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Geospatial technologies and digital geomorphological mapping: Concepts, issues and research

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ABSTRACT

Geomorphological mapping plays an essential role in understanding Earth surface processes, geochronology, natural resources, natural hazards and landscape evolution. It involves the partitioning of the terrain into conceptual spatial entities based upon criteria that include morphology (form), genetics (process), composition and structure, chronology, environmental system associations (land cover, soils, ecology), as well as spatial topological relationships of surface features (landforms). Historically, the power of human visualization was primarily relied upon for analysis, introducing subjectivity and biases with respect to selection of criteria for terrain segmentation and placement of boundaries. This paper reviews new spatio-temporal data and geocomputational approaches that now permit Earth scientists to go far beyond traditional mapping, permitting quantitative characterization of landscape morphology and the integration of varied landscape thematic information. Numerous conceptual, theoretical, and information-technology issues are at the heart of digital geomorphological mapping (DGM), and scientific progress has not kept pace with new and rapidly evolving geospatial technologies. Consequently, new capabilities exist but numerous issues have not been adequately addressed. Therefore, this paper discusses conceptual foundations and illustrates how geomorphometry and mapping approaches can be used to produce geomorphological information related to the land surface and landforms, process rates, process–form relationships, and geomorphic systems.

1. Introduction

Geomorphological mapping plays an essential role in understanding Earth surface processes, geochronology, natural resources, natural hazards and landscape evolution (Blaszczynski, 1997; Bishop and Shroder, 2004a). It involves the partitioning of the terrain into conceptual spatial units/entities based upon criteria that include morphology (form), genetics (process), composition and structure, chronology, environmental system associations (land cover, soils, ecology), as well as spatial topological relationships of surface features (landforms). The complexity associated with deterministic characterization of landforms and other geomorphological (i.e., land surface) units/entities is evident in the difficulty of: 1) establishing comprehensive taxonomic schemes; 2) geomorphological mapping at a variety of scales; 3) characterizing indeterminant boundaries; 4) establishing universally applicable criteria for characterization; and 5) obtaining objective repeatable results.

Historically, geomorphological mapping has been based upon integration of multidisciplinary information from the field, remotely sensed data, and cartographic map products. Regional-scale geomorphology and physiographic analysis and mapping (Baker, 1986), were based upon the interpretation of photography and smaller-scale maps to classify terrain types/features at the regional (physiographic) scale. Detailed geomorphological mapping was based upon surveying and other in-situ measurements, although detailed large-scale geomorphological maps did not exist for many areas. These traditional mapping approaches emphasized qualitative interpretation, as frequently dictated by the inherent limitations associated with field-work, paucity of digital space–time data, and human a priori field/geographic experience and domain knowledge. Consequently, the power of the human visualization system was primarily relied upon, introducing subjectivity and biases with respect to selection of criteria for terrain segmentation and placement of boundaries.

Relatively recent advances in remote sensing, geographic information science (GIScience), geospatial technologies, as well as developments in numerical modeling of surface processes, have revolutionized the field of geomorphology (Shroder and Bishop, 2003; Bishop and Shroder, 2004a). New spatio-temporal data and geocomputational algorithms and approaches now permit Earth scientists to go far beyond traditional mapping. It is now possible to quantify landscape morphology (Pike, 2000; Hengl and Reuter, 2009), assess surface biophysical conditions (Florinsky, 1998; Liang, 2007; Smith and Pain, 2009; Tarolli et al., 2009),

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link process with patterns (Allen and Walsh, 1993) and process with form (Montgomery et al., 2004), and improve our understanding of scale dependence and the polygenetic nature of landscape evolution (Walsh et al., 1997; Tate and Wood, 2001; Bishop et al., 2003).

Earth science investigations using geospatial technologies are commonplace (Bishop and Shroder, 2004b; Hengl and Reuter, 2009). The rapid proliferation of geospatial technologies includes advances in geodesy, photogrammetry, geophysics, computer science, statistics, remote sensing and geographic information systems (GIS), to mention just a few. Numerous conceptual/theoretical and information technology issues are at the heart of digital geomorphological mapping (DGM). We have new capabilities, but also have numerous issues in geomorphology that have not been adequately addressed. Therefore, Earth scientists need to be fully aware of current capabilities, as well as the issues and challenges related to geomorphology and GIScience (Bishop and Shroder, 2004b).

The 2010 Binghamton Geomorphology Symposium was organized with the overall goal to facilitate discussions related to the establishment of a scientific framework for understanding and addressing the issues and challenges associated with modern DGM. Topics in this volume include new sensor technology, data sources, and information-extraction technologies and capabilities, and examples of geomorphological applications. Education and training in the use of geospatial technologies will play an important role in advancing understandings of landform genesis and change, internal and external forcings, process dynamics, feedback mechanisms, and overall landscape evolution.

The objective of this paper is to set the stage for this volume and address important concepts and issues in DGM that need to be accounted for if geomorphologists are to effectively use geospatial technologies. Specifically, we focus on conceptual foundations, and illustrate how geomorphometry and mapping approaches can be used to produce geomorphological information related to landforms, process rates, process–form relationships and geomorphic systems. Practical issues associated with data selection, representation, and analysis are also covered. This paper is focused on geomorphological issues and information requirements dictating technology development and refinement, rather than attempting to cover broader aspects of GIS-based empirical research. It also highlights the importance of understanding limitations with respect to representation, scale, analysis, and remote sensing. Consequently, our treatment relates to the overall complexity of issues in DGM and does not focus on mapping specific landforms.

2. Background

From a scientific perspective, numerous concepts in geomorphology need to be formalized to facilitate geomorphological mapping and related integrative science. Concepts/entities such as landforms, boundaries, gradients, scale, organization, process, systems, complexity, and many other topics can be viewed and defined from multiple perspectives. The literature is replete with ambiguous spatial and geomorphological terms that lack precise meaning or criteria for formalization.

Geospatial technologies can be used to address some conceptual issues such as heterogeneous surface composition with fuzzy-classification membership (Warner and Shank, 1997), indeterminant boundaries and features (Burrough, 1989; Usery, 1996; Burrough et al., 2000; Smith et al., 2000; Deng and Wilson, 2008), hierarchical organization and spatial analysis using object-oriented technology (Ralston, 1994; Brändli, 1996; Schmidt and Dikau, 1999), scale-dependence of properties and patterns using geostatistics (Tate and Wood, 2001), and objective mapping using different analytical approaches (e.g., descriptive statistics, inferential statistics, artificial intelligence, and various analytical reasoning technologies). Nevertheless, numerous limitations are associated with the use of existing cartographic representations of landscape information, as parameterization schemes that uniquely link multiple processes and form in space–time are not readily available. Addressing numerous science issues will most likely require multidisciplinary collaboration between Earth and information scientists (Bishop and Shroder, 2004b).

A multitude of questions exist regarding topography and landform representation, indeterminant boundaries, process characterization, process–form characterization, pattern–process characterization, pattern–time characterization, and issues involving scale (Bishop and Shroder, 2004b). Ultimately, geospatial technologies should permit the generation of maps depicting morphogenesis, morphochronology, and morphodynamics. The integration of composition into this framework, however, has yet to be adequately addressed. Geomorphologists will need to establish a theoretical/conceptual foundation to diagnostically link mapping capabilities into a process–systems framework. No general agreement exists regarding the formalization of such a framework, although researchers have recommended and evaluated the potential of various concepts and information technologies and approaches to accomplish this (e.g., Raper and Livingstone, 1995; Lagacherie et al., 1996; Usery, 1996; Schmidt and Dikau, 1999; Burrough et al., 2000; Minár and Evans, 2008).

From a methodological perspective, advances in remote sensing have played a major role in producing new forms of spatio-temporal data that allow a variety of issues to be addressed. Ongoing research has focused on the use of imagery for geomorphological mapping at a variety of scales (Saadat et al., 2008; Schneevoigt et al., 2008). The role of remote sensing in generating high quality digital elevation models (DEMs) is critical for geomorphology (Wilson and Gallant, 2000), as topography inherently defines geomorphic form and represents the interaction of climatic, tectonic, and surface processes. The development and evaluation of new techniques and analytical approaches for information extraction from remotely sensed data and DEMs is another active research area (Bishop and Shroder, 2004b). Investigators have focused on the technical aspects of developing GIS databases (Gustavsson et al., 2008), developing geomorphometric mapping software (Klingseisen et al., 2008), mapping specific landform features, and developing new ways to visualize geomorphological information (Vitek et al., 2008). A plethora of quantitative metrics and approaches exist, however, to accomplish the same tasks, and the advantages and limitations associated with hundreds of potential algorithms and multi-stage processing approaches for diagnostic mapping have not been systematically determined. Geoscientists are not always aware of the mathematical and computational underpinnings of information extraction procedures (Bishop and Shroder, 2004b).

Numerous issues in GIScience and geomorphology need to be addressed with regards to geomorphological concepts. Software-tool development alone does not effectively address conceptual issues, because the development and evolution of parameterization schemes and software must be driven by scientific concepts and knowledge. The empirical tool-box approach and static cartographic representational schemes that characterize most commercial-based GISs pose unique challenges for DGM, even though new capabilities exist. Geospatial technologies can facilitate the formalization and testing of important theoretical and conceptual issues involving landform genesis, landform and landscape geochronology, process domains, spatio-temporal overprinting of surface processes, and landscape-evolution system dynamics. Traditional geomorphological topics of topographic organization, landform taxonomy, landform-mapping objectives, mapping terminology, and the use of qualitative and quantitative geomorphological knowledge must be revisited in an analytical framework.

2.1. Traditional mapping

Geomorphological mapping has followed considerably different courses of historical development in a variety of countries (Klimaszewski, 1982; Hayden, 1986). A brief history of the evolution of mapping traditions in North America is presented to illustrate changes in approach and content and to complement the histories of slightly different approaches to geomorphologic mapping in Europe and elsewhere (Barsch and Liedtke, 1980; Demek, 1982; Klimaszewski, 1982; Verstappen, 1983; Hayden, 1986; Goudie, 1990; Cooke and Doornkamp, 1990b; Gustavsson et al., 2006; Pavlopoulos et al., 2009).

Early in the history of geomorphic mapping, production of comprehensive geomorphological maps became a main research priority in Europe (Demek and Embleton, 1978). This is in contrast to the relatively low priority it received in North America and Britain (Evans, 1990). Nevertheless, geomorphologic mapping at the regional scale in North America has a long tradition and literature that dates back to at least the late 1800s with maps that were often included in physiographic textbooks and treatises. In the early period of regional geomorphologic mapping, information was rarely based on accurate or detailed technical, field, stratigraphic, or laboratory analyses, and was generally approached from a fluvial, mass-wasting, eolian, or glacial perspective. Knowledge of processes and systematic approaches were limited and remote-sensing data were not available. Consequently, mapping was heavily reliant upon field interpretations.

Because of the vast areas that regional maps covered in the exploration of North America, knowledge of structure, stratigraphy, and geomorphology of large areas was commonly extrapolated from a limited number of sites. Furthermore, mapping technologies and accuracies were limited, so simple tasks such as transferring information from one map to another at a different scale or projection could introduce large errors of placement. American geoscientists in the 19th and early 20th centuries produced physiographic maps from exploration of vast regions and thus enabled better understandings of the new terrains (Thornbury, 1965; Graf, 1987). Mapping progressed primarily through recognition of underlying lithologies and controlling geologic structures, which were overprinted by different surficial processes. The resulting maps were often geologically astute, remarkably rich in detail, and genuine works of art (Fig. 1). After more than a century of effort to map the geology and associated physiography or geomorphology of the United States, roughly from the time of (Lesley, 1869) and (Powell, 1896), through to Fenneman (1938), the concepts of mapping regional landform types were fairly well determined based upon hierarchical geomorphic divisions, geomorphic provinces, and geomorphic sections.

Historically, small-scale, regional geomorphic maps are extremely important. They commonly provided the first regional syntheses of geomorphic information that included interesting patterns and conceptual models of landform assemblages (Fig. 2). Regional physiographic maps were highly persuasive models that offered a synoptic view of landforms, which became important for testing, attacking, or promoting paradigmatic understandings of broad geologic and geomorphic processes. Although this older work is often marred by extensive reliance upon denudation chronologies in the style of (Davis, 1899), a number of people tried further refinements. Fenneman chaired a committee, appointed in 1914 to produce a map. The committee reported in 1916, followed by several publications (Fenneman, 1917, 1928, 1931, 1938). Some of the maps drawn by Guy-Harold Smith were precursory examples of fine geomorphic cartography of the type later produced so well by Raisz(1948). Fenneman's three orders of geomorphologic divisions for the USA remain the definitive work on geomorphological classification and mapping to this day. Atwood(1940) produced a shorter version of Fenneman's(1938) work, and included a comprehensive three-dimensional sketch diagram of the USA and southern Canada.

Highly developed artistic skills were used in the production of early landform maps and were often coupled with temporally sequential block diagrams of imaginative landscape evolutions (Lobeck, 1924; Raisz, 1948; Lobeck, 1958). Many of the early physiographic maps and block diagrams continue to be cited in descriptions of regional geomorphology, even though the theoretical interpretations of landforms may be seriously limited. After all, most of the physiographic maps pre-date plate tectonic theory. Whether accurate or not, the early interpretations greatly influenced modern concepts of regional geomorphology, and in some cases the early concepts have persisted largely intact in modern studies. The old physiographic maps remain important because they represent early geomorphic interpretations that are historically linked to our understanding of landforms in specific places. Near the beginning of the twentieth century physiographers were deeply interested in regional geomorphology, although physiography was usually defined to include soils, biogeography, and climate in addition to geomorphology.

