Thus, operational definitions are needed for all landforms to which specific morphometry is applied. In this respect, some studies are more opaque than others: the need for transparency is axiomatic. Geomorphological mappers have a poor record in providing operational definitions of the terms in their map keys.

Currently most landform delimitation is by on-screen digitising of manually identified boundaries, on maps, satellite images or rectified air photos (Clark et al., 2009). Much can be done using Google Earth. Two decades after the pioneer efforts of Tribe (1991), automated identification of specific types of landform remains difficult (van Asselen and Seijmonsbergen, 2006). We should be able to do better, at least for all forms bounded by convex and concave breaks. A promising combined approach is manual identification of a point or line within a landform, followed by algorithmic delimitation of a boundary (Schneider and Klein, 2010). Further approaches might be adopted from the pattern recognition literature. Automation of morphometric mapping has been achieved (Hengl and Reuter, 2009), and automation of morphographic mapping should not be difficult. Mapping of landforms, however, involves morphogenesis, and it is often necessary to perform fieldwork with geophysical, sedimentological and stratigraphic analyses to be confident of morphogenesis.

5. Fuzzy boundaries and leftover spaces

Even with precise operational definitions, considerable uncertainty remains. Given high-density data such as DEMs, it is realistic to recognise that some parts are more difficult to classify than others. It is easy to define mountain (peaks) as points, and valleys (thalwegs, not following the sinuosity of channels on floodplains) as lines, but assigning an area to either of them leaves much room for uncertainty and disagreement. 'Fuzzy classification' maps the degree of membership to a set of recognised classes (Irvin et al., 1997; Burrough et al., 2000; MacMillan et al., 2000). For example, Fisher et al. (2004) classified the surface of the English Lake District in terms of affinity to six topologically distinct classes of form: peaks, ridges, passes, planes, channels and pits. Affinity varied with scale: a channel at one scale might be located on a plane or peak at a broader scale — or vice versa. A single map (instead of six) could be produced by assigning each point to its modal class, over a range of horizontal scales (from 100 to 3700 m). An entropy map showed the degree of uncertainty in this assignment.

Deng and Wilson (2008) also measured 'peakness' across a range of spatial scales. This was based on four criteria: local relief, local mean slope gradient, relative altitude in a wider area, and (low) number of local (competing) summits. Each property was related to its maximum and minimum at that scale, and combined as a weighted sum between 0 and 1. Various modifiable thresholds are involved. Properties of the class 'peak' at each scale provided a comparator from which the 'peakedness' of each pixel could be calculated, providing fuzzy areas of peak entities. These are 'fuzzy' in terms of boundaries, varying typicality and non-uniform contents. I prefer to keep the term 'peak' for a point, but these fuzzy areas can provide a further definition of 'mountains'.

In a glaciated mountain area, Arrell et al. (2007) classified slopes of varying degrees of divergence, convergence or planarity, and ridges, at four scales (horizontal resolutions, grid meshes from 50 to 400 m). Each classification was 'defuzzified' by using the class for which membership (on a 0–1 scale) was greatest, except that if the ratio of the second membership to the largest exceeded 0.6 the point was identified as an 'intergrade'. They found that ridges and low-gradient planar areas – 'extreme morphometric classes' – were persistent, in that they occupied similar areas at all resolutions. The various types of slope, on the other hand, varied considerably with resolution. The classes identified could be regarded as types of elementary form.

The main value of the 'fuzzy classification' concept seems to be the recognition and measurement of uncertainty in classification of pixels. If the concept were applied to whole landforms, specific geomorphometry could be applied in the traditional way only once defuzzification was applied. A more advanced application would be to delimit a core and periphery of each landform, or a series of outlines based on different membership thresholds, and produce multiple measures of attributes such as length, height and gradient, leading to a best estimate (e.g. weighted average) bounded by a range of uncertainty. That this requires considerably more computation should no longer be an obstacle. Scatter plots would become plots of crosses showing uncertainty in x and y (as, for example, in sea level chronologies) rather than points.

