

# A Bibliography of Terrain Modeling (Geomorphometry), the Quantitative Representation of Topography —*Supplement 4.0*

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*Provides over 1600 additions and corrections to the 1993  
Bibliography of Geomorphometry and its 1995, 1996,  
and 1999 Supplements, with an update  
of recent advances*

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**U.S. DEPARTMENT OF THE INTERIOR  
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**Abstract** This report adds over 1600 annotated references on the numerical characterization of topography, *terrain modeling* or *geomorphometry*, to a 1993 literature review and its first three updates. Erroneous references from the four earlier reports are corrected and many citations of historic interest are included; the cumulative archive is at 6000 entries. An introductory essay cites several hundred of the new entries. These are listed under various topic headings or referenced in brief discussions of several other areas of research, including terrain data and new parameters, neorometry, landslide-hazard mapping, Hack's Law, and early work on the mathematical representation of ridges and drainageways.

## **Introduction**

*Terrain modeling*, the practice of ground-surface quantification, is an amalgam of Earth science, mathematics, engineering, and computer science. The discipline is known variously as *geomorphometry* (or simply *morphometry*), *terrain analysis*, and *quantitative geomorphology*. It continues to grow through myriad applications to hydrology, geohazards mapping, tectonics, sea-floor and planetary exploration, and other fields. Dating nominally to the co-founders of academic geography, Alexander von Humboldt (1808, 1817) and Carl Ritter (1826, 1828), the field was revolutionized late in the 20th Century by the computer manipulation of spatial arrays of terrain heights, or digital elevation models (DEMs), which can quantify and portray ground-surface form over large areas (Maune, 2001). Morphometric procedures are implemented routinely by commercial geographic information systems (GIS) as well as specialized software (Harvey and Eash, 1996; Köthe and others, 1996; ESRI, 1997; Drzewiecki et al., 1999; Dikau and Saurer, 1999; Djokic and Maidment, 2000; Wilson and Gallant, 2000; Breuer, 2001; Guth, 2001; Eastman, 2002). The new Earth Surface edition of the Journal of Geophysical

Research, specializing in surficial processes, is the latest of many publication venues for terrain modeling.

This is the fourth update of a bibliography and introduction to terrain modeling (Pike, 1993, 1995, 1996, 1999) designed to collect the diverse, scattered literature on surface measurement as a resource for the research community. The use of DEMs in science and technology continues to accelerate and diversify (Pike, 2000a). New work appears so frequently that a sampling must suffice to represent the vast literature. This report adds 1636 entries to the 4374 in the four earlier publications<sup>1</sup>. Forty-eight additional entries correct dead Internet links and other errors found in the prior listings. Chronicling the history of terrain modeling, many entries in this report predate the 1999 supplement. Coverage is representative from about 1800 through early-mid 2002. Papers increasingly are published exclusively or in duplicate on the Internet's World Wide Web; the dates given here for Web addresses (URLs) that lack a print publication indicate a Web site's last update or my last access of it.

The bibliography is arranged alphabetically and thus is not readily summarized. This introduction cites about 500 entries, a third of them grouped under 24 morphometric topics, as a guide to the listing's contents. Continuing the practice of previous bibliographies in the series to provide more information on a few applications (see summary of past topics in Pike, 2000a), this report elaborates further on topographic data, putative new parameters, tectonic geomorphology/neo-orometry, biogeography, ice-cap morphometry, results from the Mars Global DEM, landslide-hazard mapping, terrain modeling as physics, Hack's law, and broad-scale computer visualization. The literature of some of these subjects is large, and none of the summaries is intended to more than introduce the topic and comment on some of the current contributions of terrain modeling. Closing the essay is a discussion of pre-1900 papers that trace the evolution of ridge-line and watercourse quantification by descriptive geometry, as well as comments on some new books and an on-line bulletin board.

## **Revisions in Format**

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<sup>1</sup> The few text citations not in the main bibliography are listed at the close of this introduction or in 'Corrections' appended to the main bibliography.

With this report the title of the series incorporates *Terrain Modeling*, in an effort to broaden its readership. According to the Internet-search results illustrated in Table 1, *Terrain Modeling* (plus *Modelling*) is 15 times more frequent than *geomorphometry*. Other alternatives are inapt: *Digital Terrain Modeling* would exclude pre- or non-computer work (Penck, 1894a, b; Hack and Goodlett, 1960); *Terrain Analysis* has military and non-quantitative connotations (Graff, 1997; DARPA, 2002); *Morphometry* is a common practice in biology and paleontology (Cracraft, 1980; MacLeod, 1999); *Surface Rendering*, *Terrain Rendering*, and *Surface Modeling* have

Table 1

## Ranking Descriptors of Surface Quantification (as keywords on the World Wide Web)

<b>*Index of Hits</b>	<b>*Search Word(s)</b>
<b>100</b>	<b>Surface Modeling**</b>
<b>72</b>	<b>Surface Topography</b>
<b>57</b>	<b>Morphometry</b>
<b>53</b>	<b>Terrain Modeling**</b>
<b>40</b>	<b>Terrain Analysis</b>
<b>24</b>	<b>Surface Rendering</b>
<b>18</b>	<b>Digital Terrain Modeling**</b>
<b>14</b>	<b>Terrain Rendering</b>
<b>11</b>	<b>Topographic(al) Analysis**</b>
<b>6</b>	<b>Surface Metrology</b>
<b>3.5</b>	<b>Geomorphometry</b>
<b>2.4</b>	<b>Digital Elevation Modeling**</b>
<b>2.3</b>	<b>Digital Terrain Analysis</b>
<b>1.6</b>	<b>Quantitative Geomorphology</b>
<b>1.2</b>	<b>Landform Modeling**</b>

## 0.1 Quantitative Terrain Analysis

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\*using the exact-phrase option in the *Google* search engine, 23 September 2002; Index for each term is number of hits / number of hits (28,100) on 'surface modeling'  $\times 100$

\*\*includes the British spellings '... Modelling' and 'Topographical ...'

specialized meanings in computer vision and image analysis (Koenderink and van Doorn, 1993, 1994, 1998; López, 1997; Thompson and others, 1998); and *Surface Topography* connotes industrial micro- and nano-morphometry (Thomas and others, 1999; Blunt and Stout, 2000; Scott, 2001).

Another change with this report is the annotation of all entries except the 90 or so that were not seen but whose titles, context, or literature citations insure involvement with terrain modeling (for example, Malyavsky and Zharnovsky, 1974; Brown, 1994; Schneider, 2001). Most remarks are brief, were made hastily, and reflect the author's interest or understanding at the time—commonly descriptive parameters, techniques and data. This informal annotation is not to be construed as a summary of an entry's contents or an appraisal of the work reported—which ranges from trivial to profound. Comments tend to lengthen with the age of the publication, most early work requiring historic context to justify its inclusion. To increase the usefulness of the (eventual) consolidated bibliography, entries in the initial 1993 listing and prior updates are being annotated. Comments have been appended to 61% of the combined 6000 citations, and all entries before 1966.

### Topographic Data

Data availability and quality persist as areas of concern in terrain modeling. In the U.S. a new master DEM assembled from all 55,000 1:24,000- and 1:63,360-scale topographic maps eliminates the onerous tiling of multiple 7.5' quadrangles and other data preparation (Gesch and others, 2002). This National Elevation Dataset (NED) is a seamless, continually updated, DEM of uniform horizontal datum (NAD83), unit of height (decimal meters), and projection. Horizontal grid resolution is 1" (nominally 30 m) for the conterminous U.S., Hawaii, and Puerto Rico and 2" for Alaska. Digital filtering during compilation reduces artifacts in the source DEMs (Oimoen, 2000), seamlessly matches adjacent quadrangles,

and fills sliver areas of missing data. Because heights for much of the country increasingly are gridded at a spacing of 10 m, a 1/3" (nominally 10 m) DEM is in progress. New national DEMs are not unique to the U.S. For example, Carroll and Morse (1996) describe creation of the GEODATA 9" DEM of Australia and Hutchinson and others (2001) its subsequent upgrading, including discussion of the ANUDEM gridding algorithm to improve data accuracy. In a reversal of conventional experience, contours for the recently completed 1:50,000-scale topographic maps of Ireland were extracted from DEMs generated by digital photogrammetry (Cory and McGill, 1999).

All DEMs are in some respect flawed (Coops, 2000). Most of the error in current DEMs originated in the contour maps from which they were derived and thus cannot be reduced through efforts of the user. Map-accuracy standards vary widely and do not provide a rigorous evaluation. Production standards, moreover, guarantee only a statistical level of quality; locally, accuracy can be low. Contour maps are merely models—of varying fidelity—of topography, just as DEMs are, in turn, imperfect models of the maps (Ollier, 1967). Contour maps never were intended to provide heights of the high density and accuracy increasingly required for terrain modeling. What can be mitigated to some extent by the DEM user is error originating in contour map-to-DEM processing (Duh and Brown, 1999; Holmes and others, 2000; Lane and others, 2000; Lynch, 2002). Most DEMs currently available have been interpolated from contours by sampling designs and computer algorithms that add artifacts and other distortions inherent in the processing (Shortridge, 2001). Various procedures have been applied to repair some of these flaws (Hutchinson and Gallant, 2000; Oimoen, 2000; Hutchinson, 2001; Gesch and others, 2002).

Production methods that bypass map contours as the source of digital heights can improve DEM quality. Two emerging technologies that measure the true ground-surface directly have the potential to reduce some of the current shortcomings in DEM coverage and accuracy (Maune, 2001). Laser altimetry, particularly LiDAR (light distance and ranging), promises DEMs of fine resolution and high accuracy (Ritchie, 1995; DeLoach and Leonard, 2000; Brock and others, 2002), as well as seafloor bathymetry (Sandwell and Smith, 2000). Radar interferometry (InSAR or IfSAR) yields terrain-height accuracies and resolutions comparable with those generated by optical methods (Small, 1998; Gens, 1999; Dowman, 2000; Hanssen, 2001; Smith, 2002). Interferometry also is used to monitor displacements of topography, for example, by subsidence or surface faulting.

