Published in: Michael P. Bishop and John F. Shroder (eds.), *Geographic Information Science and Mountain Geomorphology,* Chichester, England: Springer-Praxis, 2004, 75–100.

3

A science of topography: From qualitative ontology to digital representations

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3.1 INTRODUCTION

Mountains are among the most prominent of geographic features (Smith and Mark, 2001). They also have social and emotional significance, serving as objects of worship in many cultures and as landmarks in many more. And, of course, mountains provide challenges to adventurers and scientists alike. Thus it should come as no surprise that geomorphologists and other environmental scientists have been drawn to mountains in conducting their research.

But what exactly are mountains; what is their ontology, or the nature of their reality? Certainly, mountains are not among the most typical examples of *objects*. Typical objects (apples, people, cars) have distinct, complete, closed boundaries that separate them spatially from their surroundings. Mountains, in contrast, have crisp boundaries only with the atmosphere above. Where they meet the earth below and laterally, typical mountains do not have crisp boundaries that separate them sharply from their surroundings. Instead, each mountain blends gradually into neighboring mountains, or fades into foothills or plains and into the body of the Earth beneath (which itself is a prototypical object, its boundary being constituted by an irregular crust whose surface has concave and convex regions).[1] But do mountains exist as objects of study in their own right?

Cartographers have long avoided the problems raised by the absence of crisp boundary delimitations in the case of mountains by representing the latter indirectly. The summit of the mountain is often marked on a map by a point symbol, which may have an associated name or elevation. In addition, the general shape of the mountain may be indicated by contours or hill shading, but the limits (horizontal

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[1] We do not mean to restrict our discussion to the planet Earth. Mountains and other landforms certainly exist on Mars, the Moon, and other planets with rocky crusts.

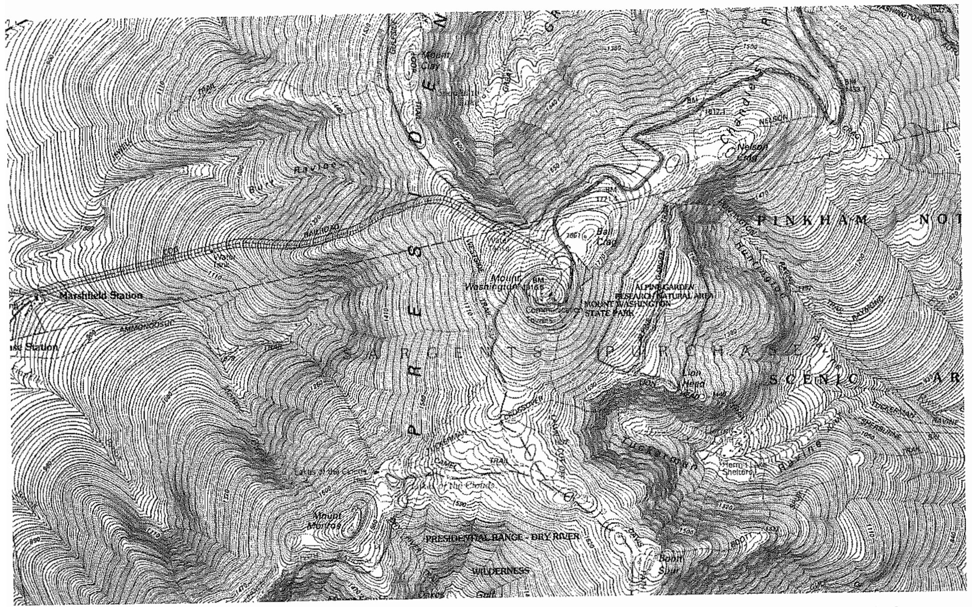

Figure 3.1. On this fragment of the Mount Washington 1 : 24,000 topographic map, it is up to the map reader to determine what feature, point, or region the words "Mount Washington" refer to.

Image obtained from http://www.terraserver.com

boundaries) of the mountain are left unmarked, to be inferred by the map reader (Figure 3.1).

It is not only individual mountains that are marked by vagueness or gradation in their boundaries. The category *mountain*, too, is somewhat problematic, for this category is not clearly delimited from other landform kinds. In English, for example, the difference between a hill and a mountain is in many contexts an arbitrary one. This is in contrast with the difference between, say, a dog and a cat, or between a parrot and a canary. As will be discussed below, however, mountains as a kind are not unusual, because categories from many inorganic domains share a similar degree of arbitrariness (Smith, 2001).

The problems just sketched may appear to be of little practical importance for geomorphology or environmental modeling. A formal specification of the ontology of a domain of reality is, however, a prerequisite for effective representations able to support scientific computing (Genesereth and Fikes, 1992; Mark et al., 2004). Thus the advancement of environmental modeling and mountain geomorphology in a computational setting requires a formal ontology of mountains and of the topographical or landform domain to which mountains belong.

In this chapter we will first review the nature of mountains and of related topographic features by describing their ontology. We will then give an overview of the methods available to represent topography in computational environments in order to support high-level (or at least high-altitude) environmental modeling.

3.2 ONTOLOGY OF MOUNTAINS AND TOPOGRAPHY

3.2.1 Ontology

Ontology is the discipline that seeks to answer the question: what exists? It seeks to establish the types and structures of objects, properties, events, processes, and relations in all domains of reality. In this sense, ontology is a branch of philosophy that deals at very high levels of abstraction with what may be the most fundamental question of all scientific inquiry. More recently the term *ontology* has been used in information science and in work on knowledge representation to refer to formal specifications of the systems of concepts employed by different groups of users in regard to domains of objects of different types. Characteristically, such specifications involve the laying down of a standardized taxonomy of the objects in a domain, or they involve some standardized lexicon of terms of a sort that can support automatic translation from one data context to another. A summary of ontology for the geospatial domain—in both senses of the term *ontology*—is provided in Smith and Mark (2001) and in Mark et al. (2004).

3.2.2 Ontology of objects

Prototypical objects are those entities in the environment that are detached from their surroundings and that can move or be moved from one place to another: pebbles, boulders, leaves, fruit, and animals, as well as such artifacts as chairs, hammers, or books. Such things have been called "detached" objects (Gibson, 1979), and we may also refer to them as *manipulable* objects. Such objects are three-dimensional, predominantly convex, have completely closed boundaries, and are movable within space independently of other objects; furthermore, they endure through some time period and have properties that persist as they are moved.

Importantly, however, our tendency to conceive of our environment as populated by objects is so pervasive that the object concept is extended far beyond its original domain of application. Thus it is extended to what Gibson (1979) called "attached" objects, which means: to such nondetachable parts of larger objects as noses or chins, and even to holes (i.e., to regions of space bounded by concave material boundaries: Casati and Varzi, 1995). Noses and chins are in the end nothing more than projecting regions of faces or heads, but they are treated as objects in their own right through cognitive extension. Likewise, our tendency to categorize in object terms is cognitively extended to nonmanipulable entities much larger than people. Mountains, for example, are not detached from their environment, yet people attribute to them many of the properties of objects of smaller scale. The same sort of cognitive extension occurs also in relation to concave or negative features of the Earth's surface, so that holes, such as valleys, canyons, and craters, may be thought of as objects also.

