section two

The Communication of Topographic Perspectives and Forms

chapter three

Human Factors in the Interpretation of Physiography by Symbolic and Numerical Representations within an Expert System

Demetre P. Argialas and
George Ch. Miliaresis

Contents

Keywords: *digital elevation model, expert system, factual knowledge, formalization, fuzzy set, geomorphometry, heuristic knowledge, human factors, image interpretation, knowledge acquisition, knowledge quantification, knowledge representation, knowledge base, landform interpretation, lexical uncertainty, linguistic variable, membership value, NEXPERT OBJECT, object oriented programming, pattern elements, physiographic analysis, region growing segmentation, remote sensing, SMART ELEMENTS, symbolic representation, terrain analysis, terrain knowledge conceptualization, terrain feature extraction*

" . . . nothing is great or little otherwise than by Comparison "

In Gulliver's Travels[29]

3.1 Introduction

This chapter examines the role of human factors in both symbolic and numerical terrain representations for the interpretation of physiography from remotely sensed images. In illustrating the human factors involved, it draws heavily on the work of the authors on expert terrain interpretation systems and physiographic feature quantification through image processing, geomorphometric and fuzzy set techniques.

This chapter is organized as follows: the introduction presents the photo-interpretation tasks and problems for physiography and landforms, earlier efforts in knowledge-based terrain representation, and the detailed objectives of the chapter. Then, the chapter follows the knowledge-based physiographic representation including the description of the study area and the implementation of the symbolic and numerical representations. Human factors and subjectivity in terrain representation and quantification are addressed throughout the chapter.

During the early part of this century, the study of regional scale geomorphology was termed "physiography."[9] Physiographic analysis was based on the partition of terrain to physiographic units by taking into account the form and spatial distribution of their component features through fieldwork and visual interpretation of topographic maps and aerial photographs.[11] Today, physiography is being stimulated by the need to explain enigmatic landscapes, newly explored on the surfaces of other planets through remotely sensed data.[9]

While physiographic analysis is concerned with regional scale geomorphology, terrain analysis is concerned with local (medium scale) geomorphology and involves the systematic study of image patterns relating to the origin, morphologic history, and composition of distinct terrain units, called landforms.[2,15,20] Landforms are natural terrain units, which when developed from the same soil and bedrock or deposited by a similar process (under similar conditions of climate, weathering, and erosion), exhibit a distinct and predictable range of visual and physical characteristics on aerial images, called "pattern elements."[33] Typical pattern elements examined include topographic form, drainage texture and pattern, gully characteristics, soil tone variation and texture, land use, vegetation, and special features.[33]

The shaded relief map of Figure 3.1[27] shows a part of the basin and range physiographic province and the landform alluvial fan commonly found in this province with its typical pattern elements: fan-shaped form, semiconical 3-D shape, dichotomic drainage pattern, medium soil tones, and barren landcover.

Problem solving for landform and physiographic region interpretation is an art.[7] The procedural framework for terrain interpretation problem solving is missing: books do not elaborate on the strategies needed to guide a novice to the terrain interpretation process through a step-by-step question-and-answer scenario. Landforms, pattern elements, physiographic features, and relevant indicators are vital and poorly described components of the landscape. Interpretation of pattern elements of a site relies on the education and experience of the interpreter, his perceptual skills, his ability for trial-and-error experimentation, his use of interpretation heuristics, his personal judgement, and his intuition. The use of prior knowledge on a specific geographic region and the use of available maps (physiographic, landcover, geologic, etc.) and bibliographic information can greatly assist terrain interpretation.

There is, therefore, a need to methodically study the physiographic and terrain-analysis reasoning process and, to better understand and formalize these processes and guide novice interpreters in terrain problem solving, develop computer-assisted interpretation procedures.

Knowledge-based expert systems (KBES) is a field of artificial intelligence that addresses complex, domain specific, problem solving that requires unique expertise.[12,14] Knowledge-based expert systems offer methods and tools for representing problem solving procedures within interactive computer programs and thus can assist in the discovery and formalization of terrain interpretation procedures. Expert system success is largely determined by the effective computer representation of domain knowledge. Knowledge representation takes place by employing facts, objects, frames, rules, and inexact reasoning procedures.

For the past twenty-five years, scientists working toward knowledge-based landform interpretation have implemented expert system prototypes for terrain analysis using different methods of knowledge representation such as rules, frames, Bayesian reasoning under uncertainty, and fuzzy descriptors.[2,6,7,21] These earlier developed prototype terrain expert systems