LiDAR's aircraft-mounted lasers record 2000-5000 height measurements per second to a vertical precision of  $\pm 15$  cm. From these voluminous observations DEMs at a horizontal resolution of about a meter can be prepared for large areas (Hill and others, 2000; Carter and others, 2001). While expensive compared to DEMs compiled photogrammetrically or from digitized contours, LiDAR data are decreasing in cost as techniques of acquisition and processing (notably, filtering out vegetation and man-made structures) improve in efficiency and economies of scale make the data more competitive in the marketplace. LiDAR could become the standard procedure, with digital photogrammetry (Gwinner and others, 2000; Lane and others, 2000; Hancock and Willgoose, 2001), for creating fine-scale DEMs of small areas. For representative applications of LiDAR to terrain modeling see Jansma and others (1999), Cowen and others (2000), and Marks and Bates (2000).

Interferometry, which requires simultaneous or repeated signal acquisitions by synthetic-aperture mapping radar, has delivered a near-global DEM at a uniform horizontal resolution of 90 m. Over ten days in February 2000, the Shuttle Radar Topographic Mission (SRTM) system onboard Space Shuttle Endeavour imaged about 80% of Earth's land surface, creating an immense set of terrain heights. The SRTM carried two radar antennas, one aboard the spacecraft, the other at the end of a 60-m mast extending from it. A 3" (nominally 90-m) DEM compiled from mission results (Farr and Kobrick, 2000; NASA, 2002) is taking its place beside the 1-km GTOPO30 DEM (Gesch and Larson, 1998; Gesch and others, 1999) that remains the current standard for elevation coverage worldwide. A global 1" (30-m) DEM also is being extracted from the SRTM but only the United States data will be publicly available.

Advanced methods do not assure DEM quality. InSAR, LiDAR, and other remotely-sensed data all contain errors, some of them severe, that are unique to their technologies (Leberl, 1998; Toutin, 1999; Endreny and others, 2000; Ahmadzadeh and Petrou, 2001; Kervyn, 2001; Nuth and others, 2002). The early SRTM results are a cautionary example. Aside from the fact that 1/5 of Earth's land mass (all at high latitudes) was excluded, *relative* vertical accuracy of the new data at the 90% level is expected to average  $\pm 10$ m, a substantial error at the 90-m grid spacing and potentially serious at 30m. Also, because the radar did not penetrate dense vegetation, data in such areas describe the tree canopy rather than bare ground—in which case the new DEM probably reproduces the terrain surface no more faithfully than the NED. NASA (2002) alerts users of SRTM data to "... be aware that the digital ... topographic data are unedited and are intended for scientific use and

evaluation. They are outputs directly from the SRTM interferometric radar processor and, for example, may contain numerous voids (areas without data), water bodies may not appear flat, and coastlines may be ill-defined." Currently available, more accurate, DEMs thus are likely to remain the better data for many areas. Slatton and others (2001) have proposed a way to fuse LiDAR with InSAR to get coverage that is at once accurate, dense, and extensive.

## **New (?) Parameters**

While Wolfgang Pauli's "the surface was invented by the devil!" was lamenting complexities of atomic structure at the surface of a solid, the physicist's exasperation applies equally to terrain modeling. Continuous topography is difficult to express, and many new parameters have been proposed to quantify attributes of terrain that existing measures cannot describe. 'New' terrain measures have included mean elevation (Huber, 1825; Sonklar, 1872) and slope gradient (Tillmann, 1915; Bonniard, 1929), relative relief (*relief energy* in European and Japanese practice; Scheer, 1933; Tada, 1937), the hypsometric integral (Hurtrez and others, 1999; Luo, 2000), and most recently the fractal dimension—which briefly revived the old philosopher's-stone fallacy that a single 'magic number' might suffice to express surface form (Evans and Cox, 1998).

Two approaches recently developed to describe *continuous topography*, as distinguished from discrete *landforms*, are the DEM-based 'terrain fabric' of Guth (1999a, b; 2001) and surface 'openness' of Yokoyama and others (1999, 2002). Terrain fabric characterizes the tendency of a surface to be organized into linear ridges rather than isotropic topography, whereas openness expresses dominance (exposure) versus enclosure of a location on an irregular surface. 'New' parameters, however, rarely are; many describe the same basic attribute of surface form and thus are redundant (Pike, 2001e). In geomorphology, for example, the hypsometric integral differs little from elevation skewness (Pike, 2001a). If, or to what extent, the two most recently proposed candidates mimic existing, and perhaps simpler, measures remains to be determined (Guth, 1999b; Pike, 2001d).

## **Tectonic Geomorphology as Neo-Orometry**

Global DEMs of Earth and Mars, as well as coverage of Earth's seafloor and ice caps, have fostered terrain modeling at broad spatial and

temporal scales (van der Beek and Braun, 1998; Clayton and Shamon, 1999; Whipple and others, 1999). In some respects, this trend returns morphometry to its origins in the quantitative generalities sought by von Humboldt (1817, 1843c) and his successors (Sonklar, 1860, 1866; Stange, 1885), but with a sophistication and emphasis on geologic process that were absent from the older work (Hurtrez and others, 1999; Yamada 1999, 2001a, b; Bendick and Bilham, 2001; Bishop and others, 2002). *Orometry*, the 19th-Century measurement of mountains (Penck, 1894b), is echoed today in *tectonic geomorphology*, which interprets landscape evolution from DEM data and assumptions of physical process that reflect the interplay of mountain building and erosion in regions of active deformation (Summerfield, 2000; Burbank and Anderson, 2001; Pazzaglia and Knuepfer, 2001).

By testing theory in controlled experiments (Ahnert, 1966), the broad-scale quantification of topography has helped transform tectonic geomorphology into one of the most active and exciting fields in the Earth sciences (Hovius, 1996; Talling, 1997; Miliareis and Argialas, 1999a-c; Miliareis, 2001a, b; Kühni and Pfiffner, 2001a, b; Dietrich and others, 2002). GTOPO30 and other DEM data are being used to model geodynamic and surface processes, rates, and physiographic effects (Whipple and Tucker, 1999; Rice-Snow and Russell, 2000; Montgomery and others, 2001; Montgomery and Brandon, 2002; Azor and others, 2002). In related work requiring large DEMs, classic drainage-basin morphometry has expanded beyond single catchments and fluvial systems (Strahler, 1956, 1958). Current applications include tidal creek systems (Cleveringa and Oost, 1999) and the hydrologic parsing of entire continents (Danielson, 1998; Kumar and others, 2000; Vaughn and others, 1999) and planets (Verdin and Verdin, 1999; Vörösmarty and others, 2000a; Cabrol and Grin, 2001; Smith and others, 2001).

## **Biogeography**

The numerical modeling of terrain is now evident in landscape ecology and wildlife and conservation biology (Meisel and Turner, 1998). These fields traditionally have emphasized spatial over relief attributes of the Earth's surface (Gustafson, 1998; Li, Lu, and others, 2001; Raines, 2002). Although land-surface form affects distribution of plants and the fauna that need them for concealment, food, nesting, and other functions, few habitat models have incorporated topography (Vales, 1996). Even when included, characterization of the ground surface usually is limited to

elementary DEM-derived parameters: elevation and slope gradient and aspect—which are insufficient for many field-biological applications.

Such attributes of terrain as roughness, which incorporates both slope steepness and spacing, and site position with respect to the nearest valley bottom or ridge crest are important to local fauna because they influence microclimate, cover from predation, and susceptibility to disturbance by humans. The literature on biogeography is starting to reflect a more complex numerical characterization of topography. Recent examples include topographic determinants of butterfly habitats (Fleishmann and Mac Nally, 2002), ruggedness indices that quantify topographic heterogeneity (Riley and others, 1999) and predict the distribution of musk oxen (Nellemann and Reynolds, 1997), and GIS models such as that by Gustafson and others (2001), which combines hillslope position and its correlation with soil moisture to model the response of salamanders to alternative plans for forest management.

## **Ice-cap Morphometry**

Dating from the pioneering hypsometric curves of Greenland and the Arctic (Meinardus, 1926) and the first DEM of Antarctica (Budd and others, 1984), over two dozen bibliographic entries describe the morphometry of Earth's largest ice-covered surfaces. Topographic measurements are needed to understand the interaction of ice sheets with global climate and sea level. Much of the 10-25 cm rise in sea level over the last 100 years may reflect waning polar ice caps. *Mass balance*, which describes whether an ice sheet is growing, shrinking, or stable, may be estimated from data on the rate of ice thickening or thinning (Krabill and others, 2000). Because polar ice sheets are large, remote, and change slowly, systematic observations on elevation and thickness have been difficult to obtain.

Remote-sensing technology dramatically increased the ease of measurement (Bamber and others, 1998; Bindschadler and others, 1999; Liu and others, 1999; Thomas and others, 1999; Rémy and others, 2001). Not only have accurate DEMs been compiled for the major ice caps (Bingham and Rees, 1999; Bamber and others, 2001), but large 'ice basins' analogous to fluvial catchments have been delimited from the DEMs (Vaughn and other, 1999; Hardy and others, 2000). Other work has quantified subglacial bedrock surfaces and thus estimated ice-cap thickness and volume (Warner and Budd, 2000; Björnsson and others, 2000; Lythe and others, 2001). Not all high-latitude morphometry is of

regional extent. Bintanja and others (2001), for example, have quantified fine-scale ripples in polar-cap ice.

## **The Mars Global DEM**

Terrain modeling is indispensable to the investigation of planetary surfaces (Pike, 2001a). Extraterrestrial landforms recently studied from height measurements include impact craters, volcanoes, scarps, and other features on the Moon (Craddock and Howard, 1999), Mercury (Watters and others, 2002), Venus (Bulmer and Wilson, 1999; Herrick and Sharpton, 2000), and the satellites of Jupiter (Schenk and others, 2001; Schenk, 2002). Measurement-driven progress in the quantitative geomorphology of Mars has been spectacular. Over a dozen entries describe morphometric results from topographic data acquired by the Mars Orbiter Laser Altimeter (MOLA), a 10-Hz pulsed infrared-ranging instrument operated in orbit around the planet from 1997 to 2001 aboard the Mars Global Surveyor.