With regard to the geomorphic components of physiography, Baker (1988) divided early 20th century physiographic studies into two types; descriptive methods or *geomorphography*, and genetic historical methods or *geomorphogeny*. At the turn of the twentieth century, the genetic

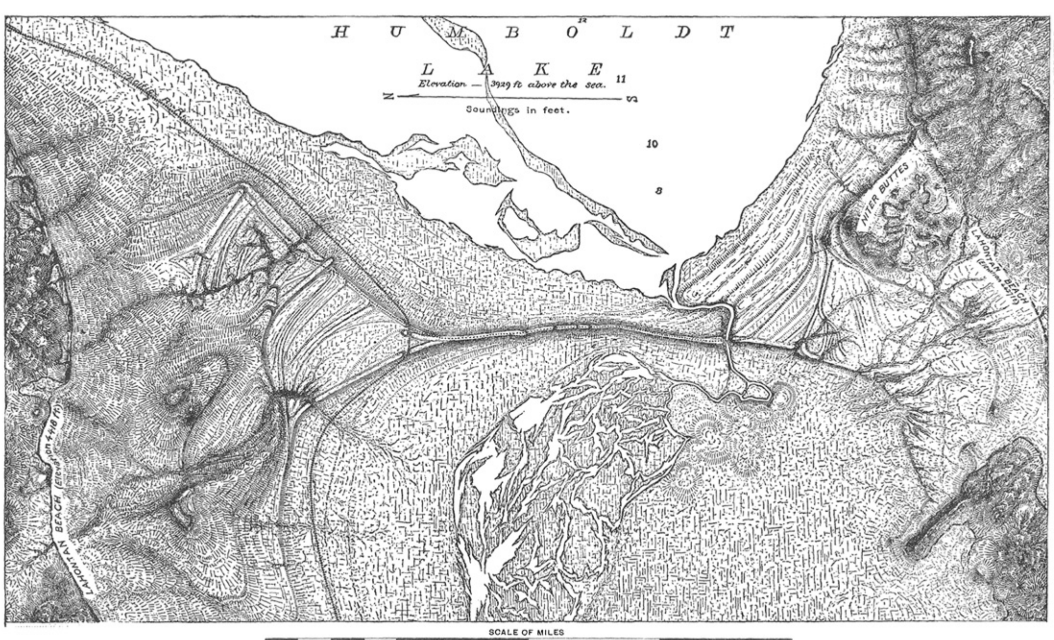

Fig. 1. Shorelines of Humboldt Lake, Nevada (north to left).
Source: First published by (Russell, 1885) and reprinted as Plate IV in (Russell, 1896) from where this printing was scanned, excluding the vertical section along the bottom.

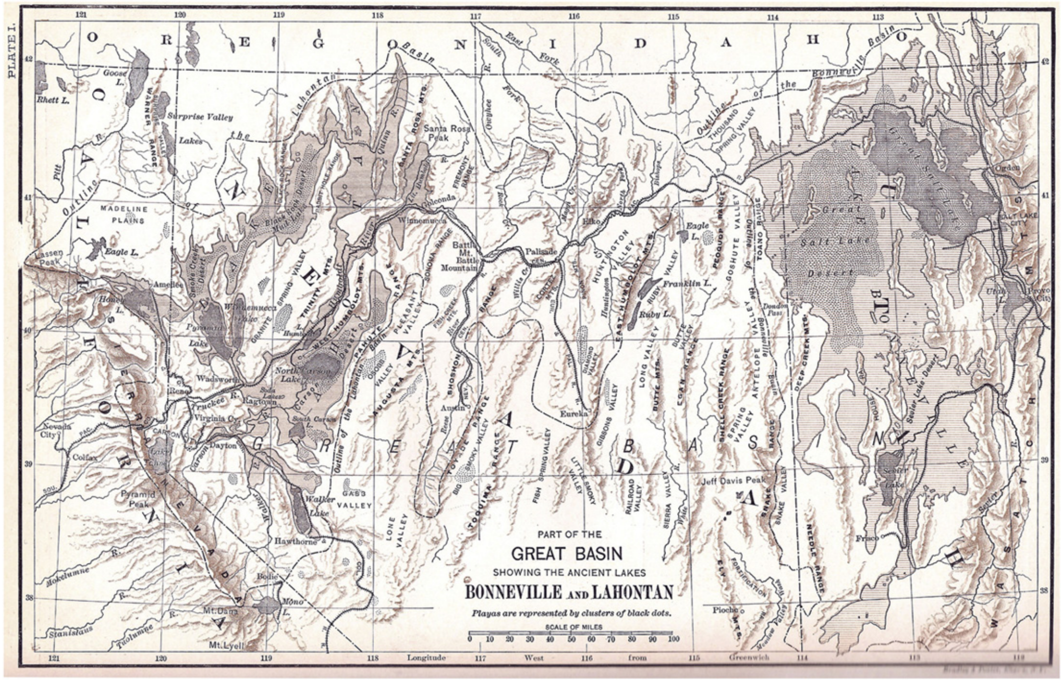

Fig. 2. Lakes Bonneville and Lahontan in the Great Basin, western USA.
Source: Plate I in (Russell, 1896). Inscribed in lower right corner is “Bradley and Poates, Engr's, N.Y.”

approach dominated and geomorphic research was largely concerned with landform evolution over millions of years (e.g., Davis, 1902; Lobeck, 1939).For example, Hinds(1952) described geomorphic provinces in California as being characterized by a distinguishing geologic record and uniform relief features.

In the early and mid-twentieth century the prevailing opinions were that geomorphic units were divisions of the land that were different from other geographic areas. Dietz(1952) thought that the topography of any area could be best defined in terms of the formative tectonics, the internal bedrock structure, the erosional and sedimentological processes acting on the land, the intensity of process, and the length of time. Later Thornbury(1965) and Hunt(1974) focused on geologic structures and materials, process, and vegetation in mapping. Their works were the beginnings of the modification and later exclusion of the Davis-inspired denudational chronologies that were beginning to be recognized as either incorrect or quite inadequate to explain more realistic courses of evolution of landforms. Thus, today, most geoscientists would agree that a geomorphic unit on a map has an individual expression that can be related to endogenetic controlling factors such as the underlying geology and its structure, as well as the exogenetic geomorphic processes that have operated in the area throughout certain periods of geologic time, which collectively influence and produce the specific topography.

Although the physiographic mapping tradition in the USA waned around the middle of the twentieth century, it did provide an important basis for the resurgence of geomorphologic mapping studies that are now emerging. Modern assessments of landscapes generally focus on primary and secondary thematic concepts of such things as climate controls, basic geology, terrain overviews, and landcover variations in soils and vegetation, although all of this information is rarely displayed on one map. These concepts are framed by understandings of various process systems, such as those within the climate, ecological, orogenic, sedimentological, and landscape-evolution domains. Such work, of course, could only have emerged and continued to be developed from the rich traditions and foundations established by generations of increasingly better trained geomorphologists.

In Europe, some of the first detailed geomorphological maps were published by Passarge(1914), but it was only after World War II that systematic mapping of landforms was promoted as a necessity (Klimaszewski, 1982). Several international congresses in the 1950s and 1960s established a series of rules for geomorphological mapping, and by the time of the 1968 meetings of the IGU (International Geographical Union) in New Delhi, India, an upgraded Commission of Geomorphological Survey and Mapping was charged with developing a manual for detailed geomorphological mapping and devising a legend for an international geomorphological map of Europe (Demek, 1972; Hayden, 1986).

The basic elements of landform analysis in European countries could be separated into two main types. For example, those maps from France, Hungary, the Czech Republic and Slovakia use lithologic-structural units as the basic element in landform analysis, whereas those from Germany, Poland, Russia, and Romania consider the landform itself as the basic unit (Hayden, 1986). This latter convention was adopted in the Demek (1972) manual of detailed mapping, as well as the legend of the international map of Europe. Demek(1972) and Klimaszewski(1982) pointed out the many possibilities, as well as the hosts of problems involving geomorphologic maps. For example, the legends of some maps had become inordinately complex and difficult to use, with as many as 500 symbols that made the legend larger than the map. Furthermore, color was being used for delineation of a plethora of quite different presentations (bedrock, surficial materials, chronology, genesis, etc.). As many as 9–15 fundamental colors could be used, and up to 45 different tints, so that subtle pastel variants of features became progressively indistinguishable by the average map user. In partial recognition of these problems, Demek(1982) called for the standardization of content and modes of representation of geomorphologic maps at the international level of coordination.

Also in Europe, numerous approaches were utilized, and specific applied problems related to economics were the focus. Consequently, thematic geomorphologic mapping was used for highway engineering design (Brunsden et al., 1975), terrain sensitivity (Rosenfeld, 1977), regional planning (Barsch and Liedtke, 1980), environmental management (Cooke and Doornkamp, 1990a), and natural hazards (Seijmonsbergen and de Graaff, 2006). Gustavsson(2006) and Gustavsson et al.(2008) attempted to overcome some of the prior problems with geomorphologic mapping by dramatically decreasing the number of symbols and providing a piece-by-piece legend construction to form numerous combinations of information.

Fookes et al.(2007) recently aggregated many applied geomorphological mapping problems under the general heading of "engineering mapping". Comparative maps of morphography, morphochronology, morphogenesis, resources, and hazards (Fig. 3) enabled recognition of the mapping essentials. Furthermore, three essential geomorphological map scales were identified: (1) Small–medium-scale regional surveys of terrain conditions (1:1 000 000) to 1:25 000) for feasibility studies, and land-use planning; (2) Medium-scale assessments of resources or hazards (1:50 000–1:10 000) to provide basic Earth-science data for land-use planning or for initial desk study stages of a project; and (3) Specific purpose large scale (1:5000–1:500) maps for detailed engineering projects. Mapping at these latter large scales has to be largely field based, although aerial photography and multispectral remote sensing can be utilized.

2.2. Modern GIS-based approaches

Today, Earth scientists are increasingly incorporating quantitative topographic information and spatial analysis and modeling into their research (Fig. 4). GIS-based applications in geomorphology range across the full suite of process domains and associated landforms. Often examined through images or scientific visualizations, more applications are assessing space–time patterns of geomorphic landscapes, multi-scale features and process domains, scenarios of landscape change, shifts in disturbance regimes, and land degradation associated with natural forces and human factors. Addressing such fundamental geomorphological and place-based questions has

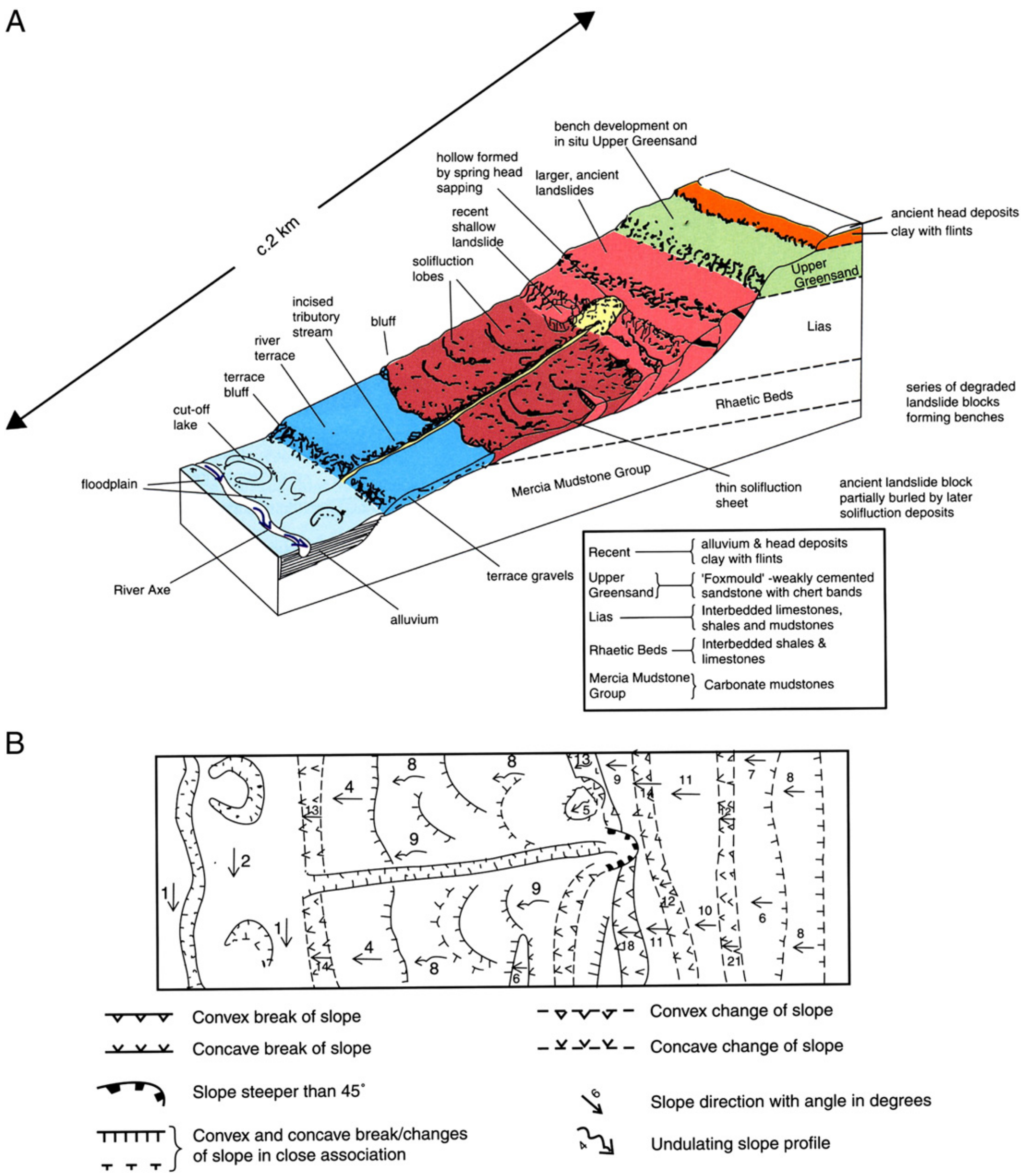

Fig. 3. Multiple geomorphologic mapping schemes for a section of gently dipping sedimentary rocks in England (after (Fookes et al., 2007)). (A) Block diagram of study area showing outcropping lithologies and characteristic landforms that developed as a result of variable rock and sediment types being modified over time into different landforms by various geomorphic processes; (B) Morphological/morphometric map of surface of block-diagram study area; (C) Morphographic map of surface of block-diagram study area showing landform features coupled with some genetic information; (D) Morphochronological map of surface of block-diagram study area showing main ages of development of landforms; (E) Morphogenetic map of surface of block-diagram study area showing genesis of landforms; (F) Map of resources associated with landforms and deposits of block-diagram study area; (G) Qualitative natural hazards map associated with the block-diagram study area.

