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Geomorphometry – diversity in quantitative surface analysis

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Abstract: A widening variety of applications is diversifying geomorphometry (*digital terrain modelling*), the quantitative study of topography. An amalgam of earth science, mathematics, engineering and computer science, the discipline has been revolutionized by the computer manipulation of gridded terrain heights, or digital elevation models (DEMs). Its rapid expansion continues. This article reviews the remarkable diversity of recent morphometric work in 15 selected topics and discusses their significance and prospects. The quantitative analysis of industrial microsurface topography is introduced to the earth science community. The 14 other topics are Internet access to geomorphometry; global DEMs; DEM modelling of channel networks; self-organized criticality; fractal and wavelet analysis; soil resources; landslide hazards; barchan dunes; harvesting wind energy; sea-ice surfaces; sea-floor abyssal hills; Japanese work in morphometry; and the emerging fields of landscape ecology and image understanding. Closing remarks note reasons for the diversity within geomorphometry, speculate on future trends and recommend creating a unified field of surface representation.

Key words: digital terrain modelling, geomorphology, geomorphometry, landform quantification, surface form, terrain analysis, topography.

I Introduction

The numerical representation of ground-surface relief and pattern has become integral to geography, geomorphology, geohazards mapping, geophysics and exploration of the earth's sea-floor and the planets. Combining earth and computer science with mathematics and engineering *(geo)morphometry* treats both specific landforms and continuous landscapes. The discipline is known variously as *terrain analysis* or *quantitative geomorphology*, although the newer term *digital terrain modelling* increasingly seems preferred (Lane *et al*., 1998; Pike, 1998). Dating back some 150 years to Alexander von Humboldt and later German geographers, geomorphometry is now undergoing an explosive growth fuelled by the computer revolution and digital elevation models (DEMs) – square-grid arrays of terrain heights that parameterize and display ground-surface form.

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Morphometry has evolved into a source of reliable methods to compute basin hydrographs, estimate soil erosion, map landslide susceptibility, predict the movement of groundwater, visualize topography and address innumerable other problems in the earth sciences and a number of engineering fields (Florinsky, 1998; Hodgson, 1998). This maturation is evident from the now-routine inclusion of terrain-modelling capabilities in geographic information systems (GIS) and the use of morphometry to analyse entire landscapes rather than just test new techniques or characterize small field sites (Ahnert, 1996; Clayton and Shamoon, 1999). The many techniques and tools of geomorphometry, as well as its conceptual basis and such philosophical issues as whether the discipline is a science in its own right, have been addressed elsewhere (Pike and Dikau, 1995: 221; Evans, 1998; Florinsky, 1998).

This article reveals the extraordinary diversity of recent advances in quantitative surface characterization. The need for an appraisal of this crossdisciplinary activity is particularly evident from the growing use of digital height data, at all resolutions, in many areas of science and technology – now including processes shaping microtopography in manufacturing (Thomas, 1999). (Traditional field and contour-map measurements remain essential for many applications.) The 15 topics reviewed here only begin to sample the broad scope of contemporary morphometry. They range from hydrogeology and fractals, modelling soil resources and landslide hazards, to sea-floor and desert geomorphology, and two emerging areas – landscape ecology and image understanding. The morphometric literature on most of these topics is vast. Recent contributions provide references to key prior work, but some older sources are included as background for such less familiar uses of geomorphometry as wind-energy prospecting and characterizing sea-ice surfaces.

II Morphometry online

The unique capacity of the Internet to concentrate information helps offset the growing diversity of geomorphometry and its practitioners, who are dispersed worldwide in many occupations. The broad range of morphometric material now residing on the Internet – digital data, computer programs, bibliographies and full papers reporting experimental results – can be consulted on the World Wide Web (WWW) and quickly downloaded. However, even web search utilities cannot locate specialized information on the Internet without extensive browsing of its ever-diversifying contents. To provide more immediate access to geomorphometry, Pike (1998) compiled 70 web addresses (http://earth.agu.org/eos_elec/97260e.html). These web sites link to many more. They emphasize the two essential ingredients of morphometry today, digital elevation data and the software to analyse them, a small sampling of which follows; WWW citations on other topics appear throughout this article.

Many programs are free for the downloading. They include Peter Guth's MicroDEM+ (ftp://ftp.nadn.navy.mil/pub/oceano/website/microdem.htm); several routines in GRASS – a public-domain GIS (http://www.baylor.edu/~grass/); and algorithms for the extraction of watersheds from DEMs by Scott Peckham (http://cires.colorado.edu/people/peckham.scott/RT.html), David Tarboton (http://www.engineering.usu.edu/dtarb/) and the late Ian Moore and others (http://cres.anu.edu.au/software/tapes.html).