As the mission progressed, a global DEM compiled from range measurements improved in spatial resolution from 59 km to 12 km and to as little as 230 m locally, and in vertical accuracy to  $\pm 1$  m (Neumann and others, 2001). The resulting global topographic map is the most accurate of any planet in the solar system (Smith and others, 1999; Zuber and others, 1998a, b, 1999, 2001). Geomorphic findings from the MOLA DEM include confirmation of the extraordinary smoothness of the planet's northern hemisphere (Aharonson and others, 1998), regional hypsometry and slope gradients (Head and others, 1999; Kreslavsky and Head, 2000; Aharonson and others, 2001), discovery of a new multi-ring impact basin (Frey and others, 1999), refinement of crater depth/diameter relations (Garvin and Frawley, 1998; Garvin and others, 2000), and delineation and interpretation of valley networks and watersheds (Smith and others, 2001; Williams and Phillips; Stepinski and others, 2002).

## **Landslide-hazard Assessment**

The flurry of activity in mapping landslide susceptibility since its earlier mention in this series (Pike, 1999) warrants revisiting the topic. Because the morphology of landslide source-areas and deposits can be described in geometric terms, slope failure rivals flooding as the geomorphic hazard most amenable to analysis through terrain modeling. The spread of DEMs

and GIS technology has shifted emphasis in morphometry from characterizing individual landslides (Collin, 1846; Simonett, 1967; Waltz, 1971) to regional assessment of slope stability (Jäger and Wieczorek, 1994; Montgomery and Dietrich, 1994; Atkinson and Massari, 1998; Dietrich and Montgomery, 1998b). Much of the recent work has involved the spatial modeling of landslide susceptibility, the relative likelihood that a hillside site will fail upon occurrence of a triggering event, such as an earthquake or heavy or persistent rainfall. Two dozen entries in this report sample a small fraction of the current literature on susceptibility mapping, which combines variously slope gradient, curvature, and aspect with geology, evidence of prior failure, and land use (Larsen and Parks, 1998; Mason and others, 1998; Pack and others, 1999; Bucknarn and others, 2001; Coe and Godt, 2001; Gritzner and others, 2001; Pike and others, 2001).

## **Physics and Terrain Modeling**

Recent interest in theoretical aspects of terrain modeling by researchers who are physicists, mathematicians, or engineers rather than Earth scientists may reflect a maturing of the discipline (Arakawa and Krotkov, 1994; Brown and others, 1994; Dodds and Rothman, 1999, 2000; Glanz, 1999). Complementing this trend, Earth scientists are beginning to publish on topography in physics journals (Clarke, 1997; Pastor-Satorras and Rothman, 1998a, b; Schörghofer and Rothman, 2001). Much of this new work was prompted by the use of topography in explicating fractal-surface phenomena (Dubuc and Dubuc, 1996; Struzik, 1996) and by recognition of self-organizing properties in the landscape (Bak and others, 1987; Halsey, 2000; Mandelbrot, 2002). More attention has been accorded to planimetric description of river networks (Tokunaga, 1994; Newman and others, 1997; Dodds and Rothman, 2001a, b, c) than to the more complicated problem of characterizing relief, or Z-domain, attributes of continuous topography (Mandelbrot, 1985; Koenderink and van Doorn, 1993, 1994, 1998).

## **Hack's Law**

The post-World War II USGS geomorphologist John Hack combined terrain modeling with a more traditional interpretation of field observations (Hack and Goodlett, 1960; Hack, 1965). His enduring 1957 contribution, known as Hack's Law, is an empirical relation with moderate scatter,  $L = 1.4 A^{0.6}$ ,

showing that drainage-basin area  $A$  increases exponentially with channel length  $L$ . (see also, Makkaveev, 1955). The significance of the equation was discussed throughout the 1960s and 1970s, centering on debate over the exact value of the exponent—the observed range was 0.47–0.65—and whether it varied regionally and with basin size (Miller, 1958; Mueller, 1972, 1973; Moseley and Parker, 1973; Shreve, 1974). Advances in understanding steady-state scaling of landscape phenomena, resulting from DEM-based analysis of topography in the early 1990s, have revived interest in Hack's Law. Hovius (1996), for example, suggested that the equation was related to the spacing of streams draining mountain belts, while Rinaldo and Rodríguez-Iturbe (1998) considered Hack's Law and basin elongation to be an outgrowth of fractal properties. Among the most recent interpretations are those of Dodds and Rothman (2000, 2001a), Willemin (2000), Birnir and others (2001), and Sivapalan and others (2002).

## **Broad-scale Visualization**

Vigil and others (2000) merged two existing digital images of the lower 48 United States, shaded relief and geologic time (expressed as geologic-map units), into one map, a colored three-dimensional perspective view of the landscape at 1:3,500,000 scale. The resulting digital 'tapestry' is among the more effective combinations of shaded relief with other spatial data and has potential for Earth-science education (Leech and others, 2002). The geologic map, a multi-color, non-uniform vector file, was converted to raster structure and overlaid on the shaded-relief file, a gray-scale raster at a uniform scale. Processing was not routine GIS. Differences between the source maps required various procedures to subdue or remove irregularities in the merged image. Adjusting transparency (opacity), color levels, and contrast of the geologic map to attain an aesthetic and visual balance between shaded relief and geologic-time units was an iterative, trial-and-error process. The final map, occupying a modest 700 MB, did not require high-end hardware or custom programming, but was processed on a PowerMacintosh desktop computer by Adobe Illustrator and Photoshop software. Barton and others (2002, 2003) have created a similar image of the entire North American continent at 1:8,000,000 scale from a later DEM (GTOPO30) and a combined geologic map of Canada, the U.S., and Latin America. Despite the reduced scale, this latest map successfully extends the original tapestry concept.

## Other Topics

Terrain modeling has progressed in areas besides those highlighted above. Over 150 references, in 24 of the many subject categories represented in the appended listing, convey the extent of recent developments in morphometry. Most of the following citations touch on several topics:

- ontology, or definition, of terrain and landforms, especially mountains (Agarwal and others, 1996; Mark and Smith, 2002a, b);
- conversion of contour lines to grid DEMs (Gousie, 1998; Gousie and Franklin, 1998; Franklin and Gousie, 1999);
- DEM error and accuracy (Webber, 1995; Giles and Franklin, 1996; Gao, 1997; Gesch, 1998; Duh and Brown, 1999; Lemmens, 1999; Toutin, 1999; Endreny and others, 2000; Gong and others, 2000; Krupnik, 2000; Rees, 2000; López, 2002);
- compression of elevation data (Franklin, 1995; Franklin and Said, 1995; Kidner and Smith, 1997; Ottoson, 2001; Park and others, 2001; Bjørke and Nilsen, 2002);
- impact of DEM error and grid spacing on terrain-modeling applications (Hunter and Goodchild, 1997; Brasington and Richards, 1998; Gesch, 1999; Guth, 1999c; Walker and Willgoose, 1999; Holmes and others, 2000; Wise, 2000; Wolock and McCabe, 2000; Canters and others, 2002);
- the triangulated irregular network, TIN (Brown and others, 1994; Mark, 1997; Ware and Kidner, 1997; Little and Shi, 1998, 2001; Park and others, 2001; Wang and others, 2001; Zhu and others, 2001);
- computing terrain parameters from square-grid DEMs (Weih and Smith, 1996; Jones, 1998; Defourny and others, 1999; Garbrecht and others, 1999; Guth, 1999a, b, 2001; Meyer and others, 2001; Luo, 2002; Shary, 2002; Shary and others, 2002);
- computing terrain parameters from elevation contours and flow lines (Schneider, 1998a, b; Menduni and Riboni, 2000; Mizukoshi and Aniya, 2002);

- visibility analysis and viewsheds (Wang and others, 1996; De Floriani and Magillo, 1999; Franklin, 2000; Messina and Stoffer, 2000; Wang and others, 2000; Kidner and others, 2001; O'Sullivan and Turner, 2001);
- computer visualization of irregular surfaces (Banks and Wickens, 1997; Duchaineau and others, 1997; Valentine and others, 1998, 2001; Eckhardt and others, 2000; Gardner and others, 2000a, b; Malzbender and others, 2001; Mossman, 2001; Yokoyama and others, 2002);
- extracting drainage lines and watersheds from DEMs (Soille and Gratin, 1994; ESRI, 1997; Danielson, 1998; ASCE Task Committee, 1999; Band, 1999; Bertolo, 2000; Djokic and Ye, 2000; Garbrecht and Martz, 2000; Liang and Mackay, 2000; Saunders, 2000; Jones, 2002);
- hillside erosion and slope evolution (Pastor-Satorras and Rothman, 1998a, b; Katsube and Oguchi, 1999; Favis-Mortlock and others, 2000; Iwahashi and others, 2001; Roering and others, 2001);
- fluvial step-pools (Chin, 1999; Chartrand and Whiting, 2000; Duckson and Duckson 2001; Madej, 2001); Jackson and Sturm, 2002);
- self-similar and fractal properties of streams and topography (Tate, 1998a, b; Cleveringa and Oost, 1999; Fagherazzi and others, 1999a–c; Peckham and Gupta, 1999; Pelletier, 1999; Sulebak, 1999; Veneziano and Iacobellis, 1999);
- scaling of river networks and runoff processes (Dietrich and Montgomery, 1998a; Dodds and Rothman, 2000; Schmidt and others, 2000; Veneziano and Niemann, 2000a, b; Fekete and others, 2001; Tang and Day, 2000);
- aeolian dunes (Kar and others, 1998; Wadhawan, 1998; Gay, 1999; Goudie and others, 1999; Jimenez and others, 1999; Sauermann and others, 2000; Bishop, 2001; Al Harthi, 2002);
- glacial landforms (Davis, 1999; Evans, 1999; Etzelmüller and Björnsson, 2000; García-Ruiz and others, 2000; MacGregor and others, 2000; Li and others, 2001a, b);
- volcanic landforms (Rossi, 1999; Stevens and others, 1999; Wichman, 1999; Carn, 2000; Schenk and others, 2001; Stoddard and Jurdy, 2002);