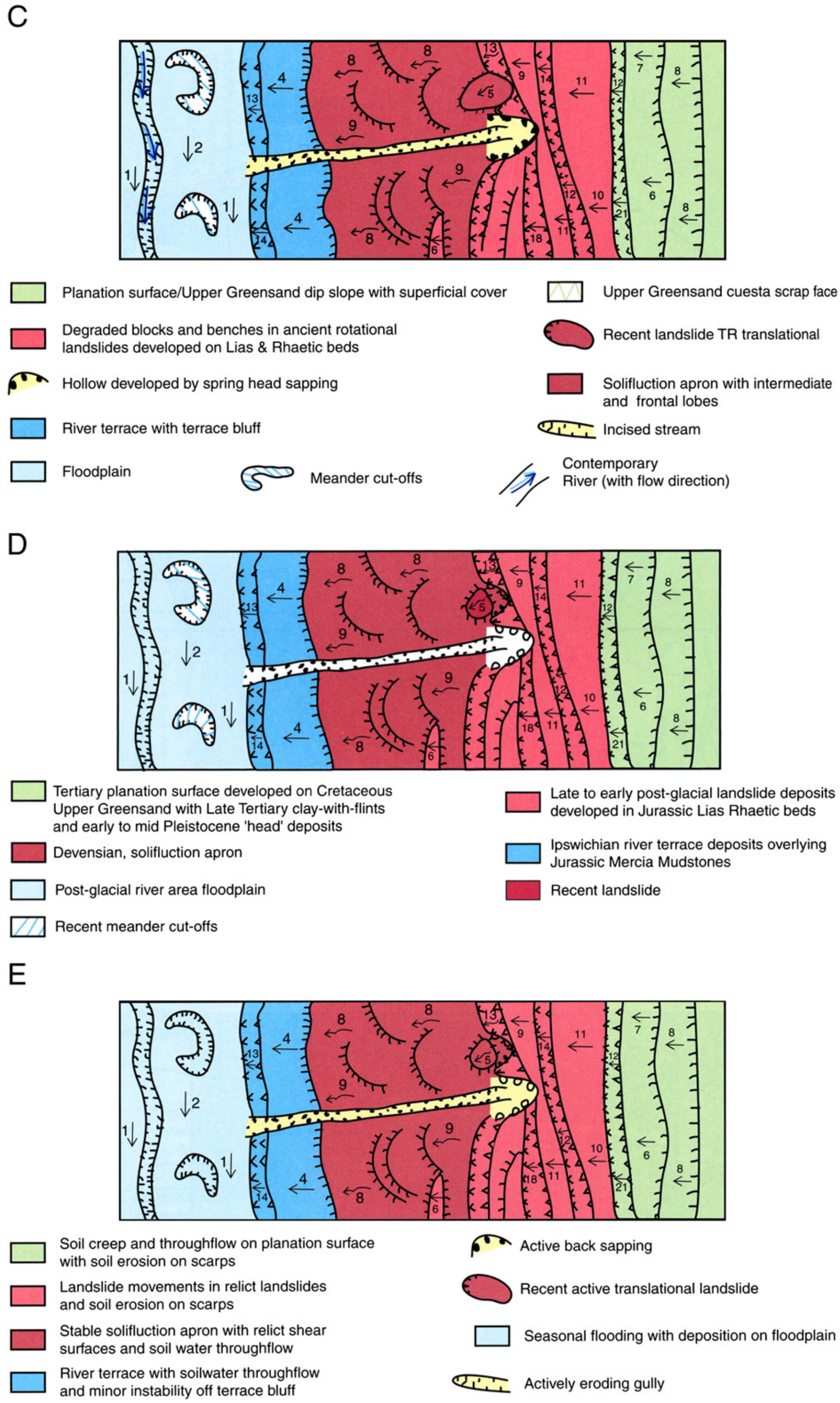

Fig. 3 (*continued*).

included the integration of terrestrial, airborne, and satellite remote-sensing technologies.

Global positioning satellite (GPS) technology has been commonly used to describe the geographic location of landscape features and unique patterns and to integrate diverse data. Increasingly, various methods of artificial intelligence are being used to examine non-linear dynamics and feedback processes that are described within the context of complexity theory (Walsh et al., 2008). These spatially explicit modeling approaches are being used to explore scenarios of landscape change, alternate futures and divergent landscape patterns. They can also be used to examine internal and external geomorphic forcing functions, that can be highly variable and exist at a multitude of space–time scales.

Such new capabilities represent a substantial evolution in geomorphology compared to traditional mapping. Yet, the traditional approaches of information integration via analytical reasoning, which

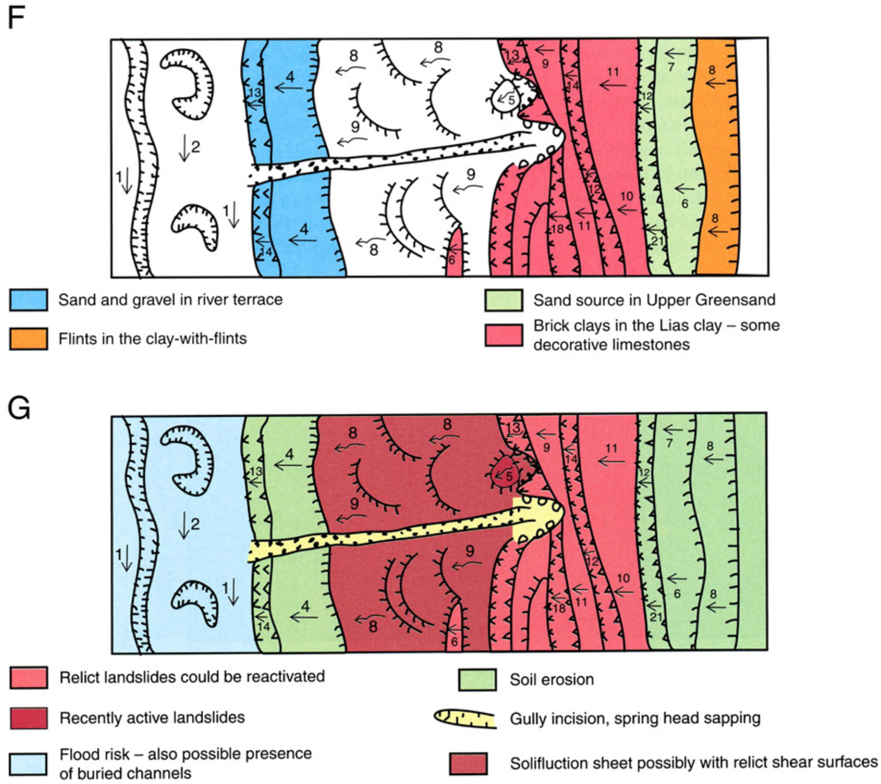

Fig. 3 (*continued*).

is the pillar of qualitative interpretation, is poorly represented by statistical metrics and mathematical operators that are so commonly used in DGM. Furthermore, results of quantitative analysis and numerical-modeling are dependent upon numerous factors and simplifying assumptions, and may not be representative of objective measurements obtained in the field. Consequently, conceptual and practical issues need to be recognized that have the potential for geospatial-technology solutions.

2.3. New challenges

Progress in DGM is routinely reported in geomorphology journals and covers most process domains. Inherent in this work is an exploratory or empirical approach that dominates DGM (Bishop and Shroder, 2004b; Deng, 2007). This approach relies upon statistical indices/metrics and subjective use of weightings or sensitivity parameters to permit flexibility in obtaining results. This is done to conform to different objectives, landform definitions or semantics. Such indices or metrics do not necessarily characterize process, but they may generalize relationships that are thought to reflect process variation. They may be interpreted in a multitude of ways, and it is not clear how they may collectively relate to more specific parameters that actually control process mechanics. A classic example includes a stream-power, bedrock-incision model with erosion indices that substitute area for discharge and parameters that do not formally characterize rock resistance or erodability.

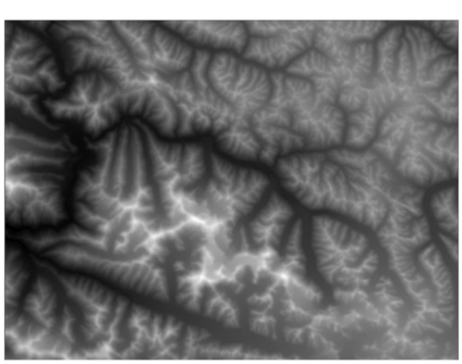

Fig. 4. Shuttle Radar Topographic Mission (SRTM) 3 arc-second DEM for the Shimshal Valley in northern Pakistan. The 90 m resolution permits relatively accurate geomorphometric characterization of the region. This region has not been adequately mapped given logistic and geopolitical constraints.

Earlier attempts have been made to develop a theoretical basis for terrain analysis and geomorphological mapping based upon concepts of spatial organization and elemental forms. Researchers from a variety of disciplines have recognized the hierarchical organization of landscapes, topography, and landforms. Therefore, hierarchy theory has been proposed as a model of how the topography is structured, and how it can be segmented (Dikau, 1990; Brändli, 1996). Consequently, investigations into object-oriented analysis, and the aggregation of geomorphic units at different scales, define the nature of the hierarchy (Schmidt and Dikau, 1999). Although this scale-dependent approach is conceptually pleasing, it is nonetheless fundamentally a cartographic approach to mapping that does not formally address issues of processes, internal and external forcing factors, feedback mechanisms and systems, or spatio-temporal dynamics. GIS-based empirical geomorphological research has yet to definitively demonstrate the analytical feasibility of addressing numerous scale-dependent mapping issues related to information integration, hierarchical organization, morphogenetics, or morphochronology in an operational way. The latest theoretical approach, described by Minár and Evans(2008), focused on the generation and aggregation of elemental forms, based upon fundamental geomorphometric analysis.

Currently, geospatial technologies facilitate geomorphological mapping by utilizing the topographic field, and applying criteria that are effectively approximations or heuristics. Most approaches to mapping represent decomposing the field based upon local criteria or relations to construct larger landscape entities or objects. When the spatial scale changes, the utility of localized parameters decreases and a synthesis approach to classification is typically based upon spatial aggregation, intersection, or pattern recognition. Unfortunately, numerous concepts involving space, time, process, and dynamics are disconnected. Furthermore, information and concepts are poorly integrated in terms of knowledge and analytical reasoning.

Bishop and Shroder(2004b) discussed these and many other issues associated with using geospatial technologies for studying mountain geomorphology that involve spatial data, representation, scale, analysis, modeling, processes and dynamics. Numerous geomorphological concepts have yet to be effectively addressed in terms of data and knowledge integration and analytical solutions. A variety of concepts are needed to answer the basic GIScience and geomorphological questions found in subsequent sections. Consequently, although it is important to recognize new capabilities, several issues and concepts may not currently have an adequate or immediate analytical or technology solution.

3. Issues in DGM

Numerous challenges should be addressed in a systematic way to promote applicability in different climate, geological and topographic settings. The theoretical basis for geomorphological mapping has not yet changed significantly, with subjectivity and application objectives driving the map-making process. Very few investigators have attempted to formalize or strictly define landform taxonomy and methodology (Minár and Evans, 2008). In addition, many new challenges focus on the concepts of land surface, landforms, homogeneity, heterogeneity/complexity, classification theory, scale, equifinality, polygenetic evolution, and the extremely difficult topic of ontology of forms and landforms. Ontological issues attempt to address the objective existence of forms and landforms. Thus semantics and interpreted meaning introduce subjectivity associated with issues of representation, analysis and mapping.

No consistent conceptual or analytical framework appears to exist to permit accurate mapping of landforms and geomorphic systems, although significant progress in specific and general geomorphometry and DGM has occurred. Problem solving has occurred largely in an ad-hoc fashion related to using new data, development and evaluation of morphometric parameters and indices, utility and evaluation of new information technologies, and demonstration of specific mapping applications. Such progress is expected to continue as geomorphologists are increasingly becoming educated in geospatial technologies and are developing new algorithms, analysis approaches, and software tools to address geomorphological problems. Consequently, establishing an objective geomorphological mapping framework to incorporate information and knowledge for the production of standardized geomorphological information is needed to support integrative science. To do so will require finding new conceptual and analytical solutions to a variety of issues.

3.1. Representation

Many topics in DGM are inherently related to space–time representation (Bishop and Shroder, 2004b). This topic is complex, and a wealth of philosophical, cognitive, and natural science perspectives exist. The reader is directed to Bishop and Shroder(2004b) for a discussion of space–time concepts in geomorphology. Our current use of representation is dominated by static cartographic map representations. This poses unique problems and challenges with respect to geomorphological mapping. It also provides numerous advantages in terms of spatial overlay, management of data, basic spatial analysis, and portrayal in conventional paper-based media.

Topographic variation can be represented in a variety of ways based upon data models. The common GIS data models are the field (layer), entity (object), and network data models, which can be linked with a relational data model (Goodchild, 1992). These data models are represented in a computer using data structures (i.e., raster and vector). Consequently, topography can be represented by numerous field models (sampled points, contours, polygons, tessellations, triangular nets) to characterize the continuous spatial variation in altitude. Object models are used to define well-defined features, assuming that discrete boundaries actually exist, while indeterminant boundaries have been recognized to pose a unique challenge, as environmental gradients or zones of homogeneous and heterogeneous surface properties can effectively represent boundaries or limits to the spatial distribution of phenomena (Burrough, 1996; Lagacherie et al., 1996; Usery, 1996). Earth scientists have noted the advantages and disadvantages of such data models and have recognized that these representations do not effectively address process mechanics or dynamics (Raper and Livingstone, 1995).