Other software is licensed; for example, Mike Hutchinson's ANUDEM (http://cres.anu.edu.au/software/anudem.html) creates a 'hydrologically sound' DEM from irregularly spaced elevations, contour lines, and water courses.

Many broad-scale terrain data are free over the web. Among these are a global 30 arc-second DEM (http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html) that incorporates elevation contours from the 1:1 000 000-scale *Digital chart of the world*; a global 5 arc-minute DEM that includes bathymetry (http://www.ngdc.noaa.gov:80/seg/fliers/se-1104.html); updated bathymetry of the earth's entire sea-floor (Smith and Sandwell, 1997; Smith, 1998; http://topex.ucsd.edu/marine_topo/mar_topo.html); and the 3 arc-second DEM of the USA (http://edcwww.cr.usgs.gov/dsprod/prod.html). The status and availability of DEMs country by country may be checked online from Bruce Gittings (http://www.geo.ed.ac.uk/geoinfo/dem.send).

III Global data coverage – the prospect

However useful these existing DEMs, elevation data compiled from contour maps and other current sources must be regarded as interim only. The Global Positioning System (GPS), synthetic aperture radar and other advanced technologies hold the greatest promise for the fine-scale synoptic coverage of topography from which geomorphometry will realize its full potential. GPS has revolutionized geodesy, accuracy of heights now approaching the one-centimetre range (Wu and Lin, 1995), but thus far its morphometric uses are few (Twigg, 1998; Wilson *et al*., 1998). Although GPS has improved control for photogrammetry (Greening *et al*., 1994) and the levelling of existing DEMs, it is not yet a direct means of DEM production. Measuring the large number of GPS heights required for a dense DEM remains uneconomical (Jeyapalan, 1995), and only small areas have been contoured at high accuracy from GPS data (Fix and Burt, 1995; Wilson *et al*., 1998). However, these problems are likely to be solved in the near future.

Synthetic aperture radar interferometry (InSAR or IFSAR) has more immediate potential for DEM production. Not as new or accurate a technique as GPS, InSAR is important for its planned deployment on the Shuttle Radar Topography Mission (SRTM), a USA government project to map the world's topography in the year 2000. Hardware modified from current instrumentation will image 80% of the land surface between 60° N and 56° S latitude. From these data a global DEM, at an anticipated spatial resolution of as little as 3 m locally (10 m worldwide), is to be created (Meade and Sandwell, 1996). Much attention has been given to evaluating and improving the quality of the anticipated InSAR measurements (Mrstik *et al*., 1996). Global DEMs, at a resolution equivalent to a 1:50 000-scale map, are also forthcoming from yet another orbital technology, ASTER, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (Welch *et al*., 1998).

IV Digital hydrogeomorphology

Modelling of fluvial systems from digital elevation data continues to lead all other developments in morphometry (Blöschl and Sivapalan, 1995; Burlando *et al*., 1996; Rodríguez-Iturbe and Rinaldo, 1997; Pelletier, 1999). Many subareas are active. These include adaptation of stream-branching topology to networks of valley glaciers (Bahr and Peckham, 1996), further development of the popular DEM-based TOPMODEL algorithm for simulating watershed hydrographs (Beven and Kirkby, 1997) and experimentation with both interactive (Pilotti *et al*., 1996) and fully automated (Peckham, 1995) approaches to extracting stream networks and drainage basins automatically from DEMs.

Refinements continue to improve results from the DEM-to-watershed transformation (Brändli, 1996; Tarboton, 1997; Rieger, 1998). Special attention has been accorded problems posed by low-relief topography (Martz and Garbrecht, 1998) and the inclusion of lakes (Mackay and Band, 1998). Emphasis in network mapping is shifting from simply automating the transformation to assessing accuracy of the results, both the numbers of extracted drainage cells (Lee and Chu, 1996) and uncertainty of the delimited catchment boundaries (Miller and Morrice, 1996). Aside from biases built into specific DEM-to-watershed algorithms, fidelity of the resulting drainage nets, basins and parameters appears to depend primarily upon accuracy and spacing of the input DEM (Lagacherie *et al*., 1996).

V Fluvial self-similarity

Channel networks extracted from DEMs and satellite images are used to build spatial models of drainage system topology (Rinaldo *et al*., 1998; Stølum, 1998). The current focus is on understanding the scale dependency of networks, notably their degree of self-similarity as expressed by fractal measures (Rigon *et al*., 1996; Costa-Cabral and Burgess, 1997). The study of scaling in topography is so active (Xia and Clarke, 1997) that its many findings, some of them contradictory, have yet to be resolved. Nikora *et al*. (1996) reviewed the prevailing conclusions on fractal structure of channels and their networks and found no common point of view among investigators. The lack of agreement extends from the validity of fractality itself to applicability of the recently emergent concept of self-organized criticality.