- submarine surfaces and features (Nolan and others, 1999; Adams and Schlager, 2000; Clague and others, 2000; McAdoo and others, 2000; Dunn and others, 2001; Mitchell, 2001);
- karst features (Magdalene and Alexander, 1995; Sykioti and others, 1996; Ferrarese and others, 1998; Whitman and others, 1999; Denizman and Randazzo, 2000);
- relation of ground-surface form to soil properties (Vivas and Paz Gonzalez, 1998; Crawford and others, 1999; Thomas and others, 1999; Bochet and others, 2000; Florinsky and Kuryakova, 2000; Sulebak and others, 2000; Fraisse and others, 2001; Manning and others, 2001; Thompson and others, 2001; Florinsky and others, 2002);
- agricultural fields (Remond and others, 1999; Inamdar and Dillaha, 2000; Fraisse and others, 2001; Takken and others, 2001; Wilson and others, 2001; Planchon and others, 2002; Zobeck and Popham, 2002);
- predicting flood inundation (Cohen and Small, 1998; Ramsey and others, 1998; Small and Cohen, 1999; Bae and others, 2000; Bates and DeRoo, 2000; Marks and Bates, 2000; Nicholls and Small, 2002); and
- numerical classification of terrain, by types and regions (Dikau, 1996; Friedrich, 1996, 1998; Brabyn, 1997; Bivand, 1999; Gimelfarb and others, 1999; Miliareisis and Argialas, 1999a–c; Schmidt and Dikau, 1999; Verdin and Verdin, 1999; Cronin, 2000).

## **New Books**

Book-length publications continue to mark advances in terrain modeling and its supporting technologies. Among recent volumes are those authored by Burbank and Anderson (2001) and edited by Wilson and Gallant (2000), Maune (2001), and Pazzaglia and Knuepfer (2001). Papers from three morphometry-oriented sessions of the 5th International Conference on Geomorphology in Tokyo (2001) are being edited by Evans, Dikau, Tokunaga, Ohmori, and Hirano for a 2003 book provisionally titled Concepts and Modeling in Geomorphology.

Publication of Terrain Analysis: Principles and Applications (Wilson and Gallant, 2000) was a major event. Celebrating the work of Ian Moore (1951-1993), the book began as the proceedings of a 1996 Australian workshop, Creation and Applications of DEMs in Land Resource

Assessment. Much updated from the papers read at the meeting, the book focuses on TAPES (Terrain Analysis Programs for the Environmental Sciences), a set of computer algorithms for quantifying terrain with special reference to hydrology and ecology (for example, Moore and others, 1988). Among the most informative of the 16 chapters are the first five—by Gallant and Wilson, Hutchinson and Gallant, Wilson and Gallant (two), and Wilson and others (all 2000)—which introduce and describe the various TAPES programs. The remaining 11 articles report a variety of applications, some of which illustrate the chronic problem of noisy DEMs.

Digital Elevation Model Technologies and Applications, edited by David Maune (2001) for the American Society for Photogrammetry and Remote Sensing, is subtitled The DEM Users Manual. Prepared by industry specialists in remote sensing rather than by academic scientists, the book is strong on the basics of acquiring and preprocessing square-grid digital elevation data, principally for the U.S. Applications in terrain modeling *per se* are limited to a few examples. After an introduction to DEM terminology and concepts, the remaining 12 chapters address vertical datums, accuracy standards, the USGS National Digital Elevation Program, photogrammetry, IfSAR, Topographic LiDAR, airborne LiDAR bathymetry, Sonar, the various enabling technologies, a sampling of DEM applications, DEM quality assessment, and likely requirements of the DEM user. While useful, much of the material could quickly become dated by advances in techniques of data acquisition and processing.

Quantified topography is essential to the analysis of landscapes shaped by diastrophism. The last two chapters of Burbank and Anderson's (2001) textbook Tectonic Geomorphology draw from published research into the DEM-based modeling of geodynamic and surface process. Illustrated are elevation and slope distributions for highland subregions, drainage spacing as a function of mountain-belt width, valley height/width ratios and other morphometric attributes, and models of landscape evolution constructed from the diffusion equation and a range of assumptions about process and temporal and spatial scale. In addition, five of the eight papers in a special 2001 volume of the *American Journal of Science* edited by Pazzaglia and Knuepfer, The steady-state orogen: concepts, field observations, and models—by Whipple, Pazzaglia and Brandon, Montgomery, Willett and others, and Stark and Stark—contain DEM-based analyses of erosion and tectonism that contribute to understanding the evolution of mountain topography.

Two books, by Stout and others (2000) and edited by Stout and Blunt (2000), update the three-dimensional quantification of micro- and nano-

surfaces from ultra-fine-scale DEMS. This 1990s breakthrough in technique revolutionized the field of industrial-surface metrology, terrain modeling's sister discipline in manufacturing and production engineering. Shorter advances in 3-D metrology include Stout and others (1999); Thomas and others (1999); Blunt and Stout (2001); Wieczorowski (2001); and Assender and others (2002). Among works of historical importance that have come to light are Abbott and Firestone (1933), Kramrisch (1935), and Schmaltz (1936). Pike (2000b, 2001b, c) explored the convergence of Earth-science and industrial practices of surface quantification.

## **A New Internet Resource**

The visibility of terrain modeling on the World Wide Web grew in 2000 with the inauguration of an on-line bulletin board, The Geomorphometry Mailing List. Maintained by Dr. George Miliareisis, a former student of Demetre Argialas (Argialas and Miliareisis, 1997b, 2000, 2001) and now in the Department of Surveying and Regional Planning at the National Technical University of Athens, the English-language list had about 400 subscribers by late 2002. The URL is <http://groups.yahoo.com/group/geomorphometry/>. Miliareisis' list "... points out information resources for ... geomorphometry and the processing of digital elevation models, related conferences, data availability, algorithms and methods, scientific news, etc. The aim is to promote geomorphometry to new scientists and to integrate advances in geomorphometry and news that are distributed in various fields (remote sensing, geography, geology, surveying, etc.)." Besides serving as a focus for the terrain-modeling community, the list supplements the aging 1999 on-line article Web Resources Compiled For Terrain Modeling, at [http://www.agu.org/eos\\_elec/97260e.html](http://www.agu.org/eos_elec/97260e.html). Other new Internet resources include Discoe (2002), on terrain rendering and animation, and Childs (2002), a repository of current hands-on experience in terrain modeling and digital mapping.

## **Early Morphometry: Ridges and Watercourses**

About 200 of the bibliographic entries listed in this report are over fifty years old and half of them predate 1900. The concepts evolved from 19th-Century orometry and later obsolete work, distant as they are, have shaped much of today's terrain modeling. John Playfair's (1802)

explication of the ideas of James Hutton, for example, recognized not only an orderly confluence of streams and their valleys, but also that the upstream angle at which a tributary meets its trunk stream generally is acute (1802, p. 113-114). The latter observation, which was known to Immanuel Kant (1803, v. 3, p. 18) may be even older. A prescient mid-19th Century contribution, although it little affected the science because it was so advanced for the time, is the 1834 paper by Julian Jackson, who devised a primitive—but unmistakable—precursor to the Gravelius-Horton-Strahler system of stream ordering.

Among the best examples of current terrain modeling rooted in early practice is the geometric representation of topographic curvature. Two dozen entries in this report, which elaborate on the historic material discussed in Rieger (1997) and López (1997, 1999) as well as on my translations of short passages from some of the following citations, chronicle the 200-year evolution of mathematical definition of ridges, watercourses, and hillside flow-lines. The 19th-Century context is revealing: While German geographers were quantifying *Küstenentwicklungen*, 'coastal development' or more accurately its degree of planform convolution (Humboldt, 1817, 1835; Nagel, 1835; Reuschle, 1869)—an intricate coastline was thought to favor the rise of 'more advanced', i.e. industrialized, societies)—or calculating the volume and mean height of mountains and continents (Humboldt, 1843c; Koristka, 1858; Sonklar, 1872; Penck, 1886, 1894b), French civil engineers and mathematicians were developing a geometric model to characterize topography's most fundamental features.

Well before Arthur Cayley's 1859 paper "On hills and dales" and Carl Gauss' (1827) paper on curved surfaces, Dupuis de Torcy and Brisson (1808, reprinted in Brisson, 1829) conceptualized topographic ridges and valleys as special cases of downslope flow-lines normal to height contours. (Cayley and Gauss cited neither of these nor their other French predecessors identified below.) This early (the first?) representation of the land surface by descriptive geometry—Barnabé Brisson, a geometer and civil engineer, was a student of Gaspard Monge, the inventor of descriptive geometry—arose from a practical problem. The French had been the first to map height contours regionally, but also were leaders in the engineering of modern canals. The lay of the land and the design compromises it forced upon civil engineers were major considerations in estimating the cost of canals, which could either follow a straight course or trace a sinuous path dictated by the terrain. A canal aligned along relief contours resulted in a longer and less direct course, but required fewer expensive earthworks and locks. Dupuis de Torcy and Brisson

proposed applying descriptive geometry to the spot heights indicated on topographic maps, rather than employing the usual field surveys, to locate the divides that separate adjacent large watersheds—thus identifying candidate canal-routes and facilitating cost estimates for cut-and-fill engineering.

This pioneering work in applied surface-geometry was picked up by J.C. Saint-Venant (1852). The French mathematician and civil engineer was perhaps the first to define ridges and valleys explicitly as points of minimum slope—compared to other points at the same elevation—although he did not specify the zero-sloping flow-lines that form the drainage pattern. Shortly thereafter, his countryman P.-E. Breton de Champ (1854) offered a new theorem to redress this shortcoming and elaborated his proposed solution in subsequent papers (1861, 1867, 1870, 1877). Breton de Champs' earliest work precedes the 1858 paper "Démonstration d'une propriété général des surfaces fermées" of Ferdinand (née Frédéric) Reech, the Alsatian thermo- and hydrodynamicist who specified 'critical points' of zero slope on continuous smooth surfaces in descriptive-geometric terms. (A free English translation of Reech's paper was rendered by Warntz, 1967). The hydrodynamicist and mathematical physicist Joseph Boussinesq, a pupil of Saint-Venant, also noted that Saint-Venant's 1852 formulation was incomplete, and developed his own ideas (Boussinesq, 1871, 1872a, b) in a series of exchanges with the French scientist and mathematician M.E.C. Jordan (1872a, b, c). None of the post-1858 works referred to here cite Reech's paper.