I know of no specific geomorphometry study where the characteristics of the 'leftover' land surface between the delimited landforms are analysed. This has seemed irrelevant to studies focused on the identified landforms. It may, however, be relevant to the interpretation of differences between regions: the specific landforms are components of a land system at a broader scale that incorporates the whole surface. In the case of drumlins, whether they rest on a plain, on undulating topography, or over a series of transverse valleys, makes a big difference to their development and morphometry. For context, therefore, I recommend relating specific geomorphometric studies to the general geomorphometry of the region and/or of the excluded land surface.

6. Landform scale-specificity and allometry

Two general concepts of size and shape, applicable to any set of specific landforms, are of interest. Given a set of measurements of a type of landform, many workers quote the range in size of 'most' of the forms, which is rather vague; the overall range, maximum–minimum, is precise but is an unstable and often unrepresentative statistic. The inter-quartile range is better, but pays no detailed attention to the tails of the distribution. The trouble with using

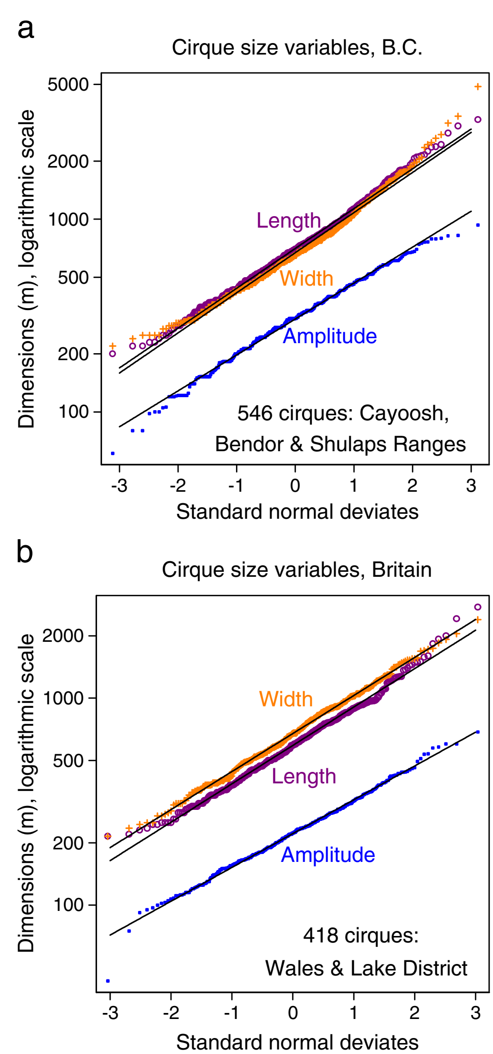

Fig. 4. Quantile–quantile plots of cirques in (a) British Columbia (Cayoosh, Bendor and Shulaps Ranges of the southern Coast Mountains), and (b) Wales and the English Lake District. The x-axis is in standard deviation units. For the method used see Cox (2005).

symmetrical pairs of other percentiles, such as 90–10, is that so many alternative pairs exist. Thus, I prefer to use the standard deviation, on a scale which is not too skewed. For most size variables, this means using a logarithmic scale to reduce positive skewness. (L-moments calculated using linear combinations of the ordered data reflect all percentiles and provide promising, robust alternatives to standard deviation and moment-based skewness (Hosking, 1990). They have often been used in hydrology and climatology but have as yet seen little application in geomorphology.)