Field and object models do not formally represent the complex nature of landforms, as landform information is typically extracted from the altitude field via a multitude of approaches. Are different representations of the terrain and specific landforms needed, and should landforms be formally represented as objects? If so, do we need to shift from a field view to an entity view, and how do issues of space representation evolve to account for indeterminant boundaries? Many have shown that fuzzy boundaries can be used to represent gradients and positional zones (Fisher, 1996; Usery, 1996; Deng and Wilson, 2008). Intuitively, the three-dimensional nature of the near-surface environment should be represented better. Compositional variations in the near-surface environment must also be accounted for, as landforms exhibit a multitude of properties based upon composition, morphometrics, genetic, and spatio-temporal relations. Furthermore, in what role should qualitative geomorphological interpretations be used to characterize and map landforms? Such interpretations lend themselves towards the entity view, whereas the science of studying process mechanics, geodynamics and landscape evolution tends to focus on continuous space (Raper and Livingstone, 1995).

What data model is best to characterize topography and landforms for geomorphic representations? Dikau(1989) indicated that a digital relief model involving the parameterization of relief units could be used to represent topography that is hierarchically organized. Relief is scale-dependent, and the concept of homogeneous relief can be defined based upon distance and direction. What direction should be used (i.e., different spatial patterns with direction) and should the anisotropic nature of the topography be characterized? Minár and Evans(2008) suggest that elementary forms (i.e., based upon higher-order derivatives) should serve as the basis of geomorphological mapping. Although it is undeniable that topographic structure and form play a large role in geomorphology, how should process mechanics, process–form relationships, and temporal dynamics be characterized?

An intriguing proposition for geomorphological mapping has been presented by Cova and Goodchild(2002) that involves the extension of spatial representation to include fields of spatial objects. This effectively represents the linking of continuous space with object representation. It also permits tremendous flexibility in terms of representing complexity associated with landforms, as the issues of homogeneity, heterogeneity, complexity and other concepts can be addressed, as a tessellation can have more than one object, and the objects can have discrete or fuzzy boundaries. In addition, an object hierarchy can be developed to address issues associated with scale. Furthermore, it also permits the representation of process via “process objects”, wherein a multitude of process objects can simultaneously alter the topography at fundamentally different scales. This permits the integration of process modeling and mapping in a seamless way and raises the important issue of parameterization schemes for characterizing the process mechanics and specific process–form relationships. Such formal representations in geomorphology are required to validate results obtained via empirical analysis using geospatial technologies. Furthermore, such representation can handle temporally changing spatial patterns by using a dynamic representational scheme that results from the process dynamics. Consequently, spatio-temporal relationships are inherently represented. Numerous complexities associated with temporal representation, however, remain.

3.2. GIS-based research

A strong empirical basis is associated with geomorphometry and the utility of geospatial technologies for analysis and modeling (Bishop and Shroder, 2004b; Deng, 2007). Whereas this provides for flexibility in developing numerical metrics, software tools, and exploratory analysis of patterns, it also raises important questions concerning the scientific validity of results, repeatable results, and the formal use of geomorphological information in integrative science.

Remote sensing, geomorphometry, and GIS-based investigations commonly rely upon an index-approach to characterize landcover, form, process, climate, and structure. A multitude of indices can be used to depict surface biophysical properties, radiation and precipitation potential, erosion potential, and surface moisture conditions, just to name a few. Numerous potential metrics exist for any one thematic attribute. These indices or metrics are frequently based upon an association with a topographic parameter, although they do not adequately characterize process mechanics, scale dependencies, or temporal dynamics. This static cartographic approach is predominately used to examine spatial patterns, and such indices have been found to be useful in GIS-based analysis and modeling efforts. Which metric, however, best characterizes the phenomena of interest? Whether or not such patterns actually represent "reality" (i.e., morphology, physical properties, genetics, dynamics) is another question. Studies involving the use of indices and empirical analysis and modeling must closely examine results to determine if patterns have a scientific basis. For example, Qin et al.(2009) developed an approach to use slope position and fuzzy logic to quantify the spatial gradation of slope positions. They conducted field work and found that their similarity index and spatial patterns of slope gradation were related to A-horizon sand percentages, and the spatial patterns ultimately characterized slope processes that govern the distribution of particle sizes. This demonstrates the importance of fieldwork in understanding GIS-based research and its role in developing new capabilities in soil mapping.

Historically, a reliance has been placed on pattern recognition for segmentation and mapping. Such thematic mapping involving remote sensing focuses on the utility of multispectral data and spectral/spatial features for land cover, ecological, geological and hydrological mapping. This approach also includes the integration of topographic information and other environmental indices to partition the landscape based upon relative patterns. Many have used statistics-based classifiers that depend upon the notion of statistical separability in *n*-dimensional feature space. This approach formally dictates the development and evaluation of metrics that ensure statistical separability to produce the desired classes. Results from the most common statistical classifiers are highly dependent upon establishing an appropriate feature space, selecting the appropriate number of classes, training, and the nature of the algorithm. Many algorithms represent a brute-force approach where the results do not necessarily relate to real geomorphological characteristics. Furthermore, classification results are highly dependent upon input data related to spatio-temporal resolution and preprocessing. The notion of *relative patterns* versus diagnostic *signatures* for universal identification and mapping must be considered. Several researchers have begun to address this issue and have evaluated the utility of more sophisticated approaches, such as Fourier and wavelet analysis to detect spectral or topographic signatures for geomorphological mapping (e.g., Wieland and Dalchow, 2009).

Another aspect of empiricism is related to the development of indices or parameters for characterizing and mapping phenomena on the basis of such concepts as protypicality, membership, scaling, ranking, weighting, thresholding, probability, and a plethora of hueristic rules. Numerous metrics have such parameters in the formula. Whereas these metrics have value in terms of flexibility to address issues associated with semantic meanings, spatial uncertainty, subjective interpretations, data integration, classification, and variable definitions, results can be highly variable. Furthermore, issues of scale and spatial context may also need to be considered. These examples of new developments in geospatial analysis are far removed from more deterministic assessment of the landscape using physics-based process parameterizations. For example, how does empirical ranking and weighting of numerous nominal and ordinal variables accurately characterize slope stability potential in a meaningful way when the disconnect between the metric and rock properties and process is so great? A better link is needed between empirical map production and more deterministic-based assessments involving processes and the utility of Earth science knowledge.

3.3. Scale

The issue of spatial and temporal scale in geomorphology and GIScience is well known (Quattrochi and Goodchild, 1997; Tate and Atkinson, 2001; Sheppard and McMaster, 2004). Numerous perspectives and practical issues of scale are associated with representation, data collection and information, analysis and modeling, and scientific inquiry. Linking these perspectives to address scale from a holistic perspective is desirable, although such progress in geomorphological mapping has been somewhat limited. Perspectives on spatial scale are varied and include concepts of:

- *Geographic scale*, representing aerial coverage or the size of objects.
- *Cartographic scale*, representing aerial distribution and detail of information presented.
- *Measurement scale*, representing the smallest area over which data can be collected or represented to maintain distinguishable parts of an object.
- *Operational scale*, representing the scale at which processes, feedback mechanisms, and systems operate.
- *Computational scale*, representing the scale at which data are analyzed.

Inherent in any treatment of scale is recognition of the extreme complexity associated with a multiplicity of temporal and spatial scales that can be associated with phenomena, processes, and systems. Consequently, research into scale dependencies of form and process is of extreme importance. Such research also introduces the concepts of scale linkages and the possibility of scale independence (Phillips, 2004).

Hierarchy theory is a theory of scale dependence and scaled systems (O'Neill et al., 1989). It essentially describes a vertical structure of levels, and that a subsystem at any level is spatially constrained by a higher level. It can be used to describe the complexity of scale associated with a landscape, and the theory has been proposed as a basis for modeling and geomorphological mapping (Dikau, 1989; Brändli, 1996). Geomorphological mapping currently focuses on geomorphometry, where the basis for identification and delineation of scale and the hierarchy is based upon the concepts of spatial homogeneity and scale dependence of topography. While it is essential to characterize the spatial variation of numerous properties of the topography, the spatial variation of other landscape information must also be accounted for, and the selection of empirical criteria can result in different characterizations of scale.

The topography inherently reflects the interaction of numerous processes, and a major goal in geomorphology is to characterize the operational scale dependencies. Consequently, researchers have utilized DEMs and new spatial analysis techniques to characterize spatial variation and attempt to validate spatial theories of phenomena (Fotheringham and Rogerson, 1994). Such spatial concepts and theories include spatial sampling, autocorrelation, stationarity, scale dependence, and self-organization. Perhaps the most popular technique has been variogram and fractal analysis to study a wide variety of landforms and topography. This exploratory analysis approach, however, suggests hypotheses about morphology and processes. Theoretical geomorphology feeds into the use of geospatial technologies, but, results may not directly translate into producing meaningful geomorphological maps. This can be demonstrated by work focusing on self-similarity of topography wherein investigators have reported on the multi-fractality of topography at different scales (e.g., Burrough, 1981; Mark and Aronson, 1984; Klinkenberg and Goodchild, 1992), because variations in patterns are thought to be related to specific operational scales. In contrast, Veneziano and Iacobellis(1999) concluded that multi-fractality is based upon the gradient amplitude method and this produces spurious multi-fractality even when a simulated surface is known to be self similar.

A multitude of controlling factors govern process dynamics and landform development and evolution, and the use of spatial data and geospatial technologies presumably can provide new insights into scale dependencies of these controls. Is it possible, however, that processes operating over different scales operate independently? That scale linkage can sometimes be important but not always? Does this mean that we need to know when to focus on the spatial, temporal, or spatio-temporal aspects of the system components (i.e., morphometry, composition, processes)? Is scale linkage necessary for DGM? Phillips (2004) suggested that scale linkage across the entire range of spatial scale might not be feasible. This may have implications for geomorphological mapping, especially as the measurement scale of imagery and the production of high-resolution DEMs becomes more commonplace and allows data resampling and aggregation at various scales. Furthermore, spatio-temporal scales could theoretically change over wide scale ranges. A seamless space–time linkage may not exist, as catastrophic events, varying process rates, and landscape evolution also produces topography that is disconnected with the surrounding spatial–topological framework that is thought to exhibit linkage. Such spatial and temporal contingency is usually required by geomorphologists for interpretation of the landscape and mapping. Rarely do we have complete chronological information, and this highlights the need for the integration of modeling and mapping, where models can be used to characterize temporal concepts of events, duration, repeat interval, and age. GIS-based analysis has already demonstrated that the topography exhibits scale-dependent and scale-independent properties (Tate and Wood, 2001). More research is required to determine the impact of such scale issues related to formalizing hierarchy theory for DGM.

Further scale issues concern data and methodology. Numerous investigators have examined spatial patterns in data sets that simulate variations in measurement scale. Implicit in this work is the assumption that processes govern the spatial patterns, although process–structure relationships and spatio-temporal relationships are rarely formalized. Moreover, results are typically based upon finding empirical relationships that are partially regulated by spatial frequencies due to the simulated measurement scale. Such generalization produces multicollinearity at larger spatial scales, and statistical issues need to be addressed before interpretation. It is also widely known that the full range of the measurement scale may not be used to assess certain processes in an accurate fashion, and, therefore, the implicit assumption associated with this approach may not be valid. Montgomery et al.(2004) clearly demonstrated this with the process of erosion and the measurement scale of DEMs. Consequently, calibration may be required based upon the measurement scale of a DEM before results could be used for simulation studies or mapping.

Finally, the notorious issue of "window size" has been recognized in the literature and is synonymous with computational scale. Investigators have developed a multitude of metrics in remote sensing and geomorphometry that are computed using data within a symmetric window of a particular size (e.g., 3×3, 5×5, etc.). The spatial patterns or statistics obtained from a particular metric are a function of spatial scale and direction (Fig. 5). The same principle applies when resampling gridded data at a coarser cell size. The computation scale appropriate to the mapping objectives must therefore be used. This scale is usually empirically determined. For many mapping applications, however, the computational scale should be based upon specific criteria (e.g., reflectance, texture or autocorrelation). Such criteria can be related to image information, composition, morphometrics, structure, process domain, or other thematic information. Consequently, more research is required to formalize the criteria upon which computation scale is determined for different mapping applications. These criteria will most likely include the integration of multiple information themes for defining a spatial pattern upon which to compute the metric for the desired pixel. This raises the important issue of multiple dynamic computational scales for different aspects of the landscape.

Fig. 5. Multi-scale positive-openness measure for the Shimshal Valley in northern Pakistan. Dark grey tones represent more relief, while lighter grey tones depict less relief (e.g., on ridges). The metric is an average value of the maximum relief angle for eight different directions and accounts for scale variations in relief. It essentially produces meso-scale relief information.

3.4. Geomorphic mapping perspectives

Various structural and functional aspects of the surface of the Earth can be mapped in different ways. For example, Verstappen (1983) noted that four different types of data could be collected for mapping landforms that include morphographic, mophogenetic, morphometric, and morphochronologic information. Each approach can provide new insights into better understandings of process domains, morphogenetics, feedback mechanisms, and polygenetic landscape evolution in which overprinting commonly confounds adequate interpretation and mapping. A sample of different perspectives includes the following:

- Land cover or land systems. Mapping can be based upon recognition of "land systems" as containing unique terrain attributes (Cooke and Doornkamp, 1990a). Any single land system ranging from 10 to 100 km^2 generally has a recurring set of topography, soils, and vegetation types that correlate with the geology, geomorphology and climate, such that predictable combinations of surface forms and associated soils and vegetation occur. Land-system mapping became a preferred method in the mid to late twentieth century to effectively investigate and provide a regional framework for relatively unknown territories in Australia, Africa, and the Middle East. This approach, however, does have limitations, particularly with its more qualitative and subjective criteria. Furthermore, surface land-cover information is routinely generated via remote sensing, although standard classification methods in remote sensing do not always characterize the complex three dimensional nature of landforms. Recent developments in using airborne LiDAR data to characterize land cover structure offers new capabilities.
- Hydrology. Water is obviously one of the most important agents in landform development and most mapping systems include hydrologic information. Numerous systems of representation have been used to delineate the hydrology of any given area (Gustavsson et al., 2006). Mapping can depict permanent, ephemeral or intermittent, and subsurface streams, together with abandoned channels, waterfalls,

rapids and dams, springs and sinkholes, periodic and permanent waterlogged areas, as well as lakes and seas, and playas and sabkhas of various kinds. Headwater stream areas dominate most terrestrial landscapes, but maps of low-order channels are notoriously incomplete and inaccurate (Heine et al., 2004). In the USA, distinctions between perennial, ephemeral, and intermittent streams are being defined, field mapping methods are being developed, and mapping programs are being implemented to provide improved maps of headwater streams (e.g., North Carolina Division of Water Quality (NCDWQ), 2009). Rates of erosion, deposition, and geomorphic processes in most fluvial landscapes are affected by the density and longitudinal connectivity of the drainage network (Fig. 6). Drainage densities are a critical parameter for hydrologic or landscape evolution modeling because concentrated flows in channels increase conveyance efficiencies. This area of research is progressing rapidly in response to high-resolution topographic data (laser swath mapping) that can penetrate vegetative canopies.