The problem of describing slope curvature appears to have attracted little further attention until Müller (1912) cited some of the older French papers in his textbook, wherein he ascribed the earliest descriptive-geometric treatment of ridges and watercourses to Dupuis de Torcy and Brisson (1808). Evidently stimulated by Müller's retrospective, Rothe (1915) further reviewed the French literature, criticizing the formulation of Jordan, and devised yet another geometric definition of ridges and valleys that he claimed solved the problem. Decades lapsed until Rothe's definition was noticed by present-day investigators concerned with the mathematical description of complex surfaces other than topography. Recently, Rothe's work was rediscovered by López (1997, 1999) and by Rieger (1997; pers. comm., e-mail, 09/2001), who disputes the Rothe solution and prefers Jordan's (1872a) definition of ridges and watercourses. Not all contemporary work stems from the foregoing evolution. The characterization of terrain-surface curvature by Shary (2001) and Shary and others (2002), for example, is grounded in the

concepts articulated by Gauss (1827) as also, evidently, has been the curvature-based terrain work of Krcho (1983, 1999).

The descriptive-geometric representation of ridge lines and watercourses is powerful and widely applied (Reeb, 1946; Kweon and Kanade, 1994; Brassard, 1998; Rana and Morley, 2002). Terrain-derived concepts have helped shape research in computer vision and image segmentation, much of which characterizes surfaces other than terrestrial landscapes (Burl and others, 1994; López, 1997; Rieger, 1997; Souille, 1999). The most recent development in machine vision, on-the-fly rendering of digital terrain (Duchaineau and others, 1997), brings the descriptive geometry of irregular surfaces full circle, to natural topography, as computer-game developers attempt to create realistic animations of landscapes for commercial video products (Lindstrom and others, 1996; Blow, 2000; Discoe, 2001). This cutting-edge application of terrain modeling to leisure-time mass entertainment probably commands more financial resources than all geomorphic and hydrologic morphometry combined. Most topographic animation employs some variant of the TIN model (Ware and Kidner, 1997). The military follows a similar approach in some of its three-dimensional simulations of battlefield scenarios (Banks and Wickens, 1997; Thompson and others, 1998), although other defense applications are based on square-grid DEMs (Franklin, 1994).

## **Citation Accuracy and Additions**

Incorrect and incomplete citations—through failure to consult original works, careless manuscript preparation, unproofed typesetting, or, recently, computer errors—are an irritating fact of life. The author tried not to perpetuate them here—or worse, create new ones. However, mistakes invariably enter a large and detailed reference list even when, as in this case, all entries were recorded by one individual in a computer file that has been repeatedly checked and updated. Instances of the errors noted above remain and are the author's responsibility. May they be few and not unduly misleading. Mistakes and omissions found by readers should be referred to the author so that corrections can be released in an addendum or in a more formal publication of the bibliography.

Contributions to this archive from its readers would help fill gaps in the terrain-modeling record, improve annotation, and correct mistakes. Especially desired are current and historical morphometric references that are not readily available in the United States, such as non-English-

language publications from central and eastern Europe and declassified military reports. Work from France and India also is underrepresented. The earlier bibliographies in this series are available for exchange for copies of contributed papers. To reduce ambiguity and ensure accuracy, please send reprints or photocopies of contributions rather than just the citations, if possible. However, new entries can be added from the following brief information:

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  - the name(s) of author(s); surname plus two initials (or, if one given name, then spelled out)
2. year of publication
3. *complete* citation of journal or other form of publication (book, conference proceedings, and so forth), including volume number, issue number, and inclusive pages. For meetings give location and dates; for books the name of city and publisher
4. for publications in languages other than French, German, and Spanish, an English translation of the title and source only.

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## B

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hands-on info for DTM, emphasizing "data sources, general technique (as opposed to specific applications), & ... demystification ..." jchilds@terrainmap.com]

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Chorowicz, Jean, Rouis, T., Rudant, J.-P., and Manoussis, S., 1998, Computer aided recognition of relief patterns on radar images using a syntax analysis: *Remote Sensing of the Environment*, v. 64, no. 3, p. 221-233. [x-band (3,2cm), 2m x 2m pixels, reqd. much filtering & processing]

Chou, Y.-H., Dezzani, R.J., Minnich, R.A., and Chase, R.A., 1995, Correction of surface area using digital elevation models: *Geographical Systems*, v. 2, p. 131-151. [for both planimetric maps & scanned images]

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- Collins, Michael, 1999, The edge of the world—revisiting Earth curvature concerns in terrain modeling: *Digital Data Digest (USACE/TEC)*, v. 5, no. 4, p. 5-7. [line-of-sight calcs. >2000m need correction for curvature]
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- Cowen, D.J., Jensen, J.R., Hendrix, Chad, Hodgson, M.E., and Schill, S.R., 2000, A GIS-assisted rail construction econometric model that incorporates LIDAR data: *Photogrammetric engineering and Remote Sensing*, v. 66, no. 11, p. 1323-1328. [3 m DEM from 0.3 m data; considerable tree-canopy cover tolerated]
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- Cox, R.T., 1994, Analysis of drainage-basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics—an example from the Mississippi Embayment: *Geological Society of America Bulletin*, v. 106, no. 5, p. 571-581. [polar plots of asymmetry vectors (calc. fr transverse topo profiles) for 271 basin segments & streams]
- Cracraft, Joel, 1980, Review of The Measurement of Biological Shape and Shape Change, by F.L. Bookstein, F.L., 1978: *Systematic Zoology*, v. 29, no. 1, p. 102-103. [quant. measurement of shape as the core os systematics; parallels in specific geomorphometry]
- Craddock, R.A., and Howard, Alan D., 2000, Simulated degradation of lunar impact craters and a new method for age dating farside mare deposits: *Journal of Geophysical Research*, v. 105/E8, p. 20,387-20,401. [validates Pike 1974 & 1977 lunar-crater d/D & h/D data]
- Crave, Alain, and Davy, Philippe, 1997, Dynamique et géométrie des réseaux hydrographiques (in French), *in* Davy, Philippe, Guillocheau, François, and Hamelin, Bruno, eds., *Géomorphologie—Processus et Modélisation*: Rennes, Geosciences-Rennes, p. 39-43. [brief examples of analysis of stream networks]
- Crave, Alain, and Davy, Philippe, 2001, A stochastic "precipiton" model for simulating erosion/sedimentation dynamics: *Computers and Geosciences*, v. 27, no. 7, p. 815-827. [based on cellular automata]
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- Cronin, Terrence, 1999, A boundary concavity code to support dominant point detection: *Pattern Recognition Letters*, v. 20, no. 6, p. 617-634. [identifies spurs & draws (small ridges & valleys) from shape of indiv. contours]
- Cronin, Terrence, 2000, Classifying hills and valleys in digitized terrain: *Photogrammetric Engineering and Remote Sensing*, v. 66, no. 9, p. 1129-1137. [fr. containment relations of nested contours, not DEM's; can use open contours at edge of map; good review of prior work]
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- Crozier, M.J., Eyles, R.J., Marx, S.L., McConchie, J.A., and Owen, R.C., 1980, Distribution of landslips in the Wairarapa hill country: *New Zealand Journal of Geology and Geophysics*, v. 23, nos. 5 & 6, p. 575-586. [slope gradient, aspect, & profile location (high, mid, low) of 2206 landslides & parent hillsides]
- Cruden, D.M., and Hu, X.-Q., 1999, The shapes of some mountain peaks in the Canadian Rockies: *Earth Surface Processes and Landforms*, v. 24, no. 13, p. 1229-1241. [slope (cataclinal, anaclinal, dihedral) varies by rock structure; 5 shape types]
- Culling, W.E.H., 1960, Analytical theory of erosion: *Journal of Geology*, v. 68, no. 3, p. 336-344. [by hypothesizing that horizontal flux of eroded material  $\approx$  slope gradient, introduced use of geomorphic 'transport laws' in the conservation of mass to explore controls on landscape form & dynamics; 1st to apply the classical diffusion equation to geomorphology]
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- Currado, Claudia, and Fredi, Paola, 2000, Morphometric parameters of drainage basins and morphotectonic setting of eastern Abruzzo: *Memorie della Società Geologica Italiana*, v. 55, p. 411-419. [relief map; stream orientations; asymmetry & transverse topo. factors]
- Currey, D.R., 1964, A preliminary study of valley asymmetry in the Ogototuk Creek area, northwestern Alaska: *Arctic*, v. 17, no. 2, p. 84-98. [232 map & airphoto slope & azimuth obs. for stream orders 1-4 quantify N (steeper) / S asymmetry]
- Curry, A.M., 1999, Paraglacial modification of slope form: *Earth Surface Processes and Landforms*, v. 24, no. 13, p. 1213-1228. [surveyed gully L, W, depth, vol; nongullied terrain slope & concavity]

Cybulz, Ignatz, 1862, Handbuch der Terrain-Formenlehre, mit einem Anhang über elementar-Unterricht in Terrain-Zeichen nach plastischem unterrichts-Material (in German): Vienna, W. Braumüller, 200 p. [maps & profiles emph. geometry of forms; earliest (?) illustr. (albeit not 3-D) of the 9 slope elements (predates all other refs.); uses Lehmann's (1799) quant. hachure method]

## D

Da Fontoura Costa, Luciano, and Cesar, R.M. Jr., 2000, Shape Analysis and Classification—Theory and Practice: Boca Raton, FL, CRC Press, 659 p. [comprehensive 2-D computer-based shape recognition & analysis, incl. measures for statistical classification; no Earth-sciences examples!]