Recent experiments on the spatial organization of river networks from DEMs have linked their observed fractal and multifractal structures with models of self-organization (Rodríguez-Iturbe and Rinaldo, 1997; Stølum, 1998; Pelletier, 1999). This connection has led some investigators to ascribe the spatial orderliness of stream patterns to *self-organized criticality*, a concept adapted from physics and claimed to have much interpretive capability in geomorphology (Hergarten and Neugebauer, 1996; Murray and Paola, 1996). Self-organized criticality is a dynamical state related to principles of energy dissipation (Phillips, 1995b). It is characterized by fractal (power-law) scaling in space and time, related to the occurrence of spatiotemporal chaos and intermittency in the operation of (here, land-shaping) processes (Sapozhnikov and Foufoula-Georgiou, 1996; Stølum, 1996).

The explanatory power ascribed to self-organized criticality (Takayasu and Inaoka, 1992) has not gone unchallenged (Agterberg, 1998). While accepting the self-affinity and self-organization of many fluvial systems, Sapozhnikov and Foufoula-Georgiou (1996) argue that current models of river networks and landscape evolution do not exhibit the necessary critical states. These authors also raise concerns over testing hypotheses on the multifractal character of topography by resorting more to computersimulations (Stølum, 1996) than to field or map-derived landscapes. Without more empirical morphometric data, perhaps all that can be concluded of this new development is that 'while . . . geomorphic evolution *can* be self-organizing, it would not be accurate to say it *is* self-organizing' (Phillips, 1995b: 318). Some broader theoretical consequences of this work are developed in Phillips (1995a).

VI Fractals and wavelets in continuous terrain

A reaction to earlier enthusiasm over the putative self-similarity of topography across many scale lengths is also emerging (Beauvais and Montgomery, 1997; Xia and Clarke, 1997). It is essential, first, to distinguish the two modes of fractal characterization now prevalent for terrain: that of planform pattern (X,Y), typically of discrete stream channels (Rinaldo *et al*., 1998), and that of continuous elevation, or relief (Z) (Outcalt *et al*., 1994). The two describe quite different attributes of topography (Pelletier, 1999, addresses both). Although some spatial measures of fluvial networks appear to be fractal, attributes of relief may not be unifractal (monofractal) at all and at most multifractal (Evans and McClean, 1995; Evans, 1998). In reviewing fractal measures of continuous terrain, Xia and Clarke (1997) noted 'still no agreement'. The west coast of Great Britain, widely regarded as a classic fractal planform, is not statistically self-similar over its measured scale range (Andrle, 1996). Of computer-drawn fractal landscapes, Rouvray (1996: 84) observes 'The initial impression of realism is soon followed by the realization that this is an entirely artificial construct'. Qualification of claims initially made for terrain fractality mark a healthy step towards a more measured incorporation of the concept into geomorphology.

In testing for scale dependence in topography by computing relief and planimetric attributes of continuous landscapes, Gallant and Hutchinson (1996) and Gallant (1997) also found the fractal model inadequate. Building on spectral analysis, they have introduced *wavelets* to landform morphometry. This statistical method decomposes a topographic surface into a set of oscillatory functions at different frequencies in a similar manner to the Fourier transform. The wavelet transform employs localized functions (wavelets) rather than infinitely repeating sine and cosine functions. Among its advantages over the elevation-variance spectrum are a better representation of azimuthally nonhomogeneous terrain and the provision of spatially variable descriptions. To accomplish this, wavelet analysis superposes multiple mathematical 'features' at various scales.

The modelled feature chosen by Gallant (1997) to develop the wavelet method for three Australian DEMs is elliptical in plan with a smooth polynomial profile, the simplest geometric form of sufficient flexibility to represent most surfaces. Gallant's experiments identified at least three numerical parameters – terrain 'complexity,' 'positivity,' and 'orientation.' These quantities almost certainly relate to descriptors computed by other approaches to terrain morphometry. Further work should investigate correlation with such standard measures as drainage density, elevation skewness and slope azimuth. While the results of this pioneering effort are difficult to judge now, few other wavelet studies having addressed natural topography (Kumar and Foufoula-Georgiou, 1997), wavelet analysis promises to be an active area of ongoing inquiry in geomorphometry.