Geographic objects

Objects are distinguished from entities in other ontological categories (e.g., events, processes, relations, properties) in that they are commonly given proper names. This applies, too, to individual geographic entities, such as landforms and water bodies. Arrays of named landforms have formed the reference frames for characterizing the locations of plant, animal, and artifact locations in scientific collections, and they likewise provide landmarks to support qualitative geospatial referencing. This is because named landforms are the units that serve as landmarks (i.e., they guide activity in the field). Individual geographic entities are also apprehended as falling under types, kinds, or categories to which general names are assigned. Thus particular landforms may be considered to be *mountains*, *valleys*, *escarpments*, *ranges*, *moraines*, etc.

There are many ways, however, in which objects and categories at geospatial scales differ from smaller objects (Smith and Mark, 1998; Mark et al., 1999). These differences have largely been ignored to date by cognitive scientists, as well as by ontologists, all of whom have thus far focused their attentions on the characteristics of small bounded objects and on the events, processes, attributes, and roles associated with these. It is rare for the location of the boundary of a manipulable object to be indeterminate or ambiguous; yet this characteristic seems relatively common for geographic objects, such as mountains, valleys, plains, and wetlands (Burrough and Frank, 1996). It is this indeterminacy that makes it difficult to develop computer algorithms that can transform in automatic fashion a natural continuum or field of geographic variation into nonarbitrary entities belonging to geographic categories. Yet people in the contexts of everyday life perform this transformation task rather easily.

3.2.3 Ontology of landforms (features)

One of the most interesting properties of landforms from an ontological perspective is that they are exactly what their name suggests: they are *forms*. Specifically, a landform is a part of the Earth's surface that is characteristically apprehended as a unitary entity because of its particular shape. As noted above, landforms are attached objects in the taxonomy of Gibson (1979); they might also be thought of as partial objects, as parts of the Earth's surface or parts of the landscape. Some forms (e.g., arêtes, horns, moraines, or cinder cones) reflect outcomes of particular processes, and others, such as valleys or plains, are marked only by the fact that they have a characteristic shape. In any case, geomorphological processes play at best a secondary role in triggering the cognitive routines that people bring to bear in conceptualizing regions of the given sorts as objects. The first step in an ontology (taxonomy) of landforms thus needs to focus on form, which means that it must exploit the tools derived from qualitative geometry, the theory that deals with such notions as convex, concave, cone-shaped, etc. (Bennett et al., 2000) and it must attempt to integrate such qualitative concepts with the quantitative concepts used by science, especially when elevations are conceived of as fields.

In addition, however, a method must be found for taking account of the already noted fact that the boundaries of shape-based landforms have the peculiar property that they exhibit *vagueness* or *gradedness* (Bennett, 2001; Bittner and Smith, 2001; Varzi, 2001). Administrative boundaries (e.g., counties) are spatially crisp, whereas landform boundaries—the boundaries around a hill or mountain—are indeterminate (Usery, 1993, 1996a, b). Many kinds of landforms, including mountains, are such that their entire margin is characterized by clines or gradients of curvature or slope. Note that this is not the case for those natural geospatial features whose definition or boundary is constituted partly or wholly by a shoreline (e.g., *island*, *isthmus*, *peninsula*), or for artificially constructed forms, such as embankments and dams (Bittner, 2001).

Landforms also are in many cases *parts* of other landforms and all are parts of the Earth's surface; thus mereology, the science of parts and wholes (Smith, 1998), will play a role in our formal understanding of landforms as entities. Every mountain is a part of a larger whole (the Earth's surface) and commonly is part of intermediate forms, such as mountain ranges. Typically, a mountain corresponds to a convex region of the Earth's surface. The mountain itself is then identified (prototypical case) with this convex protrusion, regardless of the indeterminant nature of identifying the boundary of its foot. Similar definitions can be produced for a typical mesa, hill, or butte, and the ontology of landforms must examine to what extent the same components of qualitative form are involved in all of these. To deal with concave parts of the Earth's surface, such as valleys, canyons, or trenches, the theory will also need to include such tools as the formal theory of holes presented by Casati and Varzi (1995).

3.2.4 Types and tokens: geographic kinds

It is important to distinguish between types and tokens, or in other words between kinds of entities and the individual entities themselves which instantiate these kinds. A token (e.g., Mount Everest) is an individual entity, whereas a type, such as *mountain*, *hill*, or *lake*, is a kind or category. Types and tokens are difficult to confuse when dealing practically with the real world, because tokens are tangible objects whereas types exist as abstractions. On the theoretical level, however, the type/token distinction is often beset by confusions, and it will be incumbent on us here to keep separate the issues pertaining to these two levels.

In some domains of reality, kinds or types clearly exist in the world in a way that is independent of our judgment. Two such domains are biology, where natural selection produces distinct species, and artifacts, which normally are designed for specific purposes. It probably is no coincidence that organisms and artifacts have been the primary subject matter for studies of categorization by psychologists and other cognitive scientists (Rosch, 1973, 1978). Such studies of the role of categories in human cognition have employed a conception of natural kinds ("nature cut at its joint") that operates well in relation to manipulable objects, such as pets and tools, but less well when applied to inorganic natural domains, which are marked by the absence of processes that work against the existence of continuous variation, gradual change, and intermediate kinds. For example, a rock that is midway between granite and gneiss is at no disadvantage compared with the pure types at either extreme. Thus while biological species may be present as distinct kinds in nature independent of cognition and cognizers, categories or types for inorganic natural domains might have category limits of a different type, with the cuts between categories reflecting at least some degree of human-induced arbitrariness and thus also a potential for variation across cultures.

It is against this background that landform, water body, and other natural geographic kinds are to be understood. While no hill is a valley and no mountain is a molehill, there is often no clear fact of the matter about whether a particular convex part of the Earth's surface is a mountain or a hill (Fisher and Wood, 1998). We know that different terms are often used by different speech communities within a single language to refer to identical kinds of entities in the world. A geographic example of this phenomenon is the variation in the generic portions of the terms for water courses in American English, where cultural traditions lead to regional replacement of terms for small water-courses (creek, brook, kill, etc.) in various subregions of the northeastern United States. Can the phenomenon of cultural and geographic variation be detected also in the domain of landforms? Are ravines and gullies synonyms referring to identical kinds of small valleys? If not, what are the differences in the kinds of entities to which these terms refer? Perhaps the terms *ravine* and *gully* are used systematically to distinguish two different kinds of small valleys in some languages or speech communities. Questions such as this—which are essentially questions of definition of kinds of landforms—become even more interesting in the cross-linguistic context. Mark (1993) studied the analogous question in relation to kinds of water bodies and found that while "pond" in English and "étang" in French commonly are the best translations for each other, the terms are not exact synonyms even though they are listed as equivalents in almost all French–English dictionaries.

Research on establishing a complete taxonomy of landform types is thus by no means a routine task. It cannot be solved merely by examining entries in bilingual dictionaries. Dictionary definitions themselves often reflect an inconsistent ontology, or an ontology that is biased toward the standards prevailing in some given, culturally dominant idiolect. To establish a complete taxonomy of landforms will require, rather, ontological analyses based on independent analyses of the qualitative geometry and mereotopology of the corresponding landforms themselves, complemented by comparison of definitions drawn from a range of different languages and dialects. It will also require experiments designed to gauge the ways in which different individuals classify landform types given identical topography.