Dade, W.B., 2000, Grain size, sediment transport and alluvial channel pattern: *Geomorphology*, v. 35, nos. 1-2, p. 119-126. [channel sinuosity related to slope, other params.]

Dade, W.B., 2001, Multiple scales in river basin morphology: *American Journal of Science*, v. 301, no. 1, p. 60-73. [quant. relations among area, relief, & steepness suggest influence of multiple spatial scales]

D'Alessandro, Leandro, Del Monte, Maurizio, Fredi, Paola, Lupia Palmieri, E., and Peppoloni, Silvia, 1999, Hypsometric analysis in the study of Italian drainage basin morphoevolution: *Transactions, Japanese Geomorphological Union*, v. 20, no. 3, p. 187-202. [mult. regression of H on 5 var.; Adriatic & Tyrrhenian basins differ]

Danielson, J.J., 1998, Delineation of drainage basins from 1 km African digital elevation model, *in* Human Interactions with the Environment—Perspectives from Space, Pecora 13, Sioux Falls, SD, August 20-22, 1996, Proceedings: Bethesda, MD, American Society of Photogrammetry and Remote Sensing, CD-ROM; also <<http://www.1.gsi-mc.go.jp/gtopo30/papers/danielson.html>>. [DEM-to-watershed transform applied to the GTOPO30 DEM]

DARPA, 2002, Geospatial Terrain Analysis and Representation (Geo\*): Defense Advanced Research Projects Agency, Defense Sciences Office: <http://www.darpa.mil/dso/future/geo/>. [WWW info. & forum on math. representation & analysis of geospatial data for military applics.]

Dausse, M.F.B., 1857, Note sur un principe important et nouveau d'hydrologie: *Compte Rendus de l'Academie des Sciences*, Paris, v. 44, p. 756-766. [his *pente de de'équilibre* = concept of a limiting slope for fluvial transport]

Dauteuil, Oliver, Blais, Sylvain, Miau, Delphine, Guille, Gérard, and Maury, R.C., 1988, Apports et limites de l'imagerie SPOT et du modèle numérique de terrain pour l'étude du volcanisme intra-océanique—exemple des îles de Raiatea et de Tahaa (archipel de la Société, Polynésie française): *Géologie de la France*, no. 3, 1998, p. 37-50. [20-m DEM @ +25 m vert. fr 1958 IGN contours; alt. freq., topo profiles]

Davis, P.T., 1999, Cirque morphometry, pp. 34-39, *in* Cirques of the Presidential range, New Hampshire, and surrounding alpine areas in the northeastern United States: *Géographie physique et Quaternaire*, v. 53, no. 1, p. 25-45; <http://216.239.33.100/search?q=cache:FDC2dANUwmUC:www.erudit.org/erudit/gpq/v53n01/davis/davis.htm+W.+F.+Thompson+mountains+morphometry&hl=en&ie=UTF-8>. [12 params. on 44 cirques fr 1/20K-1/25K maps, but little stat. analysis; good biblio on prior morphometry]

Davoli, Lina, Del Monte, Maurizio, De Rita, Donatella, and Fredi, Paola, 1999, Geomorphology and tectonics in the Roccamonfina Volcano (Campania - central Italy): *Zeitschrift für Geomorphologie, Supplementband 114*, p. 11-28. [relief amplitude (i.e. 'relief energy', or local relief) & drainage density on 1km squares]

- Davy, Philippe, and Crave, Alain, 2000, Upscaling local-scale transport processes in large-scale relief dynamics: Physics and Chemistry of the Earth (A), v. 25, no. 6-7, p. 533-541. [broad-scale surface model based on DEM-driven erosion dynamics]
- De Beauclair Seixas, Roberto, de Figueiredo, L.H., da Silva, C.A., and Carvalho, P.C.P., 2000, Uma metodologia para geração de modelos de elevação a partir de curvas de nível (in Portuguese; a method to generate elevation models from contours): Anais do GeolInfo 2000, p. 82-87. [contour-to-DEM interpolation; after Gousie 1998]
- De Berg, M., Bose, P., Dobrint, K., van Kreveld, M., Overmars, M., de Groot, M., Roos, T., Snoeyink, J., and Yu, S., 1996, The complexity of rivers in triangulated terrains, *in* Canadian Conference on Computational Geometry, 8th, Proceedings: p. 325-330. [worst-case edge complexity can be quadratic (i.e., bad) in TIN-to-watershed computations]
- De Blasio, F.V., 2002, Note on simulating the size distribution of glacial cirques: Earth Surface Processes and Landforms, v. 27, no. 1, p. 109-114. [narrow size-distr. reproduced fr kinematic stochastic model]
- De Chant, L.J., Pease, P.P., and Tchakerian, V.P., 1999, Modelling alluvial fan morphology: Earth Surface Processes and Landforms, v. 24, no. 7, p. 641-652. [diffusive sed. transp. & unsteady radial flow; sed & flow more important than climate & lithol.?
- De Floriani, Leila, and Puppo, Enrico, 1992, A hierarchical triangle-based model for terrain description, *in* Frank, A.K., Campari, I., & Formentini, U., eds., Theories and Methods of Spatio-Temporal Reasoning in Geographic Space: Lecture Notes in Computer Science, v. 63, no. 9, Berlin & Heidelberg, Springer Verlag. p. 236-251. [define DTM as 1 "a partition of the groundplan, & 2 a family of partially continuous functions, one specified for each part of the partition, & all fncs together form a continuous surface representing the terrain"]
- De Floriani, Leila, and Magillo, Paola, 1999, Intervisibility on terrains, ch. 38, *in* Longley, P.A., Goodchild, M.F., Maguire, D.J., and Rhind, D.W., eds., Geographical Information Systems, v. 1, Principles and Technical Issues, 2nd ed.: New York, Wiley, p. 543-556. [reviews geometric modeling of viewsheds etc.]
- De Floriani, Leila, Magillo, Paola, and Puppo, Enrico, 2000, VARIANT—a system for terrain modeling at variable resolution: Geoinformatica, v. 4, no. 3, p. 287-315. [storage, manipulation, analysis, & visualizing costs > w/ DEM resolution & accuracy]
- De Scally, F.A., Slaymaker, Olav, and Owens, I.F., 2001, Morphometric controls and basin response in the Cascade Mountains: Geografiska Annaler, v. 83 A, no. 3, p. 117-130. [moment stats on 9 params. for 36 debris torr., 79 avalanche, 45 mixed, & 14 stream basins]
- De Smet, Roger, 1951, Principes élémentaires de morphométrie (in French): Rev. Cercle des Sciences (Brussels), v. 1, no. 4, p. 13-16. [no info; see his other 1951 paper]
- De Villiers, A.B., 1986, A multivariate evaluation of a group of drainage basin variables - a South African case study, *in* Gardiner, V., ed., International Geomorphology 1986, Part II: New York, John Wiley & Sons, p. 21-32. [correl. & Fact. Anal. of 59 var. (167 basins): size (max), relief, soil type, texture, eros. index, circularity]
- Debenham, Frank, 1937, Exercises in Cartography: London, publ. unknown, p. 60. [measured contour length by opisometer to calc. clinographic curves]
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Dumoulin, C., Doin, M.P., and Fleitout, L., 2001, On the interpretation of linear relationships between seafloor subsidence rate and the height of the ridge: *Geophysical Journal International*, v. 146, no. 3, p. 691-698. [bathymetric spectrum; age/depth; ridge height/seafloor depth autocorrel.]

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Dunn, R.A., Scheirer, D.S., and Forsyth, D.W., 2001, A detailed comparison of repeated bathymetric surveys along a 300-km-long section of the southern East Pacific Rise: *Journal of Geophysical Research*, v. 106, no. B1, p. 463-471. [spectral analysis, depth differences, size/height threshold]

Dupuis-Torcy, 1st name unknown, and Brisson, Barnabé, 1808, Sur l'art de projeter les canaux de navigation (in French; on locating canals): *Journal de l'Ecole Polytechnique*, cah. 14, no. 7, p. 262-288; republished 1829 as *Un essai sur l'art de projeter les canaux à point de partage* (planning canals linking different drainage basins) in Brisson, B., *Essai sur le système général de navigation intérieure de la France*, paging unknown. [remarkable paper; defined watercourses geometrically as lines of steepest descent which are asymptotically approached by other lines of steepest descent; cited by Müller 1919 (also 1908/12?), & later Rieger 1997 (& thence López 1997) as possibly defining drainage lines analytically (altho no math shown) before their mention by Saint-Venant 1852. Shows how best line for any summit level may be laid out from topographic maps (then in infancy), particularly those of Cassini (?), rather than ground surveying. N.B. France pioneered the engineering of modern canals, which could follow either terrain contours (earlier in the 1760-1840 Canal Age) or a straight line (later); if contours, few expensive earthworks & locks were needed, but resulting route was longer & less direct; the descriptive work reported here led to more accurate cost estimates for cut-&-fill of canals linking different watersheds. See Brisson 1829; Dupuis-Torcy was a civil engineer; a canal he designed in 1804 in Cayenne (Fr. Guyana, where died ca. 1808) is named for him]

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## E

East, T.J., 1978, Mass movement landforms in Baroon Pocket, south-east Queensland—a study of form and process: *Queensland Geographical Journal*, ser. 3, v. 4, July, p. 37-67. [L, W, d, d/L, vol., & slope gradient differ among 5 types (99 landslides); slope map]

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Eastman, Ronald, 2002, *idrisi32*: Worcester, MA, ClarkLabs, Clark University; <http://www.clarklabs.org/IdrisiSoftware.asp?cat=2>. [major upgrade of world's most-used GIS, \$600-\$1500]

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Ebisemiju, F.S., 1976, Morphometric work with Nigerian topographical maps: *Nigerian Geographical Journal (Ibadan)*, v. 19, no. 1, p. 65-77. [air photos, drainage patterns, methods, slopes]

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<[http://www.bgr.de/N2/PROCEED/4\\_4.pdf](http://www.bgr.de/N2/PROCEED/4_4.pdf)>. [exemplifies methods fr simple to multivar. stats. using slope, aspect, plan & profile curv. fr Hesse DEM]
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## G