- Surface materials, lithology and structure. Gustavsson(2006) noted that the overall information on bedrock, surface sediments, stratigraphy, and tectonic structure of any region were best presented as separate overlays or small-scale maps. In cases, however, where the materials or the stratigraphies directly affect the surface morphology, such materials should be incorporated into the geomorphological legend. Distinctive properties of bedrock, regolith and tectonic structure can be depicted in various kinds of morphotectonic maps (Cooke and Doornkamp, 1990a). Rocks are differentially resistant to erosion, so a common way to differentiate resistance is by mapping rock type (e.g., most crystallines are resistant while sediments and sedimentary rocks are less resistant) (Gustavsson et al., 2006). Rock-mass strength (Selby, 1980) in which joint strength, spacing, and continuity may be key determinants of geomorphology and landform durability, and can be the most geomorphically relevant property of the bedrock. Unfortunately, information about it is rarely available from geologic maps (Goudie, 1990). Mineral composition of bedrock can also be a strong determinant of erodability and morphology in environments dominated by long-term, chemical weathering (Shroder, 1973), in contrast to bedrock geomorphic environments in mountain orogenic regimes. Maps depicting the spatial distribution of grain sizes are also important to geomorphology, because grain size controls permeability and sediment mobility. Soil maps are the most common source of data on grain-sizes and should be integrated into the development of geomorphic maps. Such maps may also include information on sediment type such as 'till,' loess' and 'alluvium,' which obviously imply much about the genesis of the associated landforms. For example, Gustavsson et al.(2006) emphasized mapping consolidated rock types, clastic grain sizes, kinds of organic sediments, together with areas of permafrost and glaciers. Single-rock blocks and erratics were also designated, along with kinds of structures. Rigorous field-sampling procedures can assist in accurate mapping (Goudie, 1990; Pavlopoulos et al., 2009).
- Morphometry and morphography. The morphometry of a landscape provides a quantitative description of landform shapes, whereas morphography is the mapped description of the configuration (Gustavsson et al., 2006; Fookes et al., 2007). Pure morphographic and morphometric maps are rather rare but information on slope gradients and azimuth are common and can be combined with morphography as well (Cooke and Doornkamp, 1990a; Goudie, 1990). Slope gradients are generally considered to be the most important morphometric parameter for the characterization of geomorphic processes and applications, so selection of appropriate scales and critical gradients represent significant issues. Collection of such data is time consuming in the field or in the laboratory with contoured topographic maps, but can be produced easily from DEMs generated from various space, airborne and terrestrial sensor systems (Smith and Pain, 2009). Morphometric information can also be subjectively reduced to ordinal data to facilitate mapping and various forms of GIS analysis. Numerous articles and books have been written on geomorphometry, and geomorphologists now have a variety of software tools to examine a plethora of morphometric parameters and indices that attempt to characterize terrain conditions and concepts (e.g., Wilson and Gallant, 2000; Hengl and Reuter, 2009). These characteristics include multi-scaled radiation parameters such as terrain shielding (widely known as the sky-view factor) and other mesoscale parameters such as *openness* (Yokoyama et al., 2002).
- Sediment-transfer cascades. Cascade systems are spatial structures on a landscape that are interconnected by flows of mass and energy at micro-, meso- and macro-scale process levels within the geomorphological system (Chorley and Kennedy, 1971). For example, in most areas numerous process subsystems (physical and chemical weathering, mass movement, glacial, eolian, fluvial, etc.) can be characterized and mapped so that process coupling, sediment cascades, and paths of sediment transfer, and sediment stores are identified (Shroder and Bishop, 2004), as well as quantified in certain cases. This can be a key tool in the analysis of geomorphic systems and serve as a basis for development of models of sediment budgets.
- Surface-process regimes. Process domain mapping can be somewhat subjective based upon the interpretation of morphometry and materials (Cooke and Doornkamp, 1990a). Geomorphic genesis is an exceptionally important parameter in mapping, but portrayal of such processes should not detract or distract from other geomorphological data so as to allow for later reinterpretations of landscape development (Gustavsson et al., 2006). The full panoply of surface processes is large and includes the main groups of endogenic, and all the exogenic forces that are denudational and depositional. Process–form relationships are used. For example, the actual flood is rarely mapped, although the upper limits of a past flood or the margins of a floodplain may be delineated. Similarly the relationship between the upslope area and the slope is frequently used to delimit the influence of overland flow and channelized flow (e.g., Cohen et al., 2008). It is currently very difficult to determine the influence of tectonic processes such as deformation and uplift on the landscape, although numerous investigations have indicated relationships with various morphometric aspects of topographic structure (Jamieson et al., 2004; Boulton and Whittaker, 2009; Ruszkiczay-Rudiger et al., 2009). Nevertheless, inferring process from form is notoriously difficult.
- Chronology. Mapping the age of landforms is difficult because of numerous problems associated with the recognition and designation of temporal attributes. The age of the landform has to be determined in some relative or quantitative sense, and many different spot ages may occur scattered across a landscape. If age heterogeneity is complex and high, reflecting the passage of time and the occurrence of multiple events in a landscape, the chronology may be overly simplistic and not very useful. Clusters of ages may occur that reflect temporal signatures more reflective of the types of dating methods and availability of datable

Fig. 6. Multi-scale negative-openness measure for the Shimshal valley in northern Pakistan. This metric highlights the drainage network and valley floors. Other methods can also be used to assess and map the drainage network.

materials. In addition, any surficial landscape that came into existence at some time in the past, may still be exposed to ongoing process-superposition overprinting so that assigning a specific or restricted chronology to a mapped area may be rather misleading. In general, many landscapes exhibit temporal ambiguities and oversimplifications that need to be carefully considered and explained. Finally, some geomorphic processes, such as a marine regression exposing shorelines, are time transgressive, so that the age of surfaces change gradually over space.

Regardless of the complexities, it may still be desirable to attempt to assign a temporal designation to parts of land surfaces, particularly those that were strongly influenced by a dominant process in the past and then modified by another process. This designation can be problematic, however, and great care must be expended to minimize subjectivity so that subtle alterations of the landscape since major events are not overlooked entirely. Individual features may be much easier to assign specific ages than larger expanses of terrain, although, despite the subjectivity involved, many geomorphology maps produced in Europe attempt to assign dates to the origin of an entire land surface (Cooke and Doornkamp, 1990a). Commonly, such attributions are conceptualized in terms of ideas of landform evolution in Quaternary time, but problems arise when evolutionary models are revised.

Another important characteristic concerning the temporal aspects of any geomorphologic map has to do with the intensity of the process (Flageollet, 1996). Several attributes could be assigned to the nature of processes. For example, in the case of mass-movement processes, it may be necessary to specify the state of the slope-failure activity in terms of being inactive, stabilized, dormant, or active. The type of activity could be singular, episodic, intermittent or continuous, and the mode of activity could be random or progressive. Similarly, the return period could range through various frequencies from long term to very high frequency, whereas the period of last activity could range from pre-Quaternary, through various divisions of Pleistocene and Holocene to the present time.

Cartographic approaches to mapping chronologic information has been done in many different ways, commonly making use of color codes, geomorphic symbols, letter codes, or whole map surfaces (Gustavsson et al., 2006). Where combined with colors that also designate bedrock or sediment ages, as well as colors for dominant process or genesis, the subtle color variations can create an overwhelmingly complex and unreadable or undecipherable system of presenting information in a static map form. All of this temporal complexity adds to potential indecipherability unless the concept of GIS layers and spatial overlay can be used for spatial query to detach the complexities one from another.

3.5. A geomorphological mapping framework

A variety of approaches and methods to address mapping issues have emerged in recent years. Given a multitude of existing capabilities and limitations in DGM, it is reasonable to question whether a formal mapping framework or DGM protocol is required. Many would argue for establishing such a framework based upon landform taxonomy, new analytical capabilities, and the need to objectively produce scientifically repeatable results that can be used by other science communities. Conversely, others correctly argue that a theoretical basis and formal analytical solutions to address a variety of issues are lacking, and that more research is required before such a formal system could be produced, given software limitations and the empirical nature of GIS-based research. The current approach appears to be one of creating digital geomorphological databases, developing and evaluating approaches for automated landform classification, and developing cartographic and visualization approaches for information dissemination. This approach focuses on information integration, although numerous deficiencies exist when examining the full range of geomorphological information.

Analytical solutions for information and knowledge integration, as well as analytical reasoning seem to be warranted. The complexity of DGM is high, and fundamental questions in geomorphology and GIScience need answers to determine future directions for establishing such a framework. A refined DGM protocol is needed to focus research and map production, so examination of the issues is timely and potentially highly productive. Some questions about the conceptual and technical nature of the problem are given in Table 1.

4. Capabilities and potential solutions

The challenges in DGM are being met with creative research and applications that will ensure rapid progress and new questions for further research. Many exciting capabilities already exist, and it is essential for geomorphologists to be familiar with such developments and explore new avenues of research.

4.1. Remote sensing

With the advent of new sensor systems and planned missions, various Earth science communities can count on utilizing a variety of spatial data sets that have already revolutionized DGM. Existing data have improved spatial, spectral, temporal, and radiometric resolutions to facilitate the extraction of critical information necessary to quantify the surface for thematic mapping. This includes surface and subsurface composition, surface biophysical parameters, topographic information, and spatio-

Table 1
Conceptual and technical questions concerning digital geomorphological mapping.

Conceptual questions
How is the concept of land surface, as it relates to process and morphometry, best addressed?
Should the semantic descriptions of specific landforms incorporate environmental, process, morphology, and materials information?
How should polygenetic landforms be characterized? Is the concept practical or does it detract from other aspects of DGM?
To what degree should the entire landscape be analyzed to produce meaningful maps that differentiate areas or regions?
Should terrain/landform taxonomic schemes be used to establish criteria for analysis and DGM?
What criteria/properties are required for identification and classification of specific landforms?
What is the nature of the spatial hierarchy of the terrain? Can scale independence be recognized?
How can the utility of hierarchy theory for landform mapping be tested given the extreme complexity associated with DGM? Should classification hierarchies be used?
Given process–rate variations, to what degree can morpho-chronological relationships be characterized?
Do diagnostic morphological signatures exist for landforms, process domains and coupled system dynamics?
To what degree are geometric patterns, such as various forms of symmetry and asymmetry, diagnostic of terrain conditions and landforms?
Technical questions
How should spatio-temporal information about geomorphological systems be presented and integrated?
Should landforms be represented with discrete or fuzzy boundaries?
How can information from remote sensing of land-cover and biophysical conditions be effectively integrated into geomorphological maps?
What specific topological relationships characterize landforms and landform assemblages?
What spatial analysis techniques can be relied upon for understanding pattern–process relationships?
How can the anisotropic nature of the topography be best characterized?
What approaches have the greatest potential for incorporating knowledge and analytical reasoning into DGM?
Should mapping landforms be done in the context of numerical process models, such that a more complete range of geomorphological conditions and landforms be accounted for?

temporal topological information. With sensor improvements, however, issues arise related to data volume, memory and processing speeds, increased information variability, algorithm suitability, data integration, analysis, and visualization. Effective use of remote sensing in DGM also requires domain knowledge and understanding of remote sensing science and technology. For a detailed treatment of the numerous sensors available to gemorphologists see Smith and Pain(2009).

The science of remote sensing plays a critical role in geomorphology, as it focuses on the physics of radiation transfer and matter–energy interactions for acquiring imagery and the production of environmental information. An understanding of the underlying science is required in order to use geospatial technologies appropriately for estimating surface parameters such as albedo, altitude, temperature, and soil and vegetation biophysical parameters. Remote sensing can also be used for thematic mapping of landscape features.

4.1.1. Near-surface information

Remotely sensed data provide thematic information regarding the location and the spatial distribution of landcover, lithology, topography, landforms, hydrology, surface biophysical properties, and subsurface characteristics. New capabilities in landcover and geological mapping via remote sensing constitute a major research theme, and such maps can be routinely produced in a variety of environments. This facilitates landform mapping, although it is complicated by lack of a one-to-one correspondence between landcover and landform materials or processes, as landforms can be composed of different materials or a multitude of landforms composed of the same material, and processes are not necessarily driven by surface materials. Remote sensing assists in differentiation of materials including minerology, lithology, moisture content, thermal properties, and surface roughness. The relatively recent emergence of imaging spectrometry/spectroscopy, which involves the use of hyperspectral data in very narrow spectral bandwidths (e.g., 8–10 nm), provides new diagnostic capabilities to assess the surface.

Imaging spectroscopy permits the diagnostic mapping of the primary landcover types via pattern-recognition approaches, as the shape of landcover spectral curves are distinctive. Furthermore, it permits biophysical assessment of chlorophyll, leaf area index, leaf moisture content, stand structure and leaf cellular structure that can be used to assess canopy variations. These capabilities permit phytogeomorphological and geobotanical assessment. Similarly, various aspects of biogeochemical cycling may be ascertained, as soil physical and geochemical properties influence plant physiology.

State-of-the-art geological, mineralogical, and soils mapping is dependent upon hyperspectral data in more arid environments. Various types of rocks and minerals have either distinctive spectral reflectance curves, or diagnostic absorption features. Oxides, primary silicate minerals of felsic and mafic composition, as well as secondary silicate minerals can be differentiated (Fig. 7). This information is important for assessing weathering and soil parent material and may provide information about sediment provenance and fate.