3.3 KINDS OF LANDFORMS

The compilation of a comprehensive list of terms that refer to kinds of landforms is not an end in itself. Rather, it is designed to provide essential input to further theorizing about a range of open questions, relating, for example, to whether the kinds of landforms recognized by people are universal across geography, culture, and language, or whether the kinds recognized by one speech community are in significant ways quite different from those recognized by another.

3.3.1 Geomorphologists' landform types

The objective of geomorphology is to elucidate the nature of landforms and the processes that shape or produce them. In a recent essay Rhoads (1999) claimed that "the extent to which geomorphology as a distinct field of science can be justified on ontological or epistemological grounds seems to depend on the extent to which landforms can be viewed as natural kinds." This strong claim can be broken down into two components: (1) geomorphology is a science of landforms; (2) only if landforms constitute natural kinds can they play a role in the making of scientific predictions. Two subsidiary claims also seem to be implied: (1′) landforms are entities or objects, rather than abstractly demarcatable parts of continuous fields of variation; and (2′) landforms must be distinguished from nonlandforms by a natural distinction that is likely to be universally recognized in all human cultures.

In assessing the validity of these claims, it is important to draw attention to the fact that the very name of the discipline of geomorphology may be misleading. The etymology of the term *geomorphology* certainly suggests that *landforms* (shapes) are its primary focus. For almost a century, however, the study of mere form or shape has been unfashionable in geomorphology, and mainstream research has focused on process, especially on mechanics. Studies of process, however, are much more easily harmonized with local or global representations of the Earth's surface in terms of fields of elevations, rather than with quantitative or qualitative representations of shapes or forms. Thus (1) and (1′) in the list above must almost certainly be questioned. On the other hand, (2) is an immediate inference from the standard definition of the term "natural kind" in contemporary philosophy of science, while (2′) is an empirical question, which is the subject of some of the ongoing research that is described in this chapter.

What, then, is to be said in defense of the ideas of Rhoads (1999)? As we argued in our paper on whether or not mountains exist (Smith and Mark, 2003), it is highly unlikely that reference to landforms—as contrasted with reference to human action and cognition in relation to landforms—can play a role in scientific predictions. Data from human subjects (Smith and Mark, 2001) confirm the importance of landforms in common sense reasoning and communicating about the Earth's surface. Our hypothesis is that landforms as objects are also important to geomorphologic science, not, however, because appeal to landforms sustains scientific predications, but rather because it is landform concepts that determine which processes are held by geomorphologists to be of scientific interest. Geomorphology is in this respect comparable with paleontology. The latter studies a world in which humans are largely absent, yet it studies features of that world at scales that are of interest to humans; if it did not do so paleontology would itself be lacking in all intrinsic interest.

3.3.2 Common and cartographic landform types

One major source of landform taxonomies is provided by spatial data standards, sometimes known as cartographic data standards. These often contain lists of real world categories (types) to which individual geographic entities (tokens) are then assigned in different database or mapping contexts. Two important standards of this type with direct relevance to the United States are the Spatial Data Transfer Standard (SDTS), discussed in the next subsection, and the Geographic Names Information System (GNIS). An important international standard is the digital geographic information standard (DIGEST) adopted by military mapping agencies of several NATO countries (DGIWG, 1992). There is also a Canadian government list of English and French landscape generic terms (Natural Resources Canada, 1997), and many other similar sources. Draft lists of landform terms in other languages may be obtained by translating the terms from the standards mentioned earlier in this paragraph using multilingual dictionaries or machine translation programs.

3.3.3 Entity types, included types, and definitions

The U.S. SDTS, a U.S. Federal Information Processing Standard (United States Geological Survey, 1994; Fegeas et al., 1992) provides a list of 199 "entity types"—the SDTS term for types (kinds) of geospatial entities that are held to exist in the real world. In order to be represented in an SDTS-compliant database, any landform (or other geographic feature) must be assigned to one of these entity types. Of the 199 SDTS entity types, 26 appear to fall under the broad superordinate category of "landform":

> bar, basin, catchment, cave, cirque, cliff, continent, crater, cut, earth surface, flood plain, gap, ground, ground surface, moraine, mount, mount range, peak, pinnacle, plain, plateau, ridge, ridge line, terrace, trough, and valley (see Table 3.1).

Each SDTS entity type also includes a list of up to 28 "included types", which are either synonyms or subtypes of the type in question. For example, the included types for *mount* are:

> bald, bank, bery, cerrito, cerro, cinder cone, cuesta, dome, drumlin, foothill, hill, hillock, hummock, kame, knob, knoll, lava cone, monadnock, mound, mountain, pingo, rise, sand dune, sand hills, seaknoll, seamount, shield volcano, and volcano (see Table 3.1).

A key research issue is: can one compile a list of landform types and subtypes that are universal for all peoples and cultures, and a set of further lists that includes all types relevant to each specific culture? Or do the types themselves form a continuum of more or less arbitrary subdivisions of reality? Are landform types like colors, which form a continuum, but nevertheless are labeled in surprisingly similar ways in different languages (Berlin and Kay, 1969)? Or are they rather analogous to temperatures, with no intrinsic significance capable of being assigned to such vague notions as hot, warm, cold, and so on? Finally, if there is a single taxonomy of landform types that is at some level of generality common to all cultures, then what will its structure be? How many independent dimensions will we need to capture all the types of entities involved in terms of basic structural components?

3.4 PROBLEM OF DELIMITATION OF INDIVIDUALS

For geographic entities, as we have seen, there is not only a problem of defining the limits of categories, kinds, or types but also a problem of delimiting individual landform tokens. Suppose some particular portion of reality A is considered to be an instance of some topographic type T? We may ask whether some slightly larger portion of reality A', or some slightly smaller portion A'', is an even better example of type T, or, on the other hand, perhaps not a case of T at all. If a slightly different region is taken, is the region likely to be identified as an object of a different type? Delimitation means here: determining the spatial extent of an individual (i.e., marking the latter's boundaries). Equivalent questions for manipulable objects, such as "where does the cup end and the table begin?" would never arise in normal discourse or in reasoning at mesoscopic scales, even though technically these questions may be nontrivial at subatomic scales. Delimitation, however, is a genuine question for landforms, and this may in part explain why landforms are seldom represented explicitly on maps or in geospatial databases. This is at least in part a question of vagueness, but it is not just vagueness, since there are circumstances where we might hold that one and the same clearly demarcated portion of reality instantiates not one but two distinct feature types (e.g., a piece of land surrounded by water can simultaneously be an island and a volcano).

Even if it is unambiguous that a geographic object of type T exists at some location, there may be disagreement or uncertainty regarding this object's spatial extent and, in particular, regarding the location and nature of its boundary. Occasionally, landforms have real boundaries composed of genuine physical discontinuities, such as breaks of slope, shorelines, or sharp changes in material. But, commonly the boundaries of landforms are graded or clinal, and robust methods for dealing with such phenomena within information systems have not yet been developed.