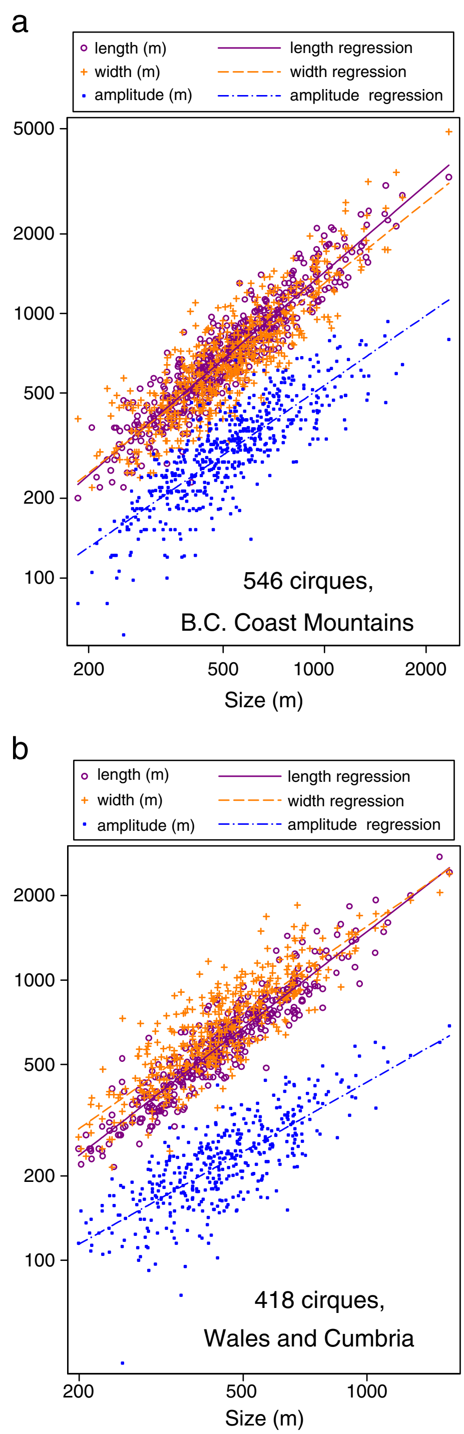

Fig. 5. Allometric plots of cirques in (a) British Columbia (Cayoosh, Bendor and Shulaps Ranges of the southern Coast Mountains), and (b) Wales and the English Lake District. Vertical scales are dimensions in metres.

For both drumlins and cirques (Evans, 2010 table 5 and p. 145) the resulting geometric standard deviations of length are around 0.2 on a $\log_{10}$ scale; this is equivalent to multiplying or dividing by $10^{0.2}$, i.e. by 1.6. Combined with symmetrical histograms, and linear quantile–quantile plots (Fig. 4), this is good evidence that the distributions are unimodal and the landforms are scale-specific. The log-normal (log-Gaussian) model may be accepted as a first approximation, and regressions and correlations should be performed on logarithmic scales. The main differences between the two data sets in Fig. 4 are that the British Columbian cirques are longer (geometric mean 705 m cf. 591 m for the British) and higher (geometric mean amplitude 301 m cf. 221 m). Geometric mean widths are 670 m and 674 m respectively. Geometric standard deviations are higher for British Columbia, but all are between 0.16 and 0.21 ($\log_{10}$ scale).

Evidence from the literature, reviewed for example in Evans (2003), suggests that similar considerations apply to other glacial and fluvial bedforms, to sinkholes (dolines), karren, karst towers, tors, impact craters, pingos, volcanoes and to some tectonic forms: all are scale-specific, regionally if not globally. The magnitude–frequency distributions of landslides, which cover a greater range of scales than cirques, have of late generated some controversy. They follow a power law (a negative Pareto distribution), but only over a limited range of scales. With due allowance for the 'censoring' of distributions – distortion by the incompleteness of detection of smaller features or the infrequency of very large features– I conclude that landslides too are scale-specific, especially for particular types or for clusters produced by single events (Evans, 2010). The lower size limit reflects a threshold 'critical mass': the upper size limit may reflect the frame, the available slope relief.