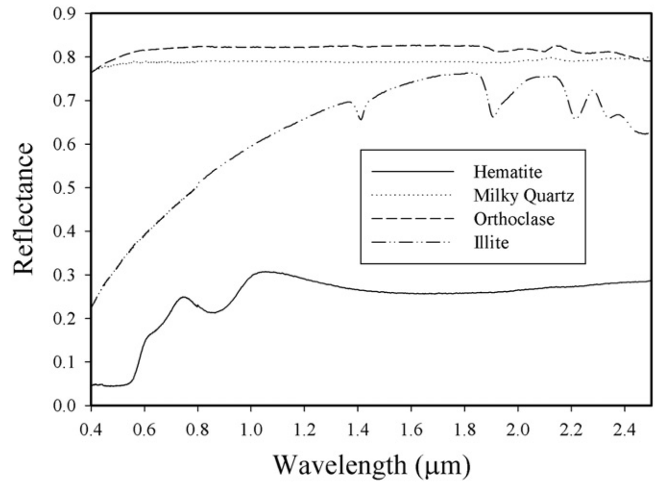

Fig. 7. Laboratory spectral reflectance curves for hematite, milky quartz, orthoclase, and illite. Spectral libraries can be used in spectral mixing models to assess the compositional nature of the surface using airborne and satellite hyperspectral sensors. Data for this figure were obtained from the USGS and/or ASTER spectral libraries.

Surface water and moisture conditions can also be mapped by remote sensing methods. Current capabilities include snow, ice, water vapor, and albedo mapping (Dozier, 1984, 1989), lake and turbidity mapping (Wessels et al., 2002), soil moisture assessment, flood hazards assessment, and other water-related applications. Much recent work has been done on mapping river channel habitats (Marcus et al., 2003; Legleiter et al., 2004; Fonstad and Marcus, 2005; Carbonneau et al., 2006; Marcus and Fonstad, 2008) and analysis of fluvial sediment budgets using morphometric methods (Brasington et al., 2003; Lane et al., 2003). Thermal variations on the landscape can be useful for assessing depositional environments (e.g., Hardgrove et al., 2009), and radar data can be used for assessing soil texture and distributions of particle sizes and the monitoring of ground motion and ground subsidence.

Although surface composition and biophysical parameters can be used for mapping, the geomorphological community needs to determine how this information is best incorporated in DGM efforts. Such biophysical parameters may exhibit highly varied spatial patterns with a multitude of boundary types (gradients, homogeneous zones, discrete, heterogeneous zones, linear trends) that may or may not be directly associated with landforms. Some patterns may be related to process, and may not always explicitly delineate the boundaries of landforms. The spatial intersection and aggregation of spatial entities, derived from biophysical surface properties combined with form units, represent a promising mapping direction.

Information on subsurface materials and characteristics can be obtained via passive gamma-ray spectrometry and geophysical techniques such as gravity, aeromagnetics and electromagnetics. Gamma-ray spectrometry may indicate the composition of materials in the upper 50 cm of the surface (Smith and Pain, 2009), whereas gravity, aeromagnetics, electromagnetics, and ground penetrating radar can be used to assess density, subsurface features, conductivity variations, and depths, respectively (Lane, 2002; Wilford, 2002). Consequently, subsurface lithological variation can be compared with surface morphometry and other properties to characterize the 3-D nature of landforms. The cost and availability of such subsurface information is currently a serious limitation as expensive airborne or field surveys are required.

4.1.2. Digital elevation models

Perhaps the most significant contribution of remote sensing to geomorphology is the use of passive and active sensors to generate surface elevation data commonly referred to as a DEM. A variety of techniques can be utilized for digital terrain modeling including image photogrammetry, radar or laser altimetry, and interferometric synthetic aperature radar. Photogrammetric applications of satellite imagery including SPOT and ASTER data are commonly used by scientists. In the case of SPOT imagery, alternate view perspectives from multiple satellite passes enable stereoscopic representations, whereas the ASTER system relies upon forward- and back-looking telescopes to characterize topography through a merged characterization. Similarly, radar imagery and specifically SRTM (Shuttle Radar Topographic Mapping Mission) data are widely used for mapping. The SRTM and ASTER mission objectives were specifically designed to produce a global DEM data product to facilitate Earth science mapping projects. These DEMs have resulted in many new developments and the ability to automate landform mapping based upon the use of geomorphometric parameters/indices.

More recently, airborne high resolution, light detection and ranging (LiDAR) systems and terrestrial laser scanning systems can generate millions of 3-D point measurements. These “point clouds” must be analyzed and manipulated to ensure accurate interpolation to generate a bare-Earth altitude field. LiDAR high-resolution DEMs permit more accurate geomorphometric characterization of the surface that potentially permits greater accuracy in mapping. These data allow developments in geomorphometry to be exploited, whereas the same techniques may not be as useful given a coarser DEM measurement scale. For example, DEMs of Difference (DoD) are emerging as a form of change detection suitable for examining spatial patterns of geomorphic dynamics and volumetric analysis, but the availability of high resolution, geo-referenced elevation grids is critical.

In addition, airborne LiDAR data have proven useful for characterizing a range of attributes of surface and plant structure in a variety of settings for geomorphological mapping. The distribution of LiDAR return times contains information about the vertical distribution of reflective elements of landscape types. LiDAR intensity (i.e., reflectance of the LiDAR signal) can be used to help classify terrain and plant objects and to calibrate SAR imagery to further describe structural features. Whereas many systems are available, the Leica-ALS60 Airborne Laser Scanner, for instance, is a 3rd generation LiDAR system that features 4-returns (first, second, third, and last) and 3-intensities (http://www.leica-geosystems.com/en/Leica-ALS60-Airborne-Laser-Scanner_57629.htm).“Returns” are used to define the ground and top of canopy, whereas the “intensities” are used for surface classifications. It is common for LiDAR systems to collect first and last returns of the plant canopy and ground surface or wave-form or continuous returns for improved 3-D structural characterization.

Whereas a host of approaches have been extensively used to characterize topography, map landforms, and assess indicators of pattern–process relations in a variety of settings, LiDAR has assumed the pre-eminent role in surface representation. For instance, Jones et al.(2008) used LiDAR data to assess the patterns and characteristics of hydrologic facets (i.e., landscape patches that have high internal surface water connectivity that function as a single hydrologic unit). Schumann et al.(2008) described hydraulic modeling applications using DEMs derived from LiDAR data, topographic contours, and SRTM data. They reported that LiDAR data are most useful, but SRTM data are useful for large geographic areas, such as homogenous floodplains.

Three-dimensional flood mapping with low-resolution, low precision surface elevation data is exceedingly difficult for small scales, as the DEMs have too many horizontal and vertical uncertainties. Puech et al.(2009) described the use of different transformations of LiDAR data that represent useful parameters in geomorphology. Glenn et al.(2006) also used LiDAR data to examine the surface morphology of landslides by deriving measures of surface roughness, slope, semi-variance, and fractal dimensions.

In glacial geomorphology, Smith et al.(2006) compared LiDAR data to field mapping results. The study focused on glacial lineaments, but attention was also given to moraine ridges and eskers. Qualitative and quantitative comparisons of data sets indicated that only NEXTMap provides results that show any approximation to the field mapping, but remote sensing, generally provides important evidence of regional significance when glaciation has had a significant influence on the landscape.

Other examples of LiDAR mapping applications include changes to barrier islands (e.g., White and Wang, 2003) and sand dune studies (e.g., Woolard and Colby, 2002). Results indicate that 1–2 m resolution DEM data provide the most reliable representation of coastal dunes and the most accurate volumetric change measurements. Finally, Hooper et al.(2003) used airborne TOPSAR (topographic synthetic aperature radar) data to derive a high resolution DEM to assess fault scarps that cut alluvium and alluvial fans. Other relevant geomorphic features were present in the DEM including splays and benches along the main fault, levees, cut-banks, gullies incising fault scarp slopes, shutter-ridges, offset drainage, and small normal faults with scarps. Research clearly indicates that new high-resolution DEM datasets are having a profound impact on DGM.

4.1.3. Image analysis

Historically, visual interpretation of photography and imagery has made use of various interpretation strategies. It has long been known that image information content can be dense, and that image information extraction is facilitated by using image elements. These elements include tone (reflectance, emission, backscatter), texture, pattern, size, shape, shadow, associations, and site. Human interpretation involves the integration of this information to segment the landscape. Great progress has been made in computer-assisted analysis with respect to assessing tone as it relates to surface composition and/or properties. Characterization of image texture, or the spatial variability in tone over a particular distance has been researched for over 30 years. A multitude of techniques include first-order statistics, second-order statistics based upon the co-occurrence matrix, structural approaches to texture, Fourier and wavelet based features, and the use of geostatistics and multi-scale approaches. Texture is important in DGM as many landforms exhibit a surface texture that is related either to land-cover structure or to surface roughness influenced by erosion and deposition. Texture analysis is based upon a computational scale, and tone and morphology can be common thematic constraints, although more complex criteria can also be used.

Substantial progress in size and shape analysis has occurred and numerous quantitative approaches can be used. Object-oriented image analysis facilitates the generation of this information. For landform mapping, segmentation of fundamental terrain units permits quantitative assessment of the size and shape of slope facets, elemental forms, valleys, relief units, drainage basins, and landforms if they can be delineated. How to initially partition a form unit, a feature of a landform, or a complete landform must be resolved first, however. Many landforms exhibit a wide range of sizes and shapes (e.g., basins, glaciers, landslides, alluvial fans).

Patterns, associations, and site all reflect spatial topological relationships that involve contextual information such as distance, direction or orientation, topographic position, connectivity, containment and other topological concepts. Such relationships are intuitively accounted for in qualitative image interpretations, and the formalization of their analysis for DGM is an important research area. With the advent of modern GISs, exploratory spatial analysis can be used to characterize patterns and account for topographic positions. The ability to accurately characterize the 3-dimensional nature of spatial topological relationships of landforms has yet to materialize.

Although geospatial technologies permit quantitative characterizations for some of these fundamental elements of image information, the elements must be collectively integrated to guide DGM. Rarely are all these elements included. They are, however, substituted by integrating spatial data via image-fusion approaches, or by the inclusion of different types of thematic information. Many researchers have integrated spectral and topographic information to accomplish their mapping objectives. Use of domain knowledge and analytical reasoning should be formalized, however, for DGM. Consequently, image analysis using a variety of artificial intelligence techniques has substantially increased.

4.2. Data fusion

Data fusion is an approach to mapping and analysis that exploits the power of multiple representations of the landscape. This involves integrating data with different spatial, spectral and radiometric resolutions. A classic example is merging multispectral satellite data with higher-resolution panchromatic data. In a GIS, multi-resolution airborne and satellite data can be fused with LiDAR as well as terrestrial photography, maps and graphics. Digital mapping can be accomplished by utilizing various feature sets that represent multiple landscape dimensions and perspectives.

For example, Soulakellis et al.(2006) combined a Landsat TM image with a DEM to produce fused images that represent a wide range of illumination azimuths and elevations to assess fault structures. The fused images combine the tonal information from the Landsat image with shaded relief patterns in the DEM. Shaded-relief maps produced by applying a lower illumination angle in combination with an azimuth perpendicular to the fault orientation produced the best results.

In another data fusion application, Townsend and Walsh(1998) use multi-temporal L-band JERS-1 and C-Band ERS-1 satellite data, a Landsat TM image time-series, and GIS coverages to model the potential of flood inundation. A DEM, derived through the scan-digitization of 1-m vertical resolution contour lines, was used to represent potential flood inundation. Regression models were developed to examine potential inundation related to known flood elevations, river position, and floodplain location. GIS models were compared to classifications of flood change that were mapped using radar data to identify areas of inundation.

Similarly, Souza and Paradella(2005) fused Landsat TM and Radarsat-1 data to study coastal geomorphological conditions related to large mangrove systems in the Brazilian Amazon. The Selective Principal Component-Synthetic Aperature Radar (SPC-SAR) product was used to fuse Landsat TM bands with fine mode radar data, represented through the Intensity–Hue–Saturation color transform. Other studies have utilized data fusion to examine landcover and topographic features (e.g., Crawford et al., 1999), and this approach has great potential, as information from existing and new sensors and GIS databases can be combined to facilitate DGM.

4.3. Geomorphometry

Geomorphometry is the science of the quantification and analysis of the land surface (Pike, 1995, 2000). It is fundamental to quantitative geomorphology, and is considered a discipline (Pike, 1995). Various aspects of specific and general geomorphometry have been presented, and more complete treatments on specific topics are presented in Wilson and Gallant(2000) and Hengl and Reuter(2009). In general, geomorphometry addresses issues of: 1) sampling attributes of land surfaces; 2) geodesy, digital terrain modeling and the generation of DEMs; 3) DEM error assessment and preprocessing; 4) generation of land-surface parameters, indices, and objects; and 5) geomorphic information production and problem-solving using parameters and objects. Each aspect of geomorphometry represents a research subdiscipline and contributes significantly towards the development of software tools and geospatial technology. Its importance in geomorphology is expected to play an increasing role as new and advanced forms of spatio-temporal data become available.

Given the multidisciplinary nature of DGM, and the need to characterize surface processes and morphology, geomorphologists should be familiar with basic morphometric parameters (Fig. 8) and objects that can be used for assessing and mapping geology and tectonics, landforms and landform elements, functional units related to water resources and hydrology, as well as climate and meteorological conditions. Standard protocols are also needed for using morphometric information for DGM, as results are highly dependent upon many of the aforementioned issues. Nonetheless, great progress has occurred and includes:

- The development and use of geomorphometric algorithms. New and modified forms of parameters and indices are being developed and evaluated for numerous mapping applications. Much of this work has focused on the neighborhood operation, although subgrid operations and other multi-scale metrics have also been developed. The primary mathematical approach has been statistical analysis and probability theory, however other approaches include geostatistics, artificial neural networks, and fuzzy-set theory. Information about hypsometry and the primary geomorphometric parameters serves as a starting point in most mapping efforts.
- Greater availability of software tools and systems for geomorphometric analysis and mapping. New software tools permit new mapping capabilities. The number of programs specifically designed to compute basic geomorphometric parameters has increased substantially. Almost all existing GISs include geomorphometry programs, and analysts can also develop their own application programs (scripts/macros) using software system commands. Consequently, geomorphometry and mapping can be accomplished using ESRI software (Reuter and Nelson, 2009), SAGA (Olaya and Conrad, 2009), ILWIS (Maathuis and Wang, 2009), LandSerf (Wood, 2009), MicroDEM (Guth, 2009), TAS GIS (Lindsay, 2009), GRASS GIS (Hofierka et al., 2009), and RiverTools (Peckham, 2009), just to name a few.
- Existing and new applications. Numerous algorithms and approaches for characterizing spatial variation, scale, landscape position, fuzzy boundaries, and complexity exist, and many landforms and features such as drainage basins and networks, ridges, and peaks can be mapped to various degrees. Nevertheless, researchers have a daunting task of determining which metrics and approaches are best for mapping different landforms and landscape components, as mapping objectives can be very different. Geomorphometry has significantly contributed to geological, soil, vegetation, landform, ecological, hydrological, mass movements, hazards, meteorological, and agricultural mapping applications, and new applications are sure to evolve (Gessler et al., 2009).