VII Soil–landscape relations

As the world's population and its need for food increase, so does morphometric research in agriculture. Measuring the fine to microscale geometry of field surfaces to model soil–landscape relations has long been intrinsic to agricultural engineering (Desmet and Govers, 1997; Saleh *et al*., 1997), but assessments of soil resources from broad-scale terrain geometry are new. Recent work equates soil properties with topographic measures computed from DEMs. Specific goals include inventories of arable land, mapping soil types and estimates of soil erosion. Earlier, Klingebiel *et al*. (1987) combined three parameters with aerial photos and topographic maps to survey soils in the western USA. Field evaluations revealed that their DEM-based data were accurate except in arid areas of both sparse vegetation and low slopes. Odeh *et al*. (1994) used the geostatistical techniques of kriging and cokriging of such DEM measures as slope curvature, combined with multiple regression analysis, to predict gravel content and other properties of soils in Australia. In later Australian work, Gessler *et al*. (1996) found that digital terrain attributes were not only good predictors of soil patterns and carbon stored in the soil but also provided pointers to the driving processes in the landscape. Gessler (1996) further showed that predictive capability declines markedly as DEMs lose resolution of hillslope detail – typically at grid spacings exceeding 40 m.

Among the most recent work, Arrouays *et al*. (1998) improved predictions of carbon storage in the first 30 cm of topsoil by calculating nine measures from a 100-m DEM. Slope steepness was the only significant control of carbon variability, but it explained over 60% of the variance. DeBruin and Stein (1998) clustered measures computed from a 5-m DEM to map soil-landscape types in a small drainage basin in southern Spain. Elevation, slope, curvature, and stream-power and wetness indices discriminated three soil types and their transition zones: alluvial terrace, divergent slopes low in the valley and dry areas higher in the basin. In comparing GIS-based estimates from the Universal Soil-Loss Equation (USLE) – which incorporates slope steepness and length – at grid spacings from 30 m to 6 km, Molnár and Julien (1998) showed that DEM spacings over 100 m underestimate soil erosion for two large watersheds in Mississippi, USA. Their simple correction factor enables the USLE to be applied at macroscales and in different climate regimes. Finally, Thompson *et al*. (1997) quantified relations between spatial patterns of terrain attributes from a 10-m DEM and patterns of a colour index associated with the occurrence of hydric soils in the glaciated landscape of Minnesota, USA. They found that slope gradient, profile curvature and local relief explained up to 65% of the index variation. Availability of regional DEMs from satellite data will extend these and other survey tools to larger areas.

VIII Landslide hazards

Slope failure levies a costly 'environmental tax' on society, particularly in urban areas that have expanded from early settled flatlands into surrounding hills. Damage from landslides across coastal California during 1997–98 El Niño rainstorms and heavy loss of life in Central America and the Philippines later in 1998 underscore the seriousness of the problem. Losses can be mitigated through a better understanding of slope failure and by mapping its likely spatial extent (El Niño Response Group, 1998;

http://elnino.usgs.gov/landslides-sfbay/). Because landslide activity correlates closely with slope angle and other attributes of ground-surface form that can be measured, increasingly from DEMs, slope failure is perhaps the natural hazard most amenable to mitigation by incorporating geomorphometry into its analysis and mapping (van Westen *et al*., 1997). Many studies have resulted.

Two approaches, landslide specific and regional, use methods of terrain quantification to model slope failure. By the first, and more established, approach landslides or the drainage basins in which they originate are considered individually, as discrete landforms (Jakob and Bovis, 1996). Measurements from field survey or contour maps are taken of landslide or catchment length, breadth, volume, planimetric shape, compass orientation and height of head scarp. These quantities are compared with each other and with bedrock and soil properties, local hydrometeorology and other physical characteristics to isolate causative factors and model the mechanics of the process (Bhandari and Kotuwegoda, 1996; Hylland and Lowe, 1997).

Availability of large DEMs and GIS technology has led to the second, regional approach wherein ground steepness, curvature and other measures that relate to landsliding are computed continuously over extensive areas (Cross, 1998; Rowbotham and Dudycha, 1998). The maps of terrain geometry are then compared and combined with digital maps of geology, materials properties and landslide inventories to delineate potentially hazardous areas (Brunori *et al*., 1996; Ellen *et al*., 1997). In both approaches to studying slope failure it is critical to distinguish different processes. The topographic and geologic conditions triggering debris flows, for example, differ markedly from those giving rise to slumps, slides and earthflows. Much new work on debris flow incorporates DEM-based analysis (Wieczorek *et al*., 1997; Boelhouwers *et al*., 1998; and Campbell *et al*., 1998). Chandra (1996), Fernández *et al*. (1996), and Cross (1998) used morphometry to map the extent of other types of rainfall-induced slope failure. Results such as these now need to be linked with the level of economic risk and incorporated into land-use regulation and emergency response (Campbell *et al*., 1998).