A further type of scale-specificity is where breaks in slope occur in plots of frequency against size, as in some landslide distributions (Brardinoni and Church, 2004), or of one dimension against another, for example the depth and diameter of impact craters (Pike, 1980). In these cases, scaling is combined with scale-specificity. More generally, scaling is observed within the single order of linear magnitude (two orders of areal magnitude) embraced by drumlins or cirques. Fig. 5 shows how different size variables scale with a combined, overall measure of size (the cube root of length × width × vertical amplitude). Again the greater lengths and amplitudes in British Columbia are noticeable, but the gradients of the three logarithmic regressions are very similar in the two study areas. The vertical amplitude of cirques increases with overall size more slowly than do length and width. With 95% confidence limits, the respective exponents are 1.10 ± 0.04 and 1.14 ± 0.04 for length, 1.03 ± 0.05 and 1.03 ± 0.07 for width, and 0.88 ± 0.05 and 0.83 ± 0.07 for amplitude, for British Columbia and Wales plus Cumbria respectively. The confidence intervals on amplitude exponents are far from overlapping the others, showing that rate of change of amplitude with size is lower than that of length and width, at a high significance level.

Cirques exhibit static allometry (Evans, 2006b; 2010): the shape of cirques varies with size. Unfortunately, it is not possible to observe change over the long periods of time involved in cirque formation. For rapidly changing bedforms, such as aeolian and fluvial dunes, frequently repeated field survey might test allometric growth directly. With modern observation techniques dynamic allometry – true allometric growth – can be established for mobile bedforms in the laboratory. Nevertheless the static allometry of scale-specific landforms shows that scaling is compatible with scale-specificity. This implies that the limits to observed scaling should always be stated; the existence of limits generates further hypotheses.

7. Hillslopes in fluvial basins: what are the landforms?

Scaling over broader ranges is observed in drainage networks. These have a long history of manual analysis by specific morphometric methods (Chorley, 1969). Much of this is based on lines and networks rather than areas. Channels, floodplains, landslides and fans are easily delimited and have been studied by specific geomorphometry, but hillslopes have more often been treated differently. Although hillslopes or hillsides are generally recognised as landforms, they have rarely been analysed as areal patches. Rather, they have been studied as profiles (Pitty, 1971; Young, 1972). This may be because in well-dissected terrain hillslopes cover almost all the landscape; or because although it is easy to delimit upper and lower boundaries (at ridges or crests and channels or floodplain margins), lateral boundaries are generally indistinct. Nevertheless, profiles can only take us so far in analysing the 3-dimensional surface and further methods are needed.

MacMillan and Shary (2009) illustrated five different classifications of form elements (or of local surface shape) based essentially on plan and profile curvature: for example convex, straight or concave in plan, and in profile. They pointed out a disadvantage in schemes that recognise 'straight' in plan: the results depend on whether plan (contour) curvature or tangential curvature is used. Any of the five classifications can be applied to any point on the surface, and mapped automatically: they are properties of the land surface rather than classes of landform. By fitting generalised surfaces, they can be applied to elementary forms in the sense of Minár and Evans (2008). Also many landforms can be forced into one or other of these curvature categories, but other properties such as elongation, gradient and position may be more important in defining landforms. Most geomorphologists use variables and form classes related to the gravity field, but Shary (1995) and Shary et al. (2002, 2005) also recognise a set of field-invariant morphometric variables such as unsphericity, mean curvature, and total Gaussian curvature, and forms such as C-depressions, dimples in the surface that are open and, thus, do not accumulate water.