There is an additional subtle issue here that may come into play: the boundary of the same entity may be different, depending on the kind of entity it is considered to be. Again, clear examples of this phenomenon can be found in the domain of water bodies and wetlands. If X is considered to be a lake, its boundary might be at one place (L), whereas if that same region is considered to be a bog, its boundary might be placed at a different location (L'). We suspect that careful cross-linguistic or cross-cultural research will uncover cases where the boundaries of landform tokens interact in similar ways with the associated landform kinds.

Table 3.1. Landform entity types, definitions, and included types.

Entity type	Definition	Included types
Basin	Any bowl-shaped depression in the surface of the land or ocean floor	Barrier basin, camber, cauldron, depression, kettle, nontidal basin, pit, sabkha, sink, sinkhole, tidal basin, wave basin
Catchment	An area drained by a single water-course; a natural drainage area which may coincide with a river basin, in which the divides direct the water from the rainfall and percolation into a river. Where underground flow is involved, however, the catchment may be larger or smaller than that which may be apparent from the surface relief	Drainage basin
Cave	Naturally formed, subterranean open area or chamber	Cavern, grotto, notch
Cirque	A deep natural hollow near the crest of a mountain	(None)
Cliff	A high, steep, or overhanging face of rock	Beach scarp, bluff, ceja, crag, escarpment, ice cliff, marine cliff, palisade, precipice, scar, scarp, scaw
Continent	One of the large, unbroken masses of land into which the Earth's surface is divided	(None)
Crater	Circular-shaped depression at the summit of a volcanic cone or on the surface of the land	Caldera
Cut	An excavation of the Earth's surface to provide passage for a road, railway, canal, etc.	(None)
Earth surface	The outermost surface of the land and waters of the planet	(None)
Flood plain	An area which is subject to periodic flooding	(None)
Gap	Low point or opening between hills or mountains or in a ridge or mountain range	Col, defile, mountain pass, notch, pass, saddle, sill
Ground	The solid portion of the Earth up to and including the ground surface	(None)
Ground surface	The land surface of the Earth, both exposed and underwater	(None)

Table 3.1. *(cont.)*

Entity type	Definition	Included types
Moraine	An accumulation of boulders, stones, or other debris carried and deposited by a glacier	Delta moraine, end moraine, glacial moraine, lateral moraine, terminal moraine
Mount	A mountain or hill	Bald, bank, bery, cerrito, cerro, cinder cone, cuesta, dome, drumlin, foothill, hill, hillock, hummock, kame, knob, knoll, lava cone, monadnock, mound, mountain, pingo, rise, sand dune, sand hills, seaknoll, seamount, shield volcano, volcano
Mount range	A series of connected and aligned mountains or mountain ridges	Mountain range, range, seamount chain, seamount group, seamount range
Peak	The summit of a mountain	Ice peak, nunatak, seapeak, summit
Pinnacle	A tall, slender, spire-shaped rock projecting from a level or more gently sloping surface	Chapeirao, coral head, crag, pillar, precipice, scar
Plain	A region of general uniform slope, comparatively level, and of considerable extent	Apron, archipelago apron, coastal plain, outwash plain
Plateau	An elevated and comparatively level expanse of land	Butte, guyot, intermontane plateau, mesa, tableknoll, tableland, tablemount
Ridge	A long and narrow upland with steep sides	Arête, beach cusps, beach ridge, cerro, crest, cuesta, drumlin, esker, kame, range, sand dune, sand hills, sill, spur, volcanic dike
Ridge line	The line seperating drainage basins	(None)
Terrace	A step-like feature between higher and lower ground: a relatively flat or gently inclined shelf of earth, backed and fronted by steep slopes or man-made retaining walls	Bench, kame terrace, marine bench, raised beach, rock terrace
Trough	A long depression of the sea floor	Deep, foredeep, runnel, swale, trench
Valley	A long, narrow depression in the Earth's surface, usually with a fairly regular downslope	Canyon, chasm, coulee, crevice, dale, defile, dell, depression, drowned valley, glacial gorge, glacial trough, glen, goe, gorge, graben, gulch, gully, hollow, moat, ravine, re-entrant, rift valley, seachannel, strath, trench, water gap

3.5 COMPUTATIONAL REPRESENTATIONS OF TOPOGRAPHY

3.5.1 Ontology of fields

We claimed earlier that the scientific approach to landforms has for some time been predominantly a matter not of the investigation of objects and (qualitative) categories, but rather of processes and (quantitative) fields. A *field* may be defined as a single-valued function of space-time position. We will restrict our attention here to geospatial fields (i.e., to surfaces that are single-valued functions of position in a 2-D space covering a geographic area.

Fields, clearly, are closely associated with the principles that underlie contour maps. Despite the fact that ancient Greek and medieval Arabic and Chinese scholars used many sophisticated concepts when describing geographic phenomena, including mathematics, it appears that they did not use contour lines or other isolines to portray fields. Also, although elevation contours may be the most familiar form of isolines today, other types of isoline maps were in fact produced earlier than the first known uses of elevation contours on maps. According to Thrower (1970), the technique of representing fields by isolines dates only from 1643, when Christoforo Borri apparently produced a simple isogonic[2] map in manuscript form. The first published contour maps of dry land areas (topographic surface elevations) were produced in France in the 1750s.

3.5.2 A mathematical model of topography

Cayley (1859) first advanced the mathematical theory of geospatial fields in a paper in which he laid out a comprehensive theory of continuous, smooth, single-valued surfaces. Contour lines connect points at which the elevation field has some specific constant value, and slope lines are lines in the direction of steepest slope, locally perpendicular to the contour lines.

Cayley (1859) appeared some four years before the first use of the term "magnetic field" in published English recorded by the *Oxford English Dictionary* (OED). Maxwell (1870) published a paper "On hills and dales", in which he rediscovered some of the principles of contour lines and slope lines from Cayley (1859), but added a naming system for surface regions. On a continuous, smooth surface, exactly one contour line and one slope line cross each other at every point, except at singularities: points at which the gradient is exactly zero. The latter, which are of particular importance to this model of surfaces, are of three kinds, called peaks, pits, and passes.

Peaks are local maxima on the surface and *pits* are local minima. An infinite number of slope lines converge at each peak at their upper ends, and likewise each pit is a point of convergence of the lower ends of the many slope lines that drain to it. *Passes* are the other kind of singularity and are especially interesting. They form saddle points, and small circles around a pass must pass through at least two high points and two low points. The two slope lines leading from the pass through these high points continue up to peaks and are called *ridge lines* in the Cayley/Maxwell terminology; they correspond precisely to what we now call drainage divides. Ridge lines are mirrored by *course lines*, the two slope lines that lead from each pass down to pits. On a smooth surface (continuous in at least the first derivative), slope lines can meet each other only at peaks, pits, or passes.