IX Barchan dune geometry

The migrating habit of barchans poses a chronic hazard of a very different sort – to dwellings, highways, railroads and other infrastructure of arid-area settlements (Al-Janabi *et al*., 1988; Khalaf and Al-Ajmi, 1993). These crescentic sand dunes are unique among landforms in that size, shape, degree of complexity and location all can change markedly over the life of the feature. Modelling the evolution of barchan forms and their migration rate is facilitated by the crisp definition and consequent ease of measurement of isolated dunes. In developing an understanding of barchan-shaping processes, dune length, cusp-to-cusp width, slip-face height and overall height, differences in cusp length and dune volume all have been measured in the field or from air photos – DEMs are not necessarily the most effective way to capture these attributes. Some dimensions correlate with dune spacing, rate of movement, wind direction and velocity and sand type and supply (Lancaster, 1989; Haff and Presti, 1995; Gay, 1999). These relations are important in predicting the speed and trajectory of migrating barchans.

The morphometry of barchans is currently unsystematic in several respects, which impedes understanding of the evolution of barchan form. Although in plan dimensions barchans vary from soup-plate sizes to several hundreds of metres across, available measurements are almost entirely of the larger dunes. Moreover, a 1:10 height:width relation is commonly assumed for barchans (Hastenrath, 1987; Hesp and Hastings, 1998), but not all data support this generalization, even for the large measured dunes (Embabi and Ashour, 1993; Gay, 1999). Although graphs from published dimensions (Hesp and Hastings, 1998) suggest that barchan height may be a nonlinear function of size, the size dependency of form has yet to be tested. Finally, not only is the nominal size-frequency distribution of barchans unknown, but more than one may exist – dunes in the Middle East (Embabi and Ashour, 1993) and the Sahara seem to be larger than those measured in Peru (Hastenrath, 1987) and the western USA (Haff and Presti, 1995).

To address these problems, measurements are needed to represent the entire size range adequately, particularly smaller, fast-moving barchans – which are so ephemeral they tend not to be measured in the field. Regional differences in size-frequency distributions need to be examined. Much work remains before the morphologic systematics of barchans are sufficiently well established to support the conclusions of form-process modelling throughout the observed size continuum of these features (Mulligan, 1995).

X Assessing wind-energy potential

Land-surface form is one of the two critical controls on the generation of electrical power from wind (Rohatgi and Nelson, 1994; Rathmann *et al.*, 1996). This renewable energy resource is growing; from 1990 to 1999 global capacity quintupled to 10 500 megawatts (http://www.risoe.dk/vea-wind/history.htm). Measures of terrain form computed from DEMs combine with meteorological data on seasonal wind speed and duration to identify promising sites for harvesting power from wind farms – large clusters of turbines (windmills) (Elliott *et al.*, 1991; Wendell *et al.*, 1993). The most favourable physiographic settings – open plains, tablelands and hilltops – are free of local obstructions; in mountainous areas, only exposed ridge crests and summits are suitable. Mapped estimates of wind-energy potential (Troen and Petersen, 1989; Elliott *et al.*, 1991) are accurate in flat terrain, but break down in more complex topography due to boundary-layer separation (Rathmann *et al.*, 1996; http://130.226.52.107/). DEM-based field experiments in a variety of rough terrains are testing and refining these predictions (Mortensen and Petersen, 1997).

Detailed topographic data help characterize near-surface air flow at potential sites for installing turbines. The position and morphology of terrain features upwind of a turbine are critical to its location (Wendell *et al.*, 1993). Local fine-scale turbulence governed by land-surface form determines not only a turbine's efficiency and cost-effectiveness in generating electricity, but also its wear and longevity and the resulting intervals for servicing (Rohatgi and Nelson, 1994). Even minor relief features off-axis from the upwind flow-path can have a significant effect. Computer modelling of the wind field, expected energy production and possible engineering constraints at a site has progressed from relatively simple algorithms (Morselli *et al.*, 1992) and now requires DEMs at several length scales and quite involved calculations (Glekas *et al.*, 1996; http://www.fluid.mech.ntua.gr/wind/jprosp/jprosp.html). Accurate windpower predictions in complex terrain require a DEM grid spacing no coarser than 50 m (Mortensen and Petersen, 1997).

Computer visualization also plays a role in the wind-energy industry. Landscape panoramas made from DEMs and other spatial data are used to assess the visual and aesthetic impact of planned wind farms, to select areas to be excluded and to identify terrain perturbations upwind of turbines (Matsuzaka *et al*., 1997). In the USA, 950 shaded-relief images made from 90-m DEMs are available in 1 degree blocks to supplement detailed topographic parameters in prospecting for wind power (Wendell *et al*., 1993; http://www.igc.org/awea/pubs/map1.html).