Starting from DEMs, surface-specific points (peaks, passes and pits) and lines (ridges and channels) can also be defined automatically at a given scale. Break lines and inflections, however, are more useful in delimiting basic units. These small patches of near-uniform morphometry are termed elementary forms by Minár and Evans (2008): see the application by Mentlík et al. (2010). They are basic geomorphological objects; they cover the whole land surface and each is united by homogeneity in altitude, slope, curvature or change in curvature, and bounded by break lines or inflections in one or more of these local surface derivatives. The positions of elementary forms within the hillslope and drainage basin may then be used to specify the broader spatial structure, and used as the basis for classification. Drăguţ and Blaschke (2006) first define forms from homogeneity in elevation, profile curvature, plan curvature and slope gradient, and then classify these in terms of slope position. Given fine-resolution data, such as DEMs with 1 m grid mesh, classification of the whole surface directly from pixels or grid points is inefficient and potentially misleading: areal geomorphological objects should be generated first (Drăguţ and Blaschke, 2006; Strobl, 2008).

Definition of elementary forms has as yet been subjective, part of geomorphological mapping (Mentlík et al., 2010). Theory suggests that more objective, repeatable definition should be approached from two directions: the recognition of breaks in slope and curvature to provide boundaries, and the measurement of internal uniformity. A basic problem, still to be solved, is the trade-off between the sharpness of a break, the degree of a change, and the lateral continuity, all of which make it more useful as a landform or elementary form boundary. Clear boundaries rarely close completely around a landform so, as in the case of cirques, compromises must often be made in closing them.

The landscape position of elementary forms can be described as upper, middle and lower slope or footslope, and terms such as crest/interfluve, buttress/nose, hollow/open depression, hillock and ridge can be applied (Speight, 1990). Types of elementary form that take position into account may be termed land elements, after Schmidt and Hewitt (2004) and Schmidt and Andrew (2005). MacMillan and Shary (2009) have applied such classification to large areas, for ecological interpretation, and Drăguţ and Blaschke (2008) have satisfactorily classified coarse (90 m) radar data. Association of land elements in a toposequence leads on to the landscape scale of analysis. Skidmore (1990) quantified slope position in a DEM by first defining a ridge network and a stream network. Relative position is (distance to nearest valley cell)/(sum of distances to nearest valley cell and nearest ridge cell). The critical phase here is agreeing on the limits of the two networks. MacMillan et al. (2009) analysed vertical as well as horizontal relative position.

Whereas Minár and Evans (2008) emphasise homogeneity in local properties before considering position, MacMillan et al. (2000; 2004) and MacMillan and Shary (2009 figs. 10 and 12) recommend defining landform elements on the basis of slope position as well as surface derivatives. They start by delimiting local catchments of downslope and notional upslope flow and intersecting these to define 'hill sheds'. These are landforms (functional regions) rather than elementary forms (formal, homogeneous regions), and are likely to contain several of the latter. See also the valley-side basins delimited by Rasemann et al. (2004). Hill sheds could form the basis of repeated landform patterns (land systems). The use of drainage tracing is also at the basis of the TAPES-C approach to fluvial landscapes outlined and applied in Wilson and Gallant (2000).

Such a mosaic map, dividing an area exhaustively and uniquely into sets of qualitatively different patches, can be analysed quantitatively in terms of proximity or contiguity of these sets. Considering the boundaries between, say, type i and type j, the number of boundary segments n_{ij} can be counted to give a matrix of proximities. This can be the evidence for a toposequence in three dimensions, down-valley as well as down-slope. More precisely, the length of common boundary l_{ij} can be measured (in a GIS, not manually). It may be necessary to standardise entries in this matrix by expressing each as a proportion of the total length of boundaries of i and j combined. Finally, the characteristics of each boundary segment can be measured and summarised: the average altitude and the average change in gradient at each boundary segment, and the difference in average altitude or other properties between the adjacent patches, can be assessed.

It would be interesting to see such analysis applied in geomorphology and landscape ecology. In structural geomorphology, Minar et al. (2011) have measured the change in average altitude across the boundaries of geomorphometric regions, but few other examples exist.