Maxwell (1870) defined a *hill* as the region filled by all slope lines that connect to a particular peak. The ontology of hills on this view defines them as 2-D surfaces with a certain relation to their surroundings. There is then a one-to-one correspondence between hills and peaks, and each hill is bounded by course lines. In similar fashion the region defined by all the slope lines draining to a particular pit was termed a *dale* by Maxwell (1870), and each dale is bounded by ridge lines. Dales, too, are ontologically two-dimensional on this theory, and each dale corresponds exactly with a drainage basin. In this way form and process are linked together. Hills as defined by slope lines, in contrast, are not known to correspond exactly with any particular kind of landform or region defined by surface process; they are regions of divergence.

Note that every point on a field, except peaks, pits, passes, and points of ridges and course lines, falls in exactly one dale and also on exactly one hill. Maxwell used the term *territory* to refer to a connected region corresponding to the intersection between one hill and one dale. Every cell in the network formed by the ridge lines and course lines is a territory; territories also are maximal regions containing no ridge lines or course lines. Warntz (1966) and Pfaltz (1976) revived interest in the Cayley/Maxwell surface theory and proved a number of properties of the graphs and associated networks determined by ridge and course lines in the context of spatial analysis and information systems. Mark (1978) showed how these mathematical models could be useful in processing elevation models. This rigorous mathematical model of surface organization has the advantage that it can be applied computationally in straightforward fashion to major topographic data models (Mark, 1979).

3.5.3 Digital representations

We said earlier that ways must be found to integrate the qualitative ontology of landform objects and categories with the quantitative field-based ontology that is commonly used for topography by environmental science. We use the term *digital elevation model* (DEM) as a generic term to refer to any digital model of elevation data, regardless of data structure.[3] Virtually all attempts to represent topography

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[2] Isogons join points of equal angle, in this case equal angle between true north and magnetic north.

[3] Some authors use the term "digital elevation model" only to refer to data structures that represent elevations by regular rectangular grids. Those authors might use the term "digital terrain model" to refer more inclusively to grids and other data structures, such as triangulated irregular networks (TINs). The terminology is further clouded by the fact that, as we shall see, the U.S. Geological Survey uses the terms "digital elevation model" and "digital terrain model" to refer to two different product lines of digital data, both in regular grid form, but compiled in different ways.

using digital computers have employed a field ontology, either explicitly or implicitly. With few if any exceptions, the terrain is conceptualized as a single-valued function of position in two dimensions, rather than as a collection of object-like features of the real world, such as hills or valleys.

A fundamental issue under this assumption is the nature of local surface variability and of how such variability interacts with the spatial resolution of sampling (the sampling interval). Topography sometimes bears striking similarity to certain classes of mathematical functions known as fractals (Mandelbrot, 1967, 1975, 1982; Mark and Aronson, 1984; Goodchild and Mark, 1987). If terrain surfaces were truly fractals with statistical self-similarity, additional local variation in height would always be found with finer spatial resolution. Most work on computer representation of altitude, however, assumes that topographic surfaces are locally smooth and employs locally smooth interpolation functions between sample points or lines. Cayley and Maxwell's mathematical models were based on a similar assumption.

Given the assumption of elevation as a single-valued function of position, $z = f(x, y)$, at least two approaches to DEMs are possible (Mark, 1979). One approach is to find an explicit mathematical function $f(x, y)$ that approximates the elevation surface throughout the spatial domain of interest—a serious challenge given the complexity of most terrain. The other approach digitizes elevations at a *sample* of points and provides a spatial interpolation function from which elevations for points not explicitly sampled can be obtained. Approaches based on mathematical equations were explored early in the history of DEMs (Tobler, 1969; Hardy, 1971), but eventually sampling-plus-interpolation approaches came to dominate fielding practice. Hybrid methods, which used more simple mathematical equations over more limited spatial domains (patches) and pieced those domains together with weighting functions, also were explored in the very early days of DEM research (Jancaitis and Junkins, 1973; Junkins et al., 1973; Jancaitis and Moore, 1978; Leifer and Mark, 1987), but these, too, disappeared from practice and from the literature at a relatively early stage.

From among the sampling-plus-interpolation approaches, attention has focused on sampling at points or along lines and on regular and irregular spatial distributions of sample points. Since contour lines (intersections of horizontal planes with the elevation surface) became the dominant form of elevation representation on analog maps in the 20th century, it is not surprising that early efforts in the digital representation and manipulation of topography simply mimicked the analog solution, storing and manipulating digitized versions of contours derived from printed maps (Piper and Evans, 1967). Indeed, researchers successfully implemented algorithms for matching elevation profiles against elevation models based on digitized contours (Freeman and Morse, 1967; Morse, 1968). But while the human visual system can easily determine which contours are adjacent to a certain point, it proved difficult to develop computationally efficient algorithms for interpolating elevations directly from contours.

Military interest in elevation data in the United States in the 1960s was driven in part by the need to develop terrain-based navigation systems for the then-still-secret cruise missiles. Given the severe data storage limits of the on-board computers that were available in the 1960s and early 1970s, there was much interest in compressing the data. The work by Junkins et al. (1973) and others was driven by such considerations, as was the early funding provided by the U.S. Office of Naval Research for research on TINs (Mark, 1997). This early support for a diversity of modeling approaches eventually appeared to settle on two main structures: regular grids and TINs.

Regular grids

It is likely that the earliest method used to represent topography on computers was the method that associated altitudes with sample points in regular square grids (Figure 3.2). To a programmer, regular grids are an obvious way to represent terrain, because 2-D arrays or matrices can be employed. This approach can also represent sampled elevations with a small number of bits, since if sample points are spaced regularly in a rectangular pattern, then the x and y coordinates do not need to be stored explicitly, but are implicit in the rows and columns in the matrix. Thus it is sufficient to encode only the elevation or z-value of each sample point in the altitude matrix. Also, information on which points are neighbors does not have to be coded explicitly, nor must neighbors be computed—rather, the neighbors are just the matrix entries adjacent to the given point in matrix notation. It is easy to write programs to manipulate such regular grids, and the grids require very little disk space per point. Because, however, the grid point locations are predetermined by the origin, orientation, and spacing (resolution) of the grid, the grid may miss key

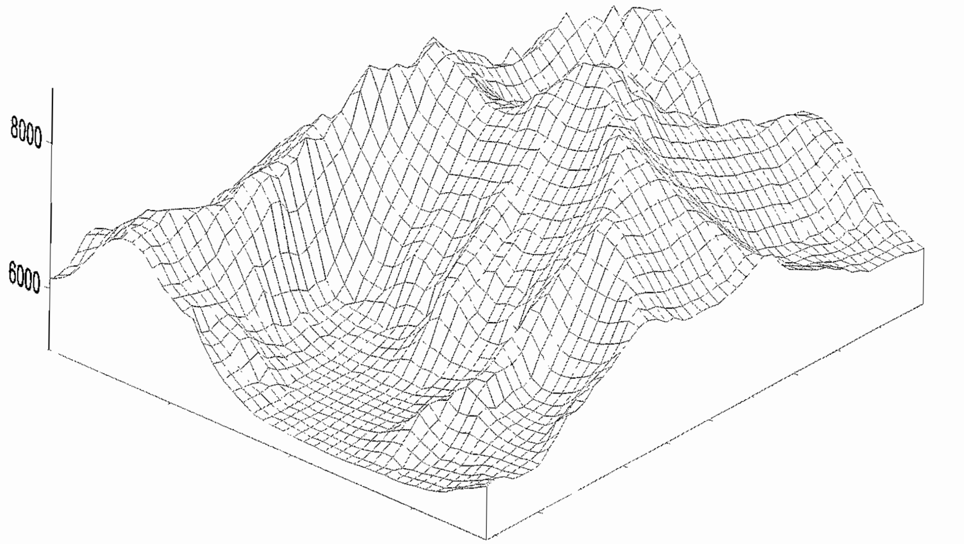

Figure 3.2. Elevations in an area centered on the summit of Mount Everest, represented by a regular grid of elevations (5,158–8,848 m) and shown in an oblique view. The scale is 10.2 km EW by 9 km NS, with S to the top.