XI Morphometry of sea-ice surfaces

Numerical characterization of the earth's polar surfaces, commonly by remote sensing, contributes to an understanding of their radiation budget and related climatic behaviour (Etzelmüller and Sollid, 1997; Davis *et al*., 1998). Several types of surfaces are important. One of these is ridged sea ice (Kankaanpää, 1997), the morphometric properties of which are perhaps less commonly known than those of continental ice and snow. An ephemeral, seasonal landscape of the high latitudes, sea ice is also a major hazard to winter navigation (including passage by submarines) and a danger to offshore structures (Evers and Jochmann, 1998). Sea ice may be either undeformed, as initially frozen, or distorted by a number of processes. Although a field of deformed sea ice is level overall, its detailed morphology can be quite rough because of varying forms of ridged ice. *Pressure ridges* are irregular slabs of sea ice imbricated by wind, ocean currents and other agents. Although sea-ice ridges tend to be limited in vertical extent, they are complex and range greatly in size and shape.

Ridge morphology has been represented both statistically, by continuous profiling (Rothrock and Thorndike, 1980) and by measurement of specific features (Wadhams and Davy, 1986). The relief of pressure ridges has two principal components, the *sail* – that portion raised above the surrounding ice surface – and the *keel* – the (much larger) portion under water. Sail and keel surfaces are measured by field methods – drilling, sectioning and photography (Wadhams, 1981) – as well as by sonar (McLaren, 1988) and laser profiling (Lewis *et al*., 1993). As for barchans, DEM data are not a requirement. Distributions of height, depth, width, cross-sectional area, slope angle and spacing for sails and keels in different ice packs have been compared with each other and with theoretical models (Lowry and Wadhams, 1979; Wadhams and Davy, 1986; Kankaanpää, 1997). Pack-ice surfaces have also been modelled by the variance (power) spectrum and other techniques of random-field analysis (Lewis *et al*., 1993).

Several conclusions have been reached thus far: new (first-year) ridged ice differs significantly in geometry from older (multiple-year) ice; keel depth and ice thickness can be predicted from sail height; ridge size – but not shape – differs from locale to locale and with degree of ridge maturity; and keel profiles appear to have a fractal size-frequency distribution (Melling *et al*., 1993; Kankaanpää, 1997; Timco and Burden, 1997; Evers and Jochmann, 1998). Some of these generalizations are being incorporated into marine navigation doctrine and infrastructure planning – for example, where to avoid locating oil pipelines on the shallow sea-floor – and into models of atmospheric circulation and climate variability.

XII Abyssal hills on the earth's sea-floor

Analysis of sea-floor evolution from digital bathymetric data (Smith, 1998) complements the modelling of continental tectonics from DEMs (Seber *et al*., 1997; Demoulin, 1998). Recent sea-floor morphometry has focused on abyssal hills – small, elongate features created at mid-ocean ridge spreading centres along faults that offset fresh basalt sea-floor. Abyssal hills are the most common morphologic feature on the ocean floor, arguably rivalling subaerial drainage basins in frequency, but they remain (unlike seamounts, their larger sea-floor counterparts; Rappaport *et al*., 1997; Wessel, 1997) among the least understood of the earth's landforms. The hills are thought to form by some unknown combination of extrusive volcanism and faulting, modified by mass-wasting and sedimentation (Goff and Tucholke, 1997). Because abyssal hill morphology carries the imprint of processes and rates of ridge-crest spreading (Ma and Cochran, 1997), hill topography constitutes a major piece of the overall plate tectonics puzzle.

Quantitative approaches to explaining abyssal hill topography tend to be either *continuous* or *discrete* in exploiting the bathymetric data obtained by new technology (Smith, 1998). Emphasizing the chaotic appearance of continuous hilly terrain, 'observationalist' workers treat the problem more stochastically, via second-order statistics of abyssal hill dimensions and spacing (Goff *et al*., 1997). 'Physical modellers', on the other hand, emphasize the regular spacing of discrete deep-sea faults and their offsets in the hilly terrain and thus address the issue more deterministically (Malinverno and Cowie, 1993; Shaw and Lin, 1993).

Because the imaging systems currently available are still too coarse to permit accurate measurement of individual hills (Smith and Sandwell, 1997), abyssal hills are commonly analysed as continuous swaths of textured topography (Goff *et al*., 1997). Among the generalized measures by which this texture is captured are relief, azimuth, slope, slope curvature, ridge-parallel spacing, ridge-normal spacing and the proportion of coarse to fine-scale roughness (Shaw and Lin, 1993). Recently, Ma and Cochran (1997) statistically distinguished abyssal hill roughness from the basic shape of the ridge axis and processes other than faulting and volcanism have been found to modify the hills (Goff and Tucholke, 1997). In attributing abyssal hills to stretching of the oceanic lithosphere, Buck and Poliakov (1998) recently suggest that the process exhibits self-organized criticality. Their detailed modelling is important because it begins to reconcile differences separating the observationalist and physical modelling approaches.