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Gustafson, E.J., Murphy, N.L., and Crow, T.R., 2001, Using a GIS model to assess terrestrial salamander response to alternative forest management plans: *Journal of Environmental Management*, v. 63, p 281-292. [position on slope between ridge crest and valley bottom fr 30 m DEM]

Guth, P.L., 1999a, Quantifying topographic fabric—eigenvector analysis using digital elevation models, *in* Merisko, R.J., ed., *Advances in Computer-Assisted Recognition: Applied Imagery Pattern Recognition (AIPR) Workshop, 27th, Washington DC, 14-16 October 1998, Proceedings: SPIE (Intl. Soc. Optical Engrg.)* v. 3584, p. 233-243. [adapts Woodcock's 1977 eigenvector method;  $\ln(S1/S2)$  or 'flatness' &  $\ln(S2/S3)$  or 'organization' to DEMs]

Guth, P.L., 1999b, Quantifying and visualizing terrain fabric from digital elevation models, *in* Diaz, J., Tynes, R., Caldwell, D., and Ehlen, J., eds., *International Conference on GeoComputation, 4th, Fredericksburg VA, Mary Washington College, 25-28 July, GeoComputation 99: CD-ROM ISBN 0-9533477-1-0; [http://www.geovista.psu.edu/geocomp/geocomp99/Gc99/096/gc\\_096.htm](http://www.geovista.psu.edu/geocomp/geocomp99/Gc99/096/gc_096.htm). [DEM-based classific. on elev., 'ruggedness', & topo fabric (fr. eigen-analysis)]*

Guth, P.L., 1999c, Contour line 'ghosts' in USGS Level 2 DEMs: *Photogrammetric Engineering and Remote Sensing*, v. 65, no. 3, p. 289-296. [3 ways to show bias in contour-to-grid comp.; Lev. 2 still better than Lev. 1]

Guth, P.L., 2001, Quantifying terrain fabric in digital elevation models, *in* Ehlen, Judy, and Harmon, R.S., eds., *The environmental legacy of military operations: Geological Society of America Reviews in Engineering Geology*, v. 14, p. 13-25. [continues work on terrain fabrics in two 1999 papers to automate the SSO diagram of Chapman 1951 & 52]

Guzzetti, Fausto, Malamud, B.D., Turcotte, D.L., and Reichenbach, Paola, 2000, Power-law correlations of Italian landslide areas (abs.): *Eos Transactions of the American Geophysical Union*, v. 81, no. 48 (Supplement, NG62C-19), p. F566. [area/freq. scaling statistics independent of trigger mech.]

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## H

Haas, C., Liu, Q., and Martin, T., 1999, Retrieval of Antarctic sea-ice pressure ridge frequencies from ERS SAR imagery by means of *in situ* laser profiling and usage of a neural network: *International Journal of Remote Sensing*, v. 20, no. 15 & 16, p. 3111-3123. [large area; 30% error; Fisher-K stats + half width & tail-to-mean ratio]

Hack, J.T., 1965, *Geomorphology of the Shenandoah Valley Virginia and West Virginia and origin of the residual ore deposits: U.S. Geological Survey Professional Paper 484, 84 p.* [map of relief / sq. mi.; hypso. curves; quant. slope-profile analysis; long. stream profiles; azimuthal asymmetry of slope]

Hack, J.T., and Goodlett, J.C., 1960, *Geomorphology and forest ecology of a mountain region in the Central Appalachians: U.S. Geological Survey Professional Paper 347, 66 p.* [early postwar USGS quant.; var. relations, long. profile, slope asymmetry, etc.; recaps G.K. Gilbert concepts; 1st? assoc. of concave-straight-convex slopes w/ var. in vegetation & moisture content]

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- Hall, D.B., 1998, Using digital elevation models to calculate a time-averaged landscape denudation rate: *Physical Geography*, v. 19, no. 4, p. 341-349. [subtr. pre- fr. post-erosion surface to get basin vol. (age interval known)]
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- Hancock, G.R., and Willgoose, G.R., 2001, The production of digital elevation models for experimental model landscapes: *Earth Surface Processes and Landforms*, v. 26, no. 5, p. 475-490. [slope/A plots fr 6.0mm±2.0mm-grid DEM of mini-terrain]
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- Hanssen, R.F., 2001, *Radar Interferometry—data interpretation and error analysis*: Dordrecht/Boston/London, Kluwer, 308 p. [useful historical background & review]
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- Hasbargen, L.E., and Paola, Chris, 2000, Landscape instability in an experimental drainage basin: *Geology*, v. 28, no. 12, p. 1067-1070. [lab analog model 1 m across; ridge density @  $1 \text{ cm}^2$  resolution]
- Hassan, M.M., 1988, Filtering digital profile observations: *Photogrammetric Engineering and Remote Sensing*, v. 54, no. 10, p. 1391-1394. [low-pass filtering of white noise to reduce error in level-1 USGS DEMs]
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- Hayashi, M., and van der Kamp, G., 2000, Simple equations to represent the volume-area-depth relations of shallow wetlands in small topographic depressions: *Journal of Hydrology*, v. 237, nos. 1-2, p. 74-85. [also profiles & % hypsometric curves]
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- Haynes, V.M., 1968, The influence of glacial erosion and rock structure on corries in Scotland: *Geografiska Annaler*, v. 50A, no. 4, p. 221-234. [curves  $y =$  of form  $k(1-x)e^{-X}$  better fit longitudinal profiles of cirques than circles]
- Head, J.W. III, Hiesinger, Harald, Ivanov, Mikhail, Kreslavsky, M.A., Pratt, Stephen, and Thomson, B.J., 1999, Possible ancient oceans on Mars—evidence from Mars Orbiter Laser Altimeter data: *Science*, v. 286, no. 5447, p. 2134-2137. [elev & slope maps, relief shading, flooding-vol. est.]
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- Herrick, R.R., and Sharpton, V.L., 2000, Implications from stereo-derived topography of Venusian impact craters: *Journal of Geophysical Research*, v. 105/E8, p. 20,245-20,262. [Venusian craters 50% deeper than complex craters on Earth; other quant. results]
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- Hevelius, Johannes, 1647, *Selenographia, sive Lunae descriptio, atque accurata tam macularum ejus, quam motuum diversorum, aliarumque omnium vicissitudinum phasiumque telescopii ope deprehensarum, delineatio. Addita est nova ratio lentis expoliendi, telescopica construendi, et horum adminiculo varias observationes exquisite instituendi* (in Latin): Danzig, Hünefeld for the author, 563 p. + 111 engravings. [1st good atlas of Moon, not surpassed for 100 yrs.; a few relative-height determinations from shadow lengths were later compared by Schröter (1791) with his]
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- Holmes, K.W., Chadwick, O.A., and Kyriakidis, P.C., 2000, Error in a USGS 30-meter digital elevation model and its impact on terrain modeling: Journal of Hydrology, v. 233, nos.1-4, p. 154-173. [used GPS data; several params. eval.; geostat. modeling; propagation error worst in drains & along streamlines]
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- Hooke, R.LeB., 1968, Steady-state relationships on arid-region alluvial fans in closed basins: American Journal of Science, v. 226, no. 8, p. 609-629. [log-log fan/basin area; basin slope/area; fan slope/basin area]
- Hooke, R.LeB., 2000, Toward a uniform theory of clastic sediment yield in fluvial systems: Geological Society of America Bulletin, v. 112, no. 12, p. 1778-1786. [elev., relief, slope angle & length]
- Horton, R.E., 1941, Sheet erosion—present and past: Transactions, American Geophysical Union, v. 22, pt. 2, p. 299-305. [measured large river-basins are 'pear-shaped ovoids' in plan, as are basins modeled fr parabolic cross & long. sections]
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- Hovius, Niels, 1996, Regular spacing of drainage outlets from linear mountain belts: *Basin Research*, v. 8, no. 1, p. 29-44. [important neo-orometry! char. stream spacing ( $n = 205$ , 1/250K-1/1000K topo maps) for 10 orogens =  $2.07 \pm 0.16$  the half-width of the mtn. belt (median = 2.13); Himalayas the exception (spacing ratio = 1.17); no explanation; related to Hack's law?]
- Howard, Alan D., 1989, Morphometry of planimetric landforms: Reports of Planetary Geology and Geophysics Program - 1988: NASA Technical Memorandum 4130, p. 313-315. ['path-cutting' & 'convex-stepping' metrics for scarps & fluvial systems]
- Howarth, P.J., and Bones, J.G., 1972, Relationships between geometric form and process on high Arctic debris-slopes, southwest Devon Island, Canada, *in* Price, R.J., and Sugden, D.E., eds., *Polar Geomorphology*: Institute of British Geographers, Special Publication 5, p. 139-153. [measured profiles of talus slopes]
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- Hsu, M.-L., and Robinson, A.H., 1970, The fidelity of isopleth maps, an experimental study: Minneapolis, University of Minnesota Press, 92 p. [depends on character of source distribution (i.e. topo), size & shape of mapping units (pixels), & the number of control points]
- Huang, C., 1998, Quantification of soil microtopography and surface roughness, *in* Baveye, Phillippe, Stewart, B.A., and Parlange, J.-Y., eds., *Fractals in Soil Science*: Berlin, Springer Verlag, p. 153-168. [used 2-D laser scanner to make DEM]
- Huang, Y.D., 2000, Evaluation of information loss in digital elevation models with digital photogrammetric systems: *Photogrammetric Record*, v. 16, no. 95, p. 781-791. [uses rms differences betw. candidate DEM & a much denser DEM 'standard']
- Hubbard, Bryn, Siegert, M.J., and McCarroll, Danny, 2000, Spectral roughness of glaciated bedrock geomorphic surfaces—implications for glacier sliding: *Journal of Geophysical Research*, v. 105, no. B9, p. 21,295-21,303. [micro- & macro-profiles combine in 5-order PSD's that yield 2 bed-roughness indices]
- Huber, William, 1825, Considérations générales sur les Alpes centrales (in French): *Bulletin de la Société Géographique de Paris*, v. 5, p. 105ff. [refined Humboldt's quant. comparison of ridge & summit mean heights by averaging all summits rather than just a sampling]
- Huggett, R.J., 1975, Soil landscape systems—a model of soil genesis: *Geoderma*, v. 13, no. 1, p. 1-22. [added flow lines to Troeh's 1964 four concave-convex elements to segment land-surface form by slope & curvature; 4 block diagrams; crude computer result]