The data were digitized by Joy Chen in 1987. The digitizing and source of the map is described by Clarke (1988).

features. Also, because the grid is two-dimensional, reducing the spacing by a factor of 2 leads to a four-fold increase in the number of grid points, which produces an unfavorable trade-off between spatial resolution and data volume. On the other hand, regular grids received a boost from the making available of considerable amounts of data in grid form. In the early 1980s, DEMs with a 30-m horizontal spacing became available from the U.S. Geological Survey under the product name "Digital Elevation Model" (Allder et al., 1982; Elassal and Caruso, 1983).

Also during the 1950s and 1960s, the U.S. Defense Mapping Agency (DMA) prepared elevation grids with a 3-arcsec resolution by interpolation from contours on a 1 : 250,000-scale topographic map (Noma and Spencer, 1978). In the mid-1980s the data sets in this series that represented U.S. territory were transferred to the U.S. Geological Survey for distribution to the public; this product line is known as "Digital Terrain Models". Since topography on a 1 : 250,000-scale topographic map has been smoothed and generalized during the cartographic design process, these elevation grids are of lower elevation precision than the 30-m DEM product, but they provide relatively uniform and complete national coverage.

Due to these activities and the U.S. national policy not to copyright U.S. government product, elevation data for mountains in the United States are available at relatively low cost from the U.S. Geological Survey (United States Geological Survey, 2001). Topographic data for mountains in other parts of the world may be more expensive or difficult to obtain.

Triangulated irregular networks

The TIN approach is well named: in this approach the topographic surface is represented by a set of triangular facets, with 3-D coordinates at their vertices (Figure 3.3). Neighbor relations are stored explicitly. Commonly the points are chosen to lie on the surface, and elevations at points other than the sample points are usually obtained through linear interpolation within a single triangle using the plane defined by the three vertices of the triangle. Triangles were used as a basis for contouring by computer as early as 1964, but the TIN approach to elevation modeling was developed independently by at least three different groups from different disciplines during a short period between 1972 and 1975 (Mark, 1997). The name TIN and much of the publicity for the method resulted from a project funded by the U.S. Office of Naval Research (Peucker and Chrisman, 1975; Peucker et al., 1978).

Much of the appeal of the TIN approach stems from its ability to adapt to variable complexity of terrain. Whereas a grid must have the same spacing throughout or lose much of its advantage of implicit coordinates and easy programming, a TIN can have small triangles in rough areas and larger ones in smooth regions. This is particularly useful for glaciated mountain areas, which have rugged, fine-scaled topography above former ice levels and smooth terrain below the trim lines (Figure 3.4). If the TIN is based on surface-specific points, such as peaks, ridges, and other breaks of slope, a maximum of information about the surface can be captured with a minimum volume of data. On the other hand, when a TIN is based on points located on a surface without regard for the form of the terrain, most of the advantage of TINs is lost. This is important in many mountain areas, where features are often sharp-edged and finely textured. Manual selection of sample points for a TIN is very labor-intensive, and so methods for automated extraction of TINs by sampling from very dense grids were developed (e.g., Peucker and Douglas, 1975; Fowler and Little, 1979). But a very fine grid is needed to capture sharply defined landscape elements, and if such features are not captured by the grid, they cannot appear in any TIN derived from that grid. Automated grid-to-TIN conversion procedures have been incorporated into commercial geographic information system (GIS) software; but if high-resolution DEM grids are available, it is often advantageous to use those directly in geomorphometric analysis and environmental-simulation models.

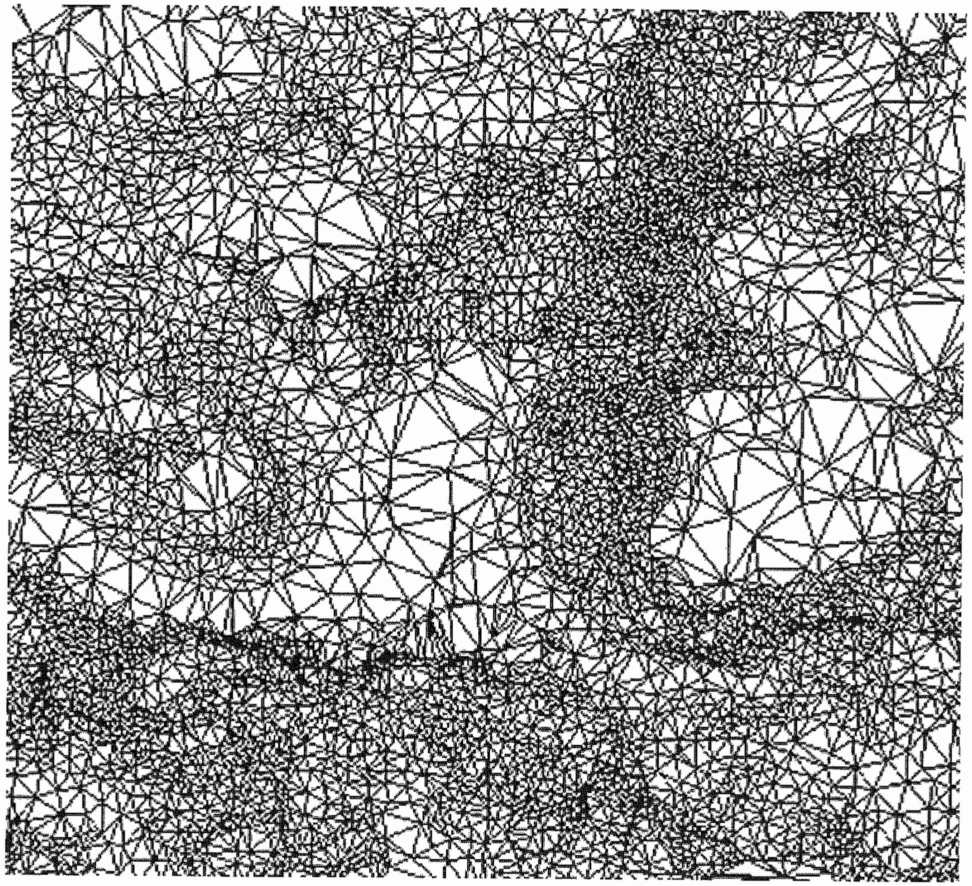

Figure 3.3. A TIN of topography including Mount Everest, depicted in a map view as seen from directly above.