XIII Geomorphometry in Japan

Japanese achievements in morphometry are not sufficiently well known outside that country. Some activity was evident even before the second world war, and postwar work was quick to explore the same geomorphic problems recognized elsewhere (Tokunaga, 1966; Hirano and Yokota, 1976; Kohchi, 1981). The pace has accelerated with recent advances in computers and digital data, although language differences still impede the communication of results (over half the works cited here are in Japanese). Morphometry in Japan typically is practised by academic geomorphologists and geographers, but also government technicians responsible for quantitative map-based input to land-use policy and public safety. The country is covered completely by several digital datasets (Japan was early in achieving 100% coverage), including topography and geology. Large-area morphometric analyses incorporating these data commonly feature the Japanese National Standard DEM at resolutions of 1 km or 250 m. DEM coverage at 50 m was completed in 1998 from digitized 1:25 000-scale contour maps. A comprehensive guide to all aspects of Japanese GIS and mapping activity is located at: http://www.cast.uark.edu/jpgis/index.html.

DEM-based research emphasizes regional slope-mapping and evaluation of the landslide hazard arising from both precipitation and earthquakes (Kobashi *et al*., 1985; Ohmori and Sugai, 1995). These are highly practical issues in the humid, mountainous and tectonically active Japan islands, where the population is concentrated downstream on alluvial flats flanked by steep slopes. Related concerns are accelerated Holocene channelling and sedimentation (Oguchi, 1996). Various digital-cartographic problems in manipulating DEM data have been encountered and solved (Shiono *et al*., 1985; Lu *et al*., 1995) and Japanese software for morphometry now includes multifunction packages based on image-processing concepts (Nogami, 1995). Important results include the three-parameter classification of Iwahashi (1994), who used the 1-km DEM to map 16 terrain types across all Japan – a major advance over prior taxonomy (Yoshida and Akojima, 1986). Among the most influential Japanese work is that of Takayasu and Inaoka (1992), who simulated the evolution of eroding stream networks and concluded that their fractal-scaled model showed evidence of self-organized criticality.

XIV Industrial surface topography

The earth sciences and industrial engineering converge in *surface metrology*, the roughness measurement of manufactured surfaces for quality control. This important application of morphometric principles and techniques (magnetic tape and computer disk-drives could not exist otherwise) is unknown to most students of topography. Some quantification of microscale surfaces, notably those of fractured and faulted rock faces, is familiar to earth scientists (Brown, 1995; Glover *et al*., 1998), but a wealth of experience is available from such fields as materials science and production engineering (Bhushan, 1997; Thomas, 1999). Highly applied and practical, metrology arose from the needs of mechanical engineers to quantify the wear of moving parts, typically metal bearings and to relate measurements of surface roughness to the properties of lubricants, the composition of alloys and methods of surface finish (Rosén *et al*., 1996). More recently numerical surface characteristics have been correlated with processes by which thin films of materials are deposited on smooth substrates and other applications in high-technology engineering (Amar and Family, 1996; Medeiros-Ribeiro *et al*. , 1998).

The descriptive tools of metrology, one of the first disciplines to model surfaces as fractals (Berry, 1979), rival those of earth science (Dong *et al*., 1994; Amar and Family, 1996). Metrologic techniques have progressed from central-tendency and dispersion descriptions of microprofiles, through the modelling of continuous surfaces as random, isotropic Gaussian fields by spectral analysis, to a major shift just now underway. This change – the advent of digital 3D imaging and microtopographic mapping (Russ, 1994;

Stout, 1994) of metal, semiconductor and even organic surfaces (Mechaber *et al*., 1996) – is revolutionizing metrology. Limitations of the traditional profile sampling have been overcome by such instruments as the atomic-force microscope and optical interferometer – which measure surfaces at resolutions sufficiently fine to create contour maps down to the atomic scale. As the linear profile gives way to the continuous surface as the preferred sampling design (Stout, 1994), the techniques of spatial analysis developed in the earth sciences are becoming available to surface metrology (Scott, 1997).

One recent microtopographic discovery is germane to the problem of size dependency in geomorphology. Medeiros-Ribeiro *et al*. (1998) revealed and quantified a nanoscopic transition, from smaller pyramids to larger domes, in the morphology of germanium crystals grown on a silicon substrate by physical vapour deposition. The pyramids (p. 355) '. . . nucleate and grow to a maximum volume that is smaller than the volume for which the domes are more stable than the pyramids plus [a critical volume of added] Germanium'. This change evidently marks a shift from one equilibrium form to another with increasing input of energy or material. Conceptually, it resembles the morphologic–morphometric transition from central peaks to inner rings observed in large impact craters on the planets (Pike, 1982) – and quite likely other size-dependent thresholds that remain to be identified in terrestrial landforms.