In summary, classificatory (atomistic) approaches to well-dissected fluvial topography still pose many challenges (Cox, 1978). Until they are fully solved, the application of profile analyses and of general geomorphometric techniques to drainage basins remains a safer option. But fluvial topography is not the most difficult terrain for the recognition of landforms and the application of specific geomorphometry.

8. Plains and difficult terrains

Further topographies exist, not discussed above, where specific morphometry encounters difficulties. One is very extensive plains, as in savanna regions such as central Chad, where no clear breaks or changes in the topography occur for tens or hundreds of kilometres. Also on extensive fluvial plains, such as the Indo-Gangetic, the only interruptions are river channels. Past channels may be mapped, but their surface expression is often more subtle than anthropogenic features on the surface.

Rather than recognising very extensive elementary forms, most of us would revert to general geomorphometry in such situations. Unless channel beds are included, these plains have very low standard deviations of altitude and of slope gradient, very low mean slope gradient and, thus, near-zero profile curvature. Plan curvatures, however, can be extreme — witness the intricate contours on floodplains. It may be useful to recognise regional slopes, governing the general

Fig. 6. A difficult terrain for specific geomorphometry: view northwest from Jebel Musa, Sinai, Egypt.

direction of flow. This would certainly be the case on submarine fans bordering abyssal plains, as it is for rather steeper subaerial fans.

Etched or scoured, largely rocky surfaces (such as southern Sinai, Fig. 6) are a different problem. Further examples are the glacially scoured Shield areas of Canada and Fennoscandia, the etched karst of Guangxi in south China, the inselbergs of southwest Jordan, and numerous other granitic terrains. Considering maps such as those in Thomas (1994), it would be possible to measure the shape, size and mutual relations of each outcrop, bounded by plain or by major joints. Alternatively, it would be less work to perform a general geomorphometric analysis of the whole region. Comparison of the two approaches would be interesting.

9. Study areas for general geomorphometry

Given these difficulties with specific geomorphometry, general geomorphometry should be more widely used. It is, indeed, generally applicable. Also "Studies of process… are much more easily harmonised with local or global representations of the Earth's surface in terms of fields of elevations, rather than with quantitative or qualitative representations of shapes or forms." (Mark and Smith, 2004 p. 81). Early studies (Evans, 1972) were restricted to local properties (altitude, slope and curvature distributions and interrelations), but once drainage tracing and positional variables could be computed for large data sets they became a major part of general geomorphometry (Dietrich et al., 2003; Wilson and Gallant, 2000).

General geomorphometry has an inherent diversity based on the way in which study areas or cases are defined. I suggest an essentially three-fold division:

1. *Arbitrary areas* such as map sheets, rectangles or circles. This is easiest, as it is the way data are provided, and convenient in that a series of cases of the same areal extent may be compared. But boundary effects are a problem when drainage tracing and regional variables are calculated.
2. *Drainage basins*. These are most evidently appropriate in fluvial landscapes (Chorley, 1969), but can be useful elsewhere. Many studies use overall attributes of drainage basins (shape, drainage density) or relate attributes to stream order, but application of general geomorphometry implies analysis of distributed attributes and interrelations.
3. *Mountain ranges* or other landforms. Mountain ranges are in many ways the dual of drainage basins, and are delimited by valleys and low passes (that is, they are more extensive than 'mountains' discussed above). They are natural units for analyses where variation with altitude is important, as for glacial features (Evans, 2006a). Mountain ranges are in themselves broad-scale landforms, and general geomorphometry can be applied also to the variability of altitude, slope, and curvature within any definable landforms, or landscapes with repeated landform patterns (land systems).

The land surface can be divided exhaustively and uniquely into map sheets (approximate rectangles), into drainage basins (bounded by divides) or into mountain ranges ('hills', bounded by thalwegs and passes). Unlike map sheets, basins and ranges cannot in general have equal areas, but each can claim to be natural divisions for some purposes, and they can be defined algorithmically. If a large area were divided into approximately equal numbers of each of these types, the summary statistics should not be expected to be similar. Each type of division can be the basis for quantitative characterization of topography, but basins and ranges are more likely to lead to interesting comparisons — of process relevance.