Data source and scale as in Figure 3.2

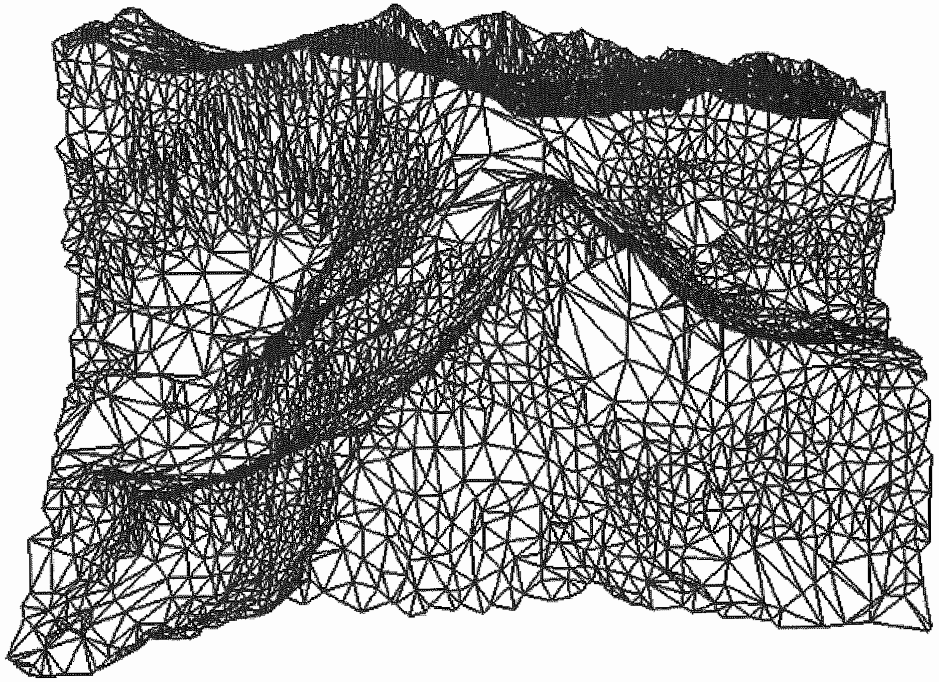

Figure 3.4. The same TIN of Mount Everest shown earlier in Figure 3.3, but presented in an oblique view.

Data source and scale as in Figure 3.2.

Comparison of DEM approaches

Very early in the development of DEMs, Boehm (1967) published a detailed comparative evaluation of several competing representations for topography. Boehm (1967) evaluated uniform regular grids, unevenly spaced regular grids, and digital contours (TINs had not yet been developed). A number of measures were employed, and the equally spaced regular grids showed the best overall performance.

Mark (1975) also conducted a quantitative comparison of representations of topography; in this case regular square grids and manually selected TINs were compared using several geomorphometric measures. He concluded that about twice as much data (in bits) were required to produce equally good estimates of land slope and subsurface volume from regular grids as were needed for TINs, but the comparison was based on a small set of test landscapes and parameters and only one resolution of grids. A much more detailed comparison of grids and TINs was conducted by Kumler (1994). He selected a large set of U.S. Geological Survey quadrangles that were representative of all major terrain types in the United States and constructed highly controlled regular grid and TIN DEMs for each quadrangle from original photogrammetric sources. Kumler (1994) conducted his evaluation using the standard measure of cartographic data quality of vertical accuracy, using independent spot elevation data as the standard against which DEM elevation estimates were compared. He found that the regular grids performed somewhat better than TINs for a given data storage volume. The storage efficiency of the TINs is probably sensitive to the triangulation criteria employed in the TIN construction (Kumler, 1994).

DEM algorithms for geomorphology

Much of the use of elevation models in geomorphology and hydrology involves the modeling of the flow of water and possibly sediment over the surface. Thus the computation of flow across elevation surfaces is of particular interest. Although TINs are more directly able to adapt to topographic variations and features, almost all work on modeling surface runoff using DEMs has involved regular grids. Useful methods for detecting channels from grid DEMs using flow models were presented in several articles in the mid-1980s. O'Callaghan and Mark (1984) described procedures for extracting drainage patterns from grid DEMs and provided methods for dealing with false pits or depressions commonly present in DEMs due to local minor errors in elevations. Around the same time, Marks et al. (1984) described an elegant yet powerful recursive approach for computation of drainage basin flow based on a very simple principle: in a grid the drainage area of any cell is just that cell itself, plus the drainage areas of any of its neighbors that drain into it. Thus, as long as each cell has at most one output and all links between neighbors are directed from the higher to the lower, then given some starting cell in the grid the recursive application of the above definition of drainage area will visit exactly those cells that constitute the drainage area of the starting cell. Furthermore, as the program returns from the recursion, it can sum up the drainage area and drive an erosion model. For reviews of drainage-based computation using DEMs, see Mark (1987) or Band (1999).

Another possible use for DEMs in geomorphology is for geomorphometry, including feature extraction, slope mapping, and slope frequency analysis. Preparing slope maps from a TIN is very straightforward and is supported by the TIN software in commercial GISs. From there it is an easy matter to classify slopes and determine relative areas by slope classes. O'Neill and Mark (1987) provided a critical review of issues surrounding slope frequency analysis from gridded DEMs. In this case one can obtain a very large sample of slope measurements, but slope values are limited by the discrete integer elevations and grid distances in many DEMs. For example, in the U.S. Geological Survey DEMs mentioned above, a grid with horizontal spacing of 30 m and a vertical resolution of 1 m is used (the vertical precision is not normally as good as 1 m; elevations are simply estimated to the nearest meter). Under these conditions, two neighboring grid points either have identical elevations, which would result in a calculated slope gradient of zero between them or they differ by at least 1 m, yielding a minimum detectable nonzero gradient of 3.3%. In many areas, variations within the range from 0 to 3.3% are significant, and the inability of analysis based on a typical U.S. Geological Survey DEM to differentiate among gentle slopes may be a significant impediment to the use of such data in slope studies.

3.6 COMPUTING WITH TOPOGRAPHIC FEATURES

What then of the object view of landforms with which we began: the world of mountains, hills, valleys, and canyons? It appears that this object view is hardly needed by either geomorphology or environmental modeling, because mapping and modeling are well served by DEMs that provide computational approximations to elevation fields. But, as we noted in the introduction, an object view is essential when people communicate about terrain using natural language and when they use landforms as landmarks for navigation and wayfinding. If landforms are not to be represented explicitly as objects in geographic databases, methods are needed to obtain such objects when they are needed by applying feature extraction methods to the field representations.

3.6.1 Field-to-object conversions

Computer programs with the capacity to recognize and delimit individual landforms based on DEMs present computational and conceptual challenges of varying complexity. Although there has been a great deal of work on delimitation of drainage basins and other terrain feature extraction, there has been very limited research on extraction and classification of other kinds of landforms. In one such study Graff and Usery (1993) extracted *mounts* from DEMs (*mount* is the generic term that the U.S. Geological Survey has used in several of its digital geographic databases to identify mountains, hills, knolls, and other such features; for more examples see Table 3.1). Their methods were based on region-growing techniques and proved successful in delimiting well-defined, relatively isolated hills and summits. No attempt was made to automatically distinguish different kinds of mounts that may have been present in a given landscape.