XV Two emerging applications

The comparatively new field of landscape ecology contributes to geomorphometry by incorporating DEM-based variables in land-unit classification (Barrio *et al*., 1997), but more importantly by quantifying the spatial (X,Y) characteristics of landscape structure (Pickett and Cadenasso, 1995). Most of the latter are topologic attributes – contiguity, interspersion, nesting and adjacency (O'Neill *et al*., 1988; Li and Reynolds, 1993) – that have not yet been computed for ground-surface units. Such measures are needed to complement slope, profile curvature and other relief (Z) parameters in creating geometric signatures of topography (Sulebak *et al*., 1997; Brown *et al*., 1998; Giles, 1998). The computer techniques developed by landscape ecologists operate on the patterns and textures formed by mosaics of *patches*, homogeneous units of landscape identified on multispectral images (Dillworth *et al*., 1994; McGarigal *et al*., 1998). With due caution, measures calculated by the ecologists' algorithms may be used to characterize the ground surface. This adaptation can be accomplished by first creating the topographic equivalents of landscape patches (Pike and Dikau, 1995: 234). Current candidates include reflectance units aggregated from shaded-relief images, sub- and half-basins derived from drainage-net analysis and the smaller *land components* (Dymond and Harmsworth, 1994) or *terrain facets* (Rowbotham and Dudycha, 1998) calculated from combinations of DEM-derived slope, aspect and curvature. The latter two developments appear particularly promising.

A second discipline to which geomorphometry is becoming essential is image understanding (Hoffman and Pike, 1995). One goal of this psychology-based field is software for vision-based navigation as it relates to human and robot perception of terrain features and consequent modelling via artificial intelligence (Pick *et al*., 1993; Thompson *et al*., 1993). Applications include autonomous vehicles – such as the Mars surface rover, navigation aids, mission planning and simulation. Field experiments with test subjects probe the various perceptual aspects of wilderness way-finding: landmark identification, vision-based localization and route-following (Sinai *et al.*, 1998). Unlike most morphometry, image understanding treats terrain viewed in profile and oblique vistas by an observer on the ground. The projections of topographic geometry needed to model the resulting visual perceptions are difficult to quantify. These viewsheds, panoramas and near-field, far-field and horizon profiles are obtained from DEMs through computerized feature extraction (Fisher, 1996). DEM quality is particularly critical in predicting such complex attributes as line-of-sight and terrain masking (Huss and Pumar, 1997). DEM-based applications related to image understanding are geomorphic interpretation of landscapes from digital images (Shaw *et al.*, 1996) and the computer visualization of very large expanses of topography, recent additions to which are Australia (Milligan *et al.*, 1997) and Alaska (Riehle *et al.*, 1997).

XVI Conclusions

Ground-surface quantification, geomorphometry, has undergone a remarkable diversification from its nineteenth-century origins in physical geography and now is indispensable to much contemporary science and technology. At least three factors are responsible for this success, exemplified by the recent work reviewed here. Because morphometric methods are scale independent, they work equally well on field-surveyed terrain heights and hillslope profiles, elevations read from contour maps and DEMs at any grid spacing. Moreover, these methods are effective in addressing both process-orientated (commonly geomorphic) scientific problems and engineering (commonly surface-roughness) applications. Finally, morphometry captures the shape of discrete landforms, such as drainage basins and barchan dunes, as well as the geometry of continuous surfaces – agricultural fields, abyssal hill complexes, deformed sea ice and other (not necessarily geomorphic) terrains that require a statistical, random-field characterization.

Geomorphometry's rapid growth is paralleling that of computer technology, chiefly GIS, mass-produced digital elevations and now the Internet. This trend is likely to continue. New and better terrain data, such as the high-resolution global DEMs forthcoming from satellite missions, will stimulate fresh applications and increase the number of locations where morphometry can be used. Software that captures the more complex, primarily spatial, attributes of surface form will improve the discriminating power of geometric signatures and increase the number of correlations between topographic form and other geographic phenomena. Such cognate disciplines as industrial surface metrology and landscape ecology are providing new analytical approaches to supplement those now routine in the study of land-surface processes.

Although these prospects bode well for geomorphometry, the swift diversification spawned by its variety of current applications is diffusing the field. Such disaggregation is to be expected during a time of rapid growth, but some unity remains desirable. One way to increase cohesiveness would be through a unified discipline of quantitative surface characterization that includes a number of fields in science and engineering. Whether to pursue this goal through the earth sciences or mathematics has been noted briefly (Pike and Dikau, 1995: 235), but the problem has yet to be explored in depth.

Because engineers in surface metrology are already using descriptive approaches that originated in the Earth sciences (Scott, 1997), a crossdisciplinary field of surface representation – even one that might encompass surfaces other than natural topography – seems likely to emerge.

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