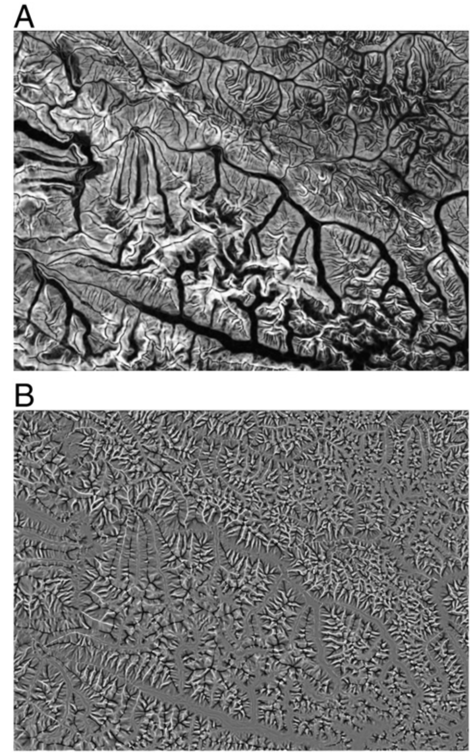

Fig. 8. Basic geomorphic parameters are commonly used in landform mapping efforts. (A) Slope angle and (B) tangential curvature for the Shimshal Valley in northern Pakistan.

Mapping other aspects of the geomorphic system related to climate and tectonic forcing, process domains, and erosion, however, are more complex and may require very different morphometric approaches. For example, quantifying the extent to which geomorphic parameters or landforms and landform elements can be used to assess and characterize tectonic signals, or the influence of tectonics on the landscape, remains a key challenge in the Earth Sciences (Boulton and Whittaker, 2009; Whipple, 2009). A typical approach includes the analysis of drainage basins and patterns, and an evaluation of the longitudinal profiles of bedrock rivers. Asymmetric drainage patterns, elongated drainage basins, and convexities and the presence of knick points are thought to reflect the system response to ongoing tectonic uplift (Jamieson et al., 2004; Boulton and Whittaker, 2009). Other applications, such as the sampling and estimation of surface cosmogenic nuclides, permit estimates of catchment erosion rates using GIS. This requires knowledge of the production rate of various isotopes related to the incoming cosmic-ray flux which is governed by latitude, altitude, slope, azimuth, and topographic shielding. Geomorphometry serves as a basis for such GIS-based models of catchment erosion.

4.4. Object-oriented analysis

Object-oriented analysis can be used for mapping a variety of landscape features. It first requires meaningful segmentation based upon specific criteria to generate spatial entities called objects. Initial segmentation is typically based upon information in imagery and DEMs. Numerous approaches can be used including homogeneity and shape analysis, region growing, pattern recognition, and rule-based segmentation. Segmentation results are then analyzed via spatial clumping to identify individual homogeneous spatial entities (Fig. 9). These objects then serve as a spatial constraint for subsequent analysis. Object-oriented analysis involves computing the attributes of the object such as its location, size, shape, and its contextual relationships such as distance and direction to all other objects on the landscape.

Mapping can be facilitated by spatial aggregation and spatial intersection of objects, as well as by identifying unique patterns of object attributes in n-dimensional feature space. This approach is widely recognized as superior to purely pixel-based analysis, as it permits the integration of information, the characterization of context and topology, and the linkage of features across multiple scales. Consequently, it has been recommended for geomorphological mapping and addressing issues associated with the hierarchical organization of the landscape (Schmidt and Dikau, 1999). For example, Moore et al. (2003) used an object-oriented expert system to identify beach and cliff landforms from a DEM on the basis of topological and morphometric rules. Miliaresis and Argialas (2002) used this approach to characterize and map mountain objects, while Stepinski and Bagaria (2009) fused spectral and contextual information to map generalized landform classes. Barlow and Franklin (2008) mapped snow avalanches and found that image objects conform to geomorphic and spectral characteristics consistent with snow-avalanche tracks. Lastly, Dragut and Blaschke (2006) used an automated classification system of landform elements to delineate objects at several levels based upon surface shape and altitudinal position of objects. Our work has demonstrated that object-oriented analysis can also be used to differentiate the influence of lithology on topographic structure and for identifying tectonic signals in mountain orogens (Fig. 10).

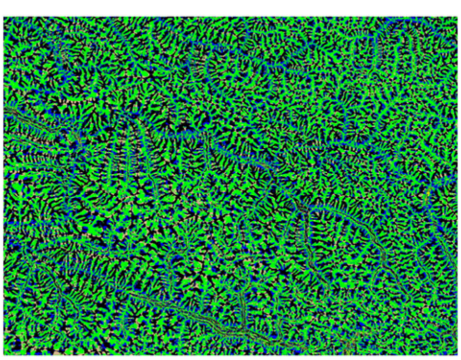

Fig. 9. Curvature form objects over the Shimshal Valley in Northern Pakistan. These map objects were generated by partitioning plan, profile, and tangential curvature. Such terrain objects can also be based upon slope azimuth and many other geomorphometric parameters using simple to complex segmentation approaches. Different colors represent unique partitioning of the curvature parameters.

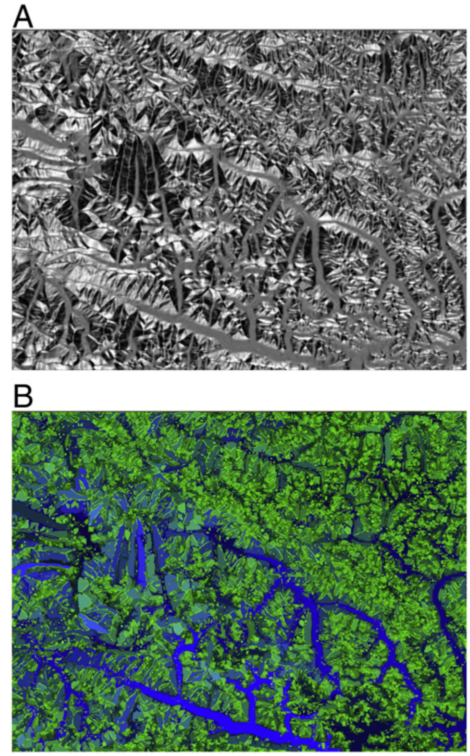

Fig. 10. Object-oriented analysis of the anisotropic nature of local slope variations in the Shimshal Valley in northern Pakistan. (A) Segmentation is based upon the extraction of unique anisotropic variations in slope that are not related to average slope angle. This information is related to basin topographic structure and differentiates valley floors, valley walls and landform features. For each spatial object we characterized relief and shape (compactness index) conditions. (B) Two-color composite of relief (blue) and compactness (green). Bright green areas in the north east (upper right) reveal objects with smaller sizes and greater compactness related to less resistant rock lithology. Areas (to the southwest) with less green coloration reflect larger elongated objects (tectonic influence) associated with more resistant rocks. Darker blue coloration reflects less relief, while lighter blue areas exhibit greater relief. Collectively, the colors and patterns suggest a tectonic signal that has not been previously mapped.

Collectively, this work demonstrates the use of object-based image and terrain analysis in geomorphological mapping that enable computational comparative geomorphology, visualization of topography, and the fusion of spectral and non-spectral information within a GIS. This approach has substantial potential, although issues involving valid segmentation and the integration of landscape objects for geomorphological mapping need to be resolved, and rules are needed for segmentation and spatial aggregation.

4.5. Numerical modeling

Numerical models are examined by Martin and Church (2004) to study landscape evolution using computational technologies and approaches that range from conceptual, to quasi-mechanistic, to generalized physics. Numerous methodological approaches are feasible and include GIS spatial modeling, cellular automata, agent-based modeling, physics-based modeling and others.

4.5.1. Cellular automata

Cellular automata (CA) models provide a map-like framework that allows a simple and deeply rooted connection with the mapping traditions of the geosciences and ecological sciences (Fonstad, 2006). They are much like expert systems with rules that are spatially and temporally dynamic and incorporate spatial and temporal interactions

(Moody and Katz, 2004). The rule base is applied iteratively through time, and CA models can be deterministic, stochastic or probabilistic in nature. These models can be used to examine process–form patterns, and an array of spatio-temporal patterns can emerge from a variety of rules and constraints. Consequently, this approach can be used for investigating complex geomorphological landscape patterns (Fig. 11).

In fluvial geomorphology, Nicholas (2005) described the principles of CA modeling, including model formulation and validation. Coulthard et al.(2007) also examined CA models as an approach for generating rapid solutions for characterizing fluvial systems at a variety of spatial and temporal scales. Runoff simulations using CA generally involve computation of the spatially distributed flow velocity. This requires estimation of surface roughness that can vary in a complex manner but with systematic spatial patterns (Abrahams et al., 1990; Hessel et al., 2003). The CA model developed by Parsons and Fonstad (2007) yields realistic flood-wave hydrographs when compared to flood observations. The conservation of mass and Manning equations are coupled with an algorithm to delay the movement of water from one cell to the next until the correct timing is reached. Coupling the unsteady flow model with simple laws of sediment erosion, transport, and deposition create realistic event-based simulations of water and river channel change. Similarly, Hooke et al. (2005) simulated changes in ephemeral river channels caused by climate and land use/land cover change. The model uses feedbacks between each event to indicate the likely outcomes for combinations of conditions. A GIS provides data input to the model and presents model outcomes (i.e., maps of erosion, deposition, morphology, sediment cover, vegetation cover and plant survival over periods of up to 30-years for the channel reach).

For vegetation and ecological applications, Nield and Baas (2008) used a CA approach to explore the relationships between ecological and morphological processes at different spatial and temporal scales. The role of vegetation in shaping themorphology of aeolian dunes in coastal and semi-arid environments was addressed. The CA model simulates the response of the morphology to changes in sediment supply, vegetation distribution, density and growth characteristics as well as initial disturbances. Smaller grid sizes generate a landscape evolution that is substantially different than those generated using larger grid resolutions. Vegetation was found to induce a characteristic length scale in aeolian environments.

Other examples include coupled human–natural systems. For example, Walsh et al. (2008) used a CA model to integrate large volumes of spatial data. Using initial conditions characterized by satellite imagery, growth or transition rules, and neighborhood associations to set the probabilities of land-use change, land-cover change scenarios were assessed, alternate outcomes visualized, and uncertainties examined. This approach can be used to assess complexity involving the interaction between social and physical systems that determine the patterns and nature of landscape change.

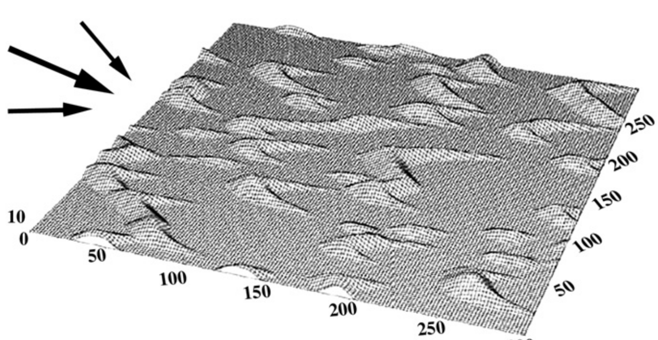

Fig. 11. Cellular automata (CA) model of barchan dunes from Fonstad (2006).

4.5.2. Agent-based simulations

Agent-based models (ABM) attempt to simulate the activities of individual agents as basic building blocks. An ABM may have multiple copies of the same type of agent. An agent could be a plant or a human. Similarly, multiple copies of multiple agents are possible. Agents differ in important characteristics. Their interactions may be dynamic in that the characteristics of the agents change over time as the agents adapt to their environment, learn from experiences through feedbacks, or "die" as they fail to alter response relative to new conditions or factors. The dynamics that describe how systems change are generally nonlinear. They are sometimes even chaotic, but are seldom in any long-term equilibrium. For systems that do reach equilibrium, however, the mechanisms that lead to such a condition are of central interest. Agents may be organized into groups of individuals or into nested hierarchies that may influence how the underlying system evolves over time. They are emergent and self-organizing in that macro-level responses emerge from the actions of individual agents as agents learn through experiences and change and develop feedbacks with finer scale building blocks.

For example, Brown(2008) developed models that integrated biocomplexity and ABM simulations to examine human interactions with the environment. Similarly, Wainwright(2008) reported on the use of a model called CYBEROSION that is designed to simulate the dynamic interactions between people and their landscapes. These approaches and simulations demonstrate the value of ABM to investigate anthropogenic forcing related to landscape and landform evolution.

4.5.3. Physical landscape evolution modeling

Simplistic relationships are thought to exist between erosion and geomorphometric parameters such as relief. Theory suggests that the topography integrates the results of processes and forcing factors. Consequently, morphometry serves as the basis for examining erosion patterns. Controlling factors at multi-scales govern topographic evolution resulting in highly complex topographic conditions, yet most geomorphometric parameters do not adequately capture this complexity. Consequently, a more deterministic approach, such as landscape–evolution modeling (LEM) is required to formalize process mechanics, assess process domains and coupling, and study feedback mechanisms and system dynamics.

Clearly, a better understanding of process–form relationships is needed for developing improved LEMs. The interrelationships between climate, tectonics, weathering, fluvial, mass movement, and glacial processes frequently make it difficult to accurately assess and map geomorphological conditions. Similarly, planetary geomorphic studies may rely heavily on LEM simulations.