Huggins, K.H., 1935, The Scottish Highlands—a regional study: *Scottish Geographical Magazine*, v. 51, p. 296-306. [delimited by relief (> 700') on 2-mi. grid (O.S. maps); used 800' contour & summits >1500']

Huggins, L.F., and Monke, E.J., 1966, The mathematical solution of the hydrology of small watersheds: Purdue University, W. Lafayette, IN, Water Resources Research Center, Technical Report No. 1, 130 p. [one of 1st true distributed-parameter hydrologic models; basis of ANSWERS model]

Hughes, D.A., 1981, An approach to the quantification of floodplain form: *Area* (London), v. 13, no. 4, p. 285-291. [no info]

Hughes, L.A., Smith, D.H., and Ryley, A., 2001, Robust data compression for digital elevation models (ext. abs.), in Kidner, D.B., and Higgs, G., eds., GIS Research UK 9th, Annual Conference (GISRUK 2001), University of Glamorgan, Wales, 18-20 April 2001, Proceedings: p. 462-467. [no info]

Hughes, R.J., Jr., 1959, Volume estimates from contours: *Economic Geology*, v. 54, no. 4, p. 730-737. [exemplified by cut-and-fill grading of an area]

Humâ, Io., and Râdulescu, D., 1978, Automatic production of thematic maps of slope stability: *Bulletin of the International Association of Engineering Geology*, no. 17, p. 95-99. [early computer map fr quant. coding of variables incl. slope & aspect]

Humboldt, Alexander von, 1808, et ann. suiv., Nivellement barométrique fait dans les régions équinoxiales du Nouveau Continent 1799-1804 (in French; barometric surveying in equatorial regions of the Americas), published as a separate *from* Recueil d'observations astronomiques, d'opérations trigonométriques et de mesures barométriques, Partie 4, 2 vol. (v. 21 & 22) Paris, F. Schoell, Treuttel & Würtz, in Alexandre de Humboldt et Aimé Bonpland, 1805-34, Voyage aux régions équinoxiales du nouveau continent fait en 1799, 1800, 1801, 1802, 1803 et 1804, 30 v., paging unknown. [500 heights calculated by Jabbo Oltmanns fr Humboldt's measurements, Laplace's formula, & Ramond's barometric coeff. It may have been here (otherwise in an unspecified 1807 work) where Humboldt complained that heights of only 62 of the world's mountains were measured and he had accounted for half]

Humboldt, Alexander von, 1817, De distributione geographica plantarum secundum coeli temperiem et altitudinem montium, Prolegomena (in Latin; on the geogr. distr. of plants in the new world, temperatures, & heights of mountains): *Lutetiae Parisiorum*, Paris & Lubeck, 250 p., hand-colored engraved foldout map. [footnote to p. 112 in *Edinb. New Phil. Jour.*, (1845, v. 39) says p. 81 & 182 (82?) of the 1817 work mention 'the distinction which is so important to climatology & human civilization, of continents having uniform, and those having indented coasts; ... the relation of the extent of coasts to the area of the continent, which is ... *the measure of the accessibility of the interior*' This is the (later) much-pursued quantification of continental area/perimeter, or 'coastal development' (*Küstenentwicklungen* i.e. 'convolution'). The concept, attributed by Humboldt to Strabo & evidently 1st quantified by Ritter (1826, 1828), claims that highly indented coasts, e.g. Europe, lead to more advanced cultures]

Humboldt, Alexander von, 1835, article title unknown: *Berghaus' Annalen der Erdkunde*, v. 12, p. 490ff. [contains material on '... the relation of the extent of coasts to the area of the continent, which is ... *the measure of the accessibility of the interior* ...' (ref. = *Edinb. New Phil. Jour.*, 1845, v. 39, p. 112 footnote is early mention in English of the (later) much-pursued quantification of continental area/perimeter, or 'coastal development' (i.e. *Küstenentwicklungen* or 'convolution'). The concept, attributed by Humboldt to Strabo & evidently 1st quantified by Ritter (1826, 1828), claims that highly indented coasts, e.g. Europe, lead to more advanced cultures]

Humboldt, Alexander von, 1843c, An attempt to determine the height of continents: *Edinburgh New Philosophical Journal*, v. 34, art. 12, p. 326-337. [measured heights refute Laplace's 1825

deduced mean height of Earth's continents of 1000 m (3028'); see several other A. von H. refs. to this work]

Hunt, C.B., 1950, Military geology, *in* Paige, Sidney, ed., *Application of Geology to Engineering Practice*: Geological Society of America, p. 295-327. [scopograph' instrument projected contour maps into landing-craft-level visualizations of terrain; basic descr. of terrain (incl. map units) for observation, concealment, cover, trafficability; WW II experience]

Hurtrez, J.-E., Lucazeau, F., Lavé, J., and Avouac, J.-P., 1999, Investigation of the relationships between basin morphology, tectonic uplift, and denudation from the study of an active fold belt in the Siwalik Hills, Nepal: *Journal of Geophysical Research*, v. 104, no. B6, p. 12,779-12,796. [of 27 params (17 basins), only basin elev & hyps. int. correl signif. w/ uplift rate; re-derives hypsometric integral (no ref. to Pike & Wilson 1971)]

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## J

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## K

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[area/perimeter relation; Küstengliederung (coastal arrangement) in %,  $e = (100/U)(U-K)$ ; for K see Rohrbach, 1890]

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## L

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## O

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## R

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- Sonklar, C.E. von I., 1862, Die Gebirgsgruppe der Hohen Tatra (in German): Petermanns Geographischen Mitteilungen, v. 8, no. 4, p. 121-125. [compares Ötzthaler Alps & Hohen Tatra across 7 of the 12 parameters later summarized in 1873 book]
- Sonklar, C.E. von I., 1866, Die Gebirgsgruppe der Hohen-Tauern, mit besonderer Rücksicht auf Orographie, Gletscherkunde, Geologie und Meteorologie, nach eigenen Untersuchungen dargestellt (in German): Vienna, Beck'sche Universitäts-Buchhandlung, 408 p. [Pt. 1, Orographie, Orometrie, Topographie; further use of some of the morphometric measures later summarized in his 1873 book]
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- Sparks, B.W., 1952, Stages in the physical evolution of the Weymouth Lowland: Transactions and Papers of the Institute of British Geographers, no. 18, p. 21. [elaborated the height-range diagram of Sparks 1949]

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- Stark, C.P., and Hovius, Niels, 2001, The characterization of landslide size distributions: *Geophysical Research Letters*, v. 28, no. 6, p. 1091-1094. [power-law scaling, but small failures are strongly undersampled]
- Stark, C.P., and Stark, G.J., 2001, A channelization model of landscape evolution, *in* Pazzaglia, F.J., and Knuepfer, P.L.K., eds., *The steady-state orogen—concepts, field observations, and models: American Journal of Science*, v. 302, nos. 4 & 5, p. 486-512. [sub-grid scale parameterization aggregates channel properties of roughness, srface morph., cross-sect.]
- Steger, Carsten, 1997, Removing the bias from line detection *in* CVPR '97, IEEE International Conference on Computer Vision and Pattern Recognition, 17-19 June, Puerto Rico, Proceedings: p. 116-122. [develops explicit model for surroundings of curvilinear structures ('lines') as well as lines themselves]
- Steger, Carsten, 1998, An unbiased detector of curvilinear structures: *IEEE Transactions on Pattern Analysis and Machine Intelligence*, v. 20, no. 2, p. 113-125. [similar to Steger 1997 (& unpubl. 1997 Ph.D. dissertation)]
- Steger, Carsten, 1999, Subpixel-precise extraction of watersheds, *in* IEEE International Conference on Computer Vision 7th (ICCV'99), 20–25 September, Corfu, Greece, Proceedings (CD-ROM): p. 884-890. [critical points & flowlines fr Gaussian filter derivatives superior to pixel-by-pixel routing]
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- Steinhauser, Dr., 1864, comments (in German) *in* Bothe (1864a), p. 406. [the area/perimeter problem; 'coastal convolution' =  $((U/4)^2)/F$ , U = coast length, F = land area]
- Stelford, Mark, 1998, Sources of error in morphometrically defined hydrologic source areas (abs.), *in* Hallam, C.A., and Salisbury, J.M., eds., GIS Applications in Water Resources Research—American water Resources Annual Meeting, Chicago Ill, November 6-10, 1994: U.S. Geological Survey, Open-file Report 98-751, p. 19. [problem = 'sinks' in glaciated & karst terrain on 7.5' DEM's not real]
- Stepinsky, T.F., Marinova, M.M., McGovern, P.J., and Clifford, S.M., 2002, Fractal analysis of drainage basins on Mars: *Geophysical Research Letters*, v. 29, no. 8, p. 30-1 to 30-4. [4-point network descriptor fr Tarboton algorithm on 0.5 km DEMs of old mtn. terrain fr MOLA data]
- Sternberg, H., 1875, Untersuchungen über Längen- und Querprofil geschiebeführender Fluss (study of the longitudinal & transverse profile of the most (?) prominent river; in German): *Zeitschrift für Bauwesen*, v. 25, no. 11-12, p. 483-506. [the Rhine; 1st to suggest long. profile = exponential curve; related slope to sediment size—see Gilbert 1877]
- Stevens, N.F., Wadge, G., and Murray, J.B., 1999, Lava flow volume and morphology from digitised contour maps—a case study at Mount Etna, Sicily: *Geomorphology*, v. 28, nos. 3-4, p. 251-261. [differences 10-m DEM's fr 1969 & 1991 1/25K maps, 25-m Cl; not OK for thin flows]
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## V

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