10. Geomorphological mapping in a GIS environment

To most Europeans, 'geomorphological maps' mean comprehensive multi-colour, multi-layer maps covering morphography, morphometry, genesis, current processes, materials (lithology, structure) and chronology, plus a base map, such as the two German series (Barsch and Liedtke, 1980). Most North American and British scientists, on the other hand, regard comprehensive geomorphological maps as too complex and difficult to read — especially if the legend covers more space than any map sheet. They see major problems in integrating so much information on one map, overloading the power of the human visualisation system. They prefer simpler and clearer maps focused on a group of related landforms

(Evans, 1990), even if this means ignoring other aspects of the land surface. In other words they are more specialised and more in tune with specific geomorphometry, but at risk of missing interactions between different geomorphic systems. Some convergence has occurred, as the legends of comprehensive coloured geomorphological maps have tended to simplify some components, for example in Dutch (de Graaff et al., 1987) and Italian examples (Pasuto et al., 2005) which have little chronological or morphometric information. A Greek view of traditional geomorphological mapping, abundantly illustrated and with many proposed symbols, is given by Pavlopoulos et al. (2009). Further simplification may be required to incorporate maps into GIS (Gustavsson et al., 2006, 2008).

The rationale of putting everything on one map was to permit visual interrelation of the different components. This was generally unsuccessful in correlating spatial patterns because of the non-relevant information interfered; comprehensive maps permitted 'data mining' by reading off the various attributes of a particular point, rather than giving a synoptic view of spatial patterns. A successful multi-layered GIS (Minár et al., 2005; Gustavsson et al., 2008) avoids these problems by permitting any one layer to be viewed with any other, and coded subsets of any layer to be used. Together with the use of simpler, clearer, more specialised maps, this has revived interest in geomorphological mapping (Paron and Smith, 2008; Pavlopoulos et al., 2009; Smith et al., in press). Modern computing has also provided many new ways, including animation, of visualising complex data (Dykes et al., 2005).

The general-purpose geomorphological map may be dead, but long live geomorphological maps! With the abundance of data now available, and the range of visualisation techniques, geomorphological mapping is more important than ever before.

11. Discussion and conclusions

I have attempted to relate geomorphometry to geomorphological mapping through their common dependence on defining and delimiting landforms and elementary forms. This leads to fuller development of concepts of specific and general geomorphometry. As yet, both have rarely been applied together and compared in a specific landscape. Specific geomorphometry is clearly more applicable to some landscapes than to others, and the number of studies published reflects these differences. Landscapes of bedforms and of distinct erosional forms lend themselves to specific geomorphometry of areal forms, whereas analysis of fluvial landscapes is more often linear-based: both, of course, should have a vertical dimension. Point-based analysis seems less applicable, because most features of interest (most geomorphological objects except for peaks, passes and pits) have linear or areal extent. (Point pattern analysis has been applied for example to drumlins, but it is problematic because each drumlin covers an area that is large relative to the separation of drumlin centroids.)

Specific morphometry can lead on to various types of generalisation, including scale-specificity and allometry. We are much more likely to define types of feature as 'landforms' if they have limited and characteristic size ranges. Scale specificity relates either to process thresholds or to the scale of controlling frameworks (e.g. relief of a whole valley-side, for mass movements) (Evans, 2003; 2010).