Dynamic simulations of geomorphic processes account for the conservation of mass and energy. Consequently, a series of mass continuity equations constrain numerical models to address erosion and deposition of rock and sediment. Continuity assumes that the rate of change of altitude, z, that is based upon a changing reference level (sea level), is proportional to the volumetric sediment flux (Q, [kg m^{-3} yr^{-1}]) such that:

$$\frac{\partial z}{\partial t} = U - \alpha\left[\frac{\partial Q}{\partial x} + \frac{\partial Q}{\partial y}\right], \quad (1)$$

where t is time, and U is the uplift or subsidence rate in m yr^{-1}, and α is a conversion factor to convert volumetric sediment flux to m yr^{-1} of erosion ($\alpha = xy/Q$). Uplift should account for isostatic and tectonic forcing components. Tectonic forcing includes the advection of rock mass given structural controls and the alteration of rock strength given topographic stress fields and far-field velocities. The tectonics component requires the integration of mechanical models, as feedbacks exist between the topographic stress field, rock strength and erosion and uplift (Koons, 1995; Koons et al., 2002). Maps of rock strength and erosion are notoriously difficult to produce, however, geomorphometry can assist in mapping the anisotropic nature of the topography, which is thought to be related to rock strength and deformation patterns. The magnitude of denudation also influences the isostatic compensation that is a function of the flexural rigidity of the crust and the wavelength of the topography (Gilchrist et al., 1994).

Landscape–evolution models can be used to map the overall characteristics of system response that include the spatial distribution of uplift and subsidence, and to determine what portions of the landscape are eroding and where deposition is occurring, irrespective of considerations of surface processes. New parameterization schemes that include various states of the landscape can be accounted for. Perhaps the most difficult aspect of system characterization is the issue of scale, as forcing factor constraints related to climate, tectonics, and denudation typically operate over a multitude of space–time scales. Furthermore, most models are parameterized to operate over an annual period, although diurnal and seasonal variation in climate parameters significantly govern numerous surface processes, whereas tectonic processes usually have less of an effect over shorter time periods.

Most models use a flexible parameterization scheme that accounts for the depth of regolith production from weathering (Tucker and Hancock, 2010). Parameterization schemes should be developed for weathering and regolith production that account for variations in lithology, temperature, and precipitation. Remote sensing and terrain analysis of surface and atmospheric conditions can be used to generate maps that may be associated with weathering patterns. Key variables include surface irradiance, temperature variation, atmospheric water vapor content and precipitation patterns. In mountain environments, temperature and precipitation variations may be considerable given highly variable topography and forcing factors (Barros et al., 2006).

Hillslope sediment flux, q_s, varies with the hillslope gradient (S). A linear or nonlinear relation can be used to characterize the sediment flux. Diffusivity coefficients are commonly used in LEMs, with different values for different environments. Empirical laboratory research indicates that the relationship between the sediment flux and hillslope gradient is nonlinear, and that results are inconsistent with the linear transport law (Roering et al., 2001). Consequently, a nonlinear transport law has been used to characterize empirical sediment–flux curves such that:

$$q_s = \frac{KS}{1.0 - \left[\frac{S}{S_c}\right]^2}. \tag{2}$$

where S_c is the critical slope. Remote sensing and terrain analysis can be used to determine the locations on the landscape where steep slopes are not erosive due to rock strength.

Numerous investigators have utilized the stream-power bedrock river incision law to account for fluvial erosion. In general, the change in elevation is modeled as:

$$\frac{\partial z}{\partial t} = KA^m S^n, \tag{3}$$

where K is bedrock erodability, A is the upstream catchment area that is used as a proxy for discharge. The exponents m and n are constants used to differentiate between the stream power and shear stress-based rules. Geomorphometric analysis and mapping can be utilized to improve the estimation of some of the needed parameters.

Simulations of glacier erosion have also been conducted where erosion is based upon basal sliding velocity and ice thickness (MacGregor et al., 2000; Tomkin and Braun, 2002; Pelletier et al., 2010). An abrasion model (Hallet, 1979) can be used such that the rate of erosion is

$$\frac{\partial z}{\partial t} = -au_s^b \tag{4}$$

where u_s is the basal sliding speed, and a and b are empirical coefficients usually set to 1 or 2. Basal sliding is primarily dependent upon the basal shear stress, τ_b and a bed-friction parameter. Simulations of glacier erosion demonstrate the complexity associated with relating process to form as glacier erosion can enhance or reduce relief and controls valley spacing and slope variability (Harbor, 1992; Tomkin and Braun, 2002; Bishop et al., 2003; Pelletier et al., 2010).

Other processes such as slope failures and landsliding may be evaluated using slope stability criterion. For example, the Culman slope stability criterion (Spangler and Handy, 1982) indicates that the maximum height that a hillslope can reach is dependent upon the balance between the shear stress on a plane and the shear strength. The potential for failure, P_{fail}, represents the ratio of the hillslope height, H, to the maximum stable height of the hillslope, H_c, such that

$$P_{fail} = \frac{H}{H_c}. \tag{5}$$

The maximum stable height of the hillslope can be defined as

$$H_c = \frac{4C}{\rho g}\frac{\sin\beta\cos\phi}{1.0 - \cos(\beta - \phi)}, \tag{6}$$

where ρ is rock density, g is gravitational acceleration, β is the surface slope, and ϕ is the effective friction angle. C is the effective cohesion on the plane and can be expressed as

$$C = 0.5\rho g H \frac{\sin(\beta - \theta)\sin(\theta - \phi)}{\sin\beta\cos\phi}, \tag{7}$$

where θ is the angle of the potential failure plane. Using this parameterization scheme coupled with geomorphometric analysis, the critical angles of β and θ can be determined. Values of ϕ reported in the literature can be used. Bedrock landsliding would be initiated when P_{fail} values exceed a particular value.

DGM has the potential to generate new information that can be used to develop more rigorous parameterization schemes. The aforementioned schemes can link process, morphometry, erosion, and deposition in LEMs. Geomorphometric characterization is required at each time interval to drive process mechanics and process domain states, such that the contribution of mass by specific processes or coupled systems can be characterized and mapped. This additional information can be linked with scale-dependent morphometric characteristics to better establish the linkages between process and form. Such dynamic mapping capabilities are important to go beyond traditional space-dominated DGM.

4.6. Visualization

Visualization techniques can be used to display spatial data in a variety of ways. This enables effective communication about the land surface and its features, properties, and temporal evolution. Numerous visualization methods are routinely utilized. Animations of 2-D and 3-D views are commonplace and can greatly assist in understanding the nature of spatial data and comparisons of results. Image display of topographic information serves as a foundation. Numerous approaches exist for visualizing DEMs. Shaded-relief visualizations are perhaps the most popular although they can be particularly prone to azimuth biasing. Surface illumination algorithms are used to form shaded-relief visualizations. For example, Borgeat et al. (2005) developed a real-time visualization of multi-resolution geometric models. Color and texture information were developed with static pre-optimized geometry to display information at low and high resolution with minimal artifacts. Grabner (2001) addressed the problem of interactive visualization of multi-resolution triangle meshes by smoothly interpolating mesh geometry between different levels. The interpolation parameter improved the transition of the frames in the visualization.

Mapping results can also be visualized. Smith and Clark (2005) compared landform maps derived from DEMs and stereo aerial photography. Such basic comparison of differences can be extremely useful for identifying errors in mapping results. Similarly, the visualization of basic relationships between surface conditions can be insightful. For example, Kim et al.(2008) examined the relationships between dune configuration, soil factors, and topographic attributes. The visualization approach integrates fore-dune, dune slack, and inner dune ridge into one continuous system connected by topography, geomorphic processes, vegetation, and edaphic conditions across the dune area. Other approaches that integrate various geospatial technologies can also be used to visualize pattern–process relationships. Walsh et al. (2003) modeled and mapped geomorphic processes that influence the spatial organization of the alpine treeline ecotone. Multi-resolution sensor data were linked with other spatial information to generate 2-D and 3-D visualizations.

5. Conclusions

Geomorphological maps are needed at a variety of scales, because surface materials and topography constrain and govern numerous chemical, biological, meteorological and lithospheric processes. Numerous multi-scale topographic effects influence forcing factors and environmental change. Consequently, geomorphological maps are essential for assessing and managing natural resources and promoting sustainability. Historically, such information was predominately generated via the power of human visualization, using knowledge and analytical reasoning. This permitted great flexibility in integrating multiple information themes. To date, human interpretation still represents the most sophisticated approach for producing complex geomorphological maps at multiple scales, although the issues of subjectivity, reproducibility, and validity remain. Furthermore, the increasing volume of data and need for sophisticated analysis collectively require computational efficiency and formalization with respect to information extraction. In many respects, the ongoing evolution of geospatial technologies for mapping represents an attempt to automate and simulate human-interpretation capabilities.

Given this objective, numerous advancements in geospatial technologies have occurred. Standard location information and land-surface measurement technologies permit a wealth of information to be generated regarding the spatio-temporal nature of planetary surfaces. Access to information has increased dramatically, greatly facilitating analysis and mapping efforts. Commitment is needed to provide a more consistent multi-temporal data record, temporal analytical methods, and software to facilitate long-term analysis of change. Much of the theoretical development in DGM and many of the applications have been in the realm of geomorphometry, and have greatly emphasized the analysis of topography. Increased consideration and fusion of other pertinent geomorphic variables is needed for both theoretical and applied use.

Advancements in science are driven by theoretical and conceptual developments. Geomorphologists now have access to a plethora of new data and software capabilities, and can manipulate and analyze data by many methods, given multi-stage processing sequences. This is advantageous for DGM, although concerns over empiricism and error propagation exist. Scientific progress, particularly with regard to theoretical developments, has not kept pace with new and rapidly evolving information technology.

The discipline of geomorphology is rich in theory and concepts related to time, processes, systems, and landforms. Such concepts need to be formalized and tested using geospatial technologies and modeling to establish the scientific basis of DGM. Results from process dynamics and landform mapping must be consistent such that process–form relationships are characterized, and the ability to reproduce mapping results should be based upon knowledge of landscape evolution and empirical observations. In other words, the ability to predict the spatial entities resulting from forcing factors, processes and polygenetic evolution is essential.

Geospatial theory has greatly facilitated the evolution of geospatial technologies and mapping, although issues related to space–time variation still remain, in the context of processes and surface-object evolution. According to Pike (1995) a formalized unifying theory of geomorphometry does not yet exist, where morphometric parameters serve as a foundation in process geomorphology and DGM. Conceptual advancements that include dynamic representation are sorely needed. Such advancements are not inherently feasible by using static cartographic approaches to representation and mapping or by using ambiguous terminology related to scale and spatial entities.

Terrain segmentation is an important issue, and any scheme of geomorphic division is an attempt to constrain and conceptualize reality into spatial entities, but some phenomena are not easily constrained. Clear-cut boundaries in nature at many scales may not actually occur, and continuous variation may best represent a concept at a particular scale. New mathematical approaches for segmenting various forms of spatial variation are possible, although discrete or transition zones rather than cartographic primitives may exist. Outliers of a certain type may need to be included within a geomorphic unit of which they are a part, rather than one they most resemble. Overall, however, greater clarity and identification of the fundamental information and criteria needed for geomorphic division are required (this may need to involve taxonomic schemes).

CA, LEMs and other simulation models can integrate geomorphometry with process mechanics and DGM. This will address the need to better link process and form and permit assessment of form evolution. Currently, DGM is closely tied to the nature and processing of the data, and largely disconnected from process and dynamics. New parameterization schemes are required to investigate multi-scale organization, spatio-temporal relationships and process mechanisms. Given the rapid developments that are sure to continue, the results of such dynamic simulation and mapping efforts are likely to be constrained by data from in-situ sensor networks that will permit better evaluations of representation schemes, rate estimates, and mapping results.

As various aspects of process–form relationships and system dynamics become better understood, geomorphological knowledge libraries can begin to be developed. Miliaresis (2001) indicated that knowledge and existing taxonomic schemes need to include information about spatio-temporal topology. Such information is just beginning to be formalized and integrated into numerical process models. Progress will be made as the science evolves from predominant use of morphometric indices and pattern recognition into geospatial technology solutions for formalizing space–time topology.

DGM is supported by a tremendous diversity in approaches for different mapping applications. Mapping applications will remain an important research area. Progress in the methods and format of each mapping application (e.g., soils, vegetation, landforms, terrain types, erosion), however, should be better formalized into a DGM protocol for critical evaluation and the establishment of standardized information products. The geomorphometric atlas of the world, as described by Gessler et al. (2009) and work by Miliaresis and Argialas (1999) represent excellent examples of information that can be of value to a wide range of users. In this way, standardized products can be used with known advantages, limitations, errors, and uncertainties. The formulation of DGM protocols or sets of guidelines is a challenging goal in DGM that will facilitate objective mapping, but also permit subjectivity to be utilized effectively within the constraints of information requirements.

Given the state of geospatial technologies, progress towards DGM protocols, however, will depend upon the integration of knowledge from geomorphology and GIScience, and by those individuals who choose to bridge the gap between the two disciplines, and make contributions to computational geomorphology. A framework is needed to address individual mapping objectives, as well as integrative mapping of complex systems. Such a framework requires formal linkages between form, process and dynamics.

A regional foundation for establishing relevant landscape information as a basis for larger-scale DGM efforts should be pursued. This foundation can be similar in principle to old-fashioned physiographic mapping but will be much more sophisticated with regard to information content, accuracy, and geomorphic theory. Such an endeavor seems warranted as the inherited lithology and structure, along with tectonics, governs the geometric topographic structure that confines surface processes and partially defines landforms. Collectively, this approach also serves as a means to produce standardized types of regional terrain. Given the global availability of DEMs and satellite imagery, geomorphologists should focus on map information content, terminology, establishment of required mapping criteria, evaluation of objective methods, and repeatable results. Such a focused effort in effectively utilizing geospatial technologies to accomplish this goal would elevate the status of DGM in the science community and permit routine use of such geomorphological maps in integrative science and practical problem solving.

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