In general, we can distinguish two related problems that call for different types of solutions. One case assumes a known location and type: given a point on a topographic surface and a type of landform known to be located there, the task is to determine the extent of that landform. The other problem assumes that nothing is known except the elevation field, and the task is to delimit and identify whatever individual landforms might be present. The first version of the landform problem is more constrained and is also quite pressing, because the GNIS files from the U.S. Geological Survey contain names, kinds (feature codes), and coordinates for millions of geographic features in the United States, but no boundaries or geometry. The GNIS information could be used as seeds for landform delimitation algorithms. An important research issue is to develop algorithms to accomplish this, based perhaps on diffusion from a landform region seed point, with stopping criteria based on slope or other local geometric thresholds specific to the type of landform. This problem appears to be tractable but nontrivial, not least because the stopping criteria will need to take account of the issue we emphasized at the beginning of this chapter—the issue of vagueness or gradation of landform boundaries (Bittner and Smith, 2001).

If the landform type is unknown, the problem is much more complicated. We believe that computational solutions are obtainable, however, especially since many landforms are defined or formed by runoff or gravitational processes, which enables detection and identification to be based on first-order and second-order geomorphometric properties. Discrete computational representations of topographic surfaces can be converted to flow networks by local computation of drainage directions from slopes (Mark, 1987). Such surface flow networks can then be used to drive algorithms for extracting drainage networks and drainage basins from DEMs (Mark, 1984; Marks et al., 1984; O'Callaghan and Mark, 1984; Band, 1986) and for simulating erosion processes over such surfaces (Hugus and Mark, 1985). Such approaches can be used to identify complex topographic features in mountainous areas. In particular, the recursive drainage-tracing procedure described by Marks et al. (1984) can be used to drive landform detection algorithms in many cases. Another possible approach would begin with the fact that hills, as defined by Maxwell (1870), are easily delimited computationally and can be used to provide automatically generated first approximations to hills, mountains, and other similar convex landforms. Likewise, the dales of Maxwell (1870) can be used to provide first approximations to valleys, gullies, etc. The goal would then in each case be to find methods to move from these first approximations to feature delineations and identifications that correspond more directly to the ways in which geomorphologists comprehend mountain landscapes. Paradoxically, this will mean finding ways to move from crisp first approximations to more adequate delineations that are more adequate precisely because they involve the right kind and degree of imprecision or vagueness.

3.7 DISCUSSION AND CONCLUSIONS

Geographic information science goes beyond the routine use of commercial GIS software and seeks to develop conceptual foundations for computer applications involving geographic information that may require extensions of the capability of the software (Goodchild, 1992; Mark, 2000). A critical examination of information systems for mountain geomorphology reveals gaps between scientific requirements and the analytical capabilities of current software. As information systems become ever-more closely linked to scientific applications, decision making, and public use, they will increasingly require algorithms for converting between object and field representations of topography and other environmental phenomena. Yet existing GISs and geospatial data infrastructures have in general followed the scientific practice of representing topography as fields, discretely approximated either by grids of regularly spaced elevation readings or as TINs, approximating a surface. Such databases may contain explicit digital objects representing linear geospatial features, such as roads, political and administrative boundaries, streams, and shorelines; but they rarely if ever contain digital objects representing mountains, hills, ridges, valleys, ravines, escarpments, plains, etc. Rather, at best they contain in each case representations for the *type* of feature, its *proper name*, and the *coordinates* of one or two representative points on the feature. This follows established cartographic practice in relying on the map reader's cognitive system to construct the actual entity being named out of the field of elevations represented on printed maps via contours. Computers, however, have not yet been programmed to extend features across fields in similar fashion.

The field view underpins geomorphological science, but the object view underpins the ways people perceive and act in relation to the environment. Problems arise because the field view makes it difficult to provide explicit representations of landform as objects. The research described in Smith and Mark (2001) and in this chapter represents a first step toward establishing an ontology of landforms and of terrain that can both do justice to the sorts of category systems that human beings employ when dealing with natural environments and preserve the linkage to the field views used for topographic mapping and computation.

Much work still needs to be done, however, to design complex data models that can be implemented in digital databases. The following questions must be answered if landforms, such as mountains, rivers, valleys, moraines, slopes, and mass movements, are to be incorporated into geographic databases as features or objects:

- What exactly is topography and what are landforms? What is a landscape? What is an environment (Smith and Varzi, 2002)?
- What kinds of landforms do people recognize, reason about, store, retrieve, and process?
- To what extent are types of landforms cross-culturally universal and to what extent do they vary by region, language, culture, and type of interaction?
- What if any are the interactions between the way an individual landform is delimited and the kind of landform that the entity in question is believed to be?
- What algorithms or other computer-processing methods can be used to extract landforms from representations of topographic surfaces and to delimit (bound) those landforms?

If GISs are to be built that will help us to understand mountain environments, it will be necessary to provide definitions for landform types within a formal theory. The ultimate goal of such research would be to provide a system of definitions and taxonomy of landform objects which would yield a representation system that is compatible not only with digitized representations but also with the types of qualitative spatial reasoning about topography and spatial relations used by humans. A system of this sort would provide a crucial supplement to standard treatments of topographic surfaces in terms of fields, grids, TINs, and contours.

ACKNOWLEDGMENTS

This chapter is based on work supported by the National Science Foundation, Geography and Regional Science Program, under Grant No. BCS-9975557. Support of the National Science Foundation is gratefully acknowledged. Thanks also to Keith Clarke for supplying the Mount Everest data and to James Craig and Yixin Zhou for production of the figures.

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4

Geomorphometry in mountain terrain

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4.1 INTRODUCTION

This chapter focuses on the geomorphometry of mountain landforms and their forelands. Landform features considered here range from small landforms, such as cirques and rock glaciers, to large or coarse-scale landforms, such as mountain ranges. Although the extensive topic of drainage basin geomorphometry is one of the roots of modern geomorphometry, especially in the United States (e.g., Horton, 1945a; Strahler, 1950a, b), it will not be treated in this chapter unless it contains mountain-specific methods and parameters.

We define geomorphometry as the science of quantitative description and analysis of the geometric–topologic characteristics of the landscape. Within the framework of process-form relationships fundamental to geomorphology, geomorphometry deals with the recognition and quantification of landforms. Landforms carry two geomorphological meanings. In relation to present formative processes, a landform acts as a boundary condition that can be dynamically changed by acting processes. On the other hand, formative events of the past are inferred from the appearance of a recent or paleolandform and the material (sediment, rock) it consists of. Therefore, the task of geomorphometry is twofold: (1) quantification of landforms to derive information about past forming processes, and (2) determination of parameters of recent processes. Geomorphometry is therefore a means for description and explanation. Despite much empirical research, there is no systematic and general textbook or statement about the specific character of mountain geomorphometry. Global digital elevation data, however, now permit the analysis of larger mountain areas and regions. It is necessary to discuss these topics not only in terms of conceptualizing landforms, but also in relation to the analytical capabilities of software tools.

As discussed in Chapter 3, the definition of mountains and mountain areas is difficult and has been approached several times since the end of the 19th century