Cox (1978) objected to 'atomistic' approaches to subdivision of the land surface. Cox makes the case that extracting patches from a continuous surface is unphysical in that the whole surface forms together (Cox, 2007, and personal communication, 2010), whether subaerial, subaqueous, supraglacial or subglacial. Diffusive processes tend to flatten the surface, limiting relief and slope gradients and blurring boundaries. The demand for subdivision of the surface into manageable objects, however, continues and even grows — for example among soil scientists (MacMillan et al., 2004; Deng, 2007; and chapters in Hengl and Reuter, 2009). A psychological need to subdivide seems to exist: also processes such as undercutting, incision and faulting produce numerous breaks in slope that provide useful, non-arbitrary boundaries. In geomorphometry and in geomorphological mapping, both general and specific (i.e. both continuous field and object-based) approaches are needed, and are complementary.

One facet that has been missing from most quantitative work is the spatial pattern of areas (rather than points or channel networks). Scope exists to develop mosaic analysis for 'patch maps' where the whole area is allocated to one form or another; contiguities are of genetic significance, and relative positions affect current processes. Some ideas are discussed in Fortin and Dale (2005, ch. 4), in an ecological context. Further development is needed for patches such as drumlins and cirques which do not occupy the whole surface: representation as points is problematic, but Fortin and Dale (2005 p. 64–75) discuss definitions of neighbour and the use of Minimum spanning trees. The importance of land systems implies that we should relate landforms to context (MacMillan et al., 2004; Deng, 2007), to position within the broader system, but this has rarely been quantified. Studies of systems are now well entrenched in process geomorphology: the components produced by geomorphological mapping and analysed by specific geomorphometry should, accordingly, be reassembled and interrelated quantitatively. Object delimitation should be followed by contiguity and contextual (positional) analysis and system synthesis.

The land surface of Earth is complex because of the range of processes that have fashioned it from a variety of materials, and to the way these processes have changed over time, both interacting and alternating. Even if the view of the surface is simplified to a single-valued function of latitude and longitude (no pipes, caves, overhangs or vertical slopes), and human modifications are excluded, the land surface cannot be represented accurately by any mathematical model with a small number of parameters (Evans and McClean, 1995; McClean and Evans, 2000). Such models (e.g. fractal or spectral; also Fourier series and other families of polynomials) have uses, but it is dangerous to regard them as realistic, or even as capturing the essence of a real land surface. The science of geomorphology has devoted much effort to classifying land surfaces and to recognising specific surface features (landforms and elementary forms) and measuring relationships between surface attributes. Specific global and regional scales are recognised in the form of the land surface. We need to apply both specific and general geomorphometry, and to supplement multiple geomorphological maps with numerous geomorphometric maps, interrelating them in a GIS environment.

Apart from demonstrating the scale-specificity and static allometry of many landforms, this paper has reviewed semantic and conceptual frameworks for mapping and analysing landforms. Situations where specific or general geomorphometry are appropriate have been discussed. The importance of fine resolution DEMs, especially LiDAR, for this enterprise has been emphasised, and a number of proposals for further work have been made. Some parts of the land surface belong to more than one landform, and there are 'leftover' areas difficult to allocate. Classification, therefore, need not be exclusive, or exhaustive: nesting and superposition occur, and hierarchies are common.

Algorithms are needed that produce results that are consistent, and very accurate in approximating geomorphologists' views of landforms. We need to move from manual delimitation, whether on-screen or on printed images, to automated recognition and delimitation of landforms and elementary forms from DEMs. (Measurement of delimited forms is a more easily automated task.) Local properties such as altitude, slope and curvature are fundamental, but many forms need to be related to the flow network as position and context are important for their classification or recognition as land elements or types of landform. Extensive plains and highly irregular topographies pose special challenges.

In conclusion, a quotation from Chorley (1969, pp. 96–97) has proved highly prescient:

> "In the past, morphometric analysis from maps has been a rather tedious and time-consuming task, …. programming … promises to release the masses of data locked up in topographic maps and will obviously allow much more extensive sampling and generalisation of morphometric properties. Before too long these methods will be applied directly to the output from aircraft and satellite scanning equipment, obviating the necessity for the actual compilation of many maps." The 'Holy Grail' of full automation remains elusive, but progress has been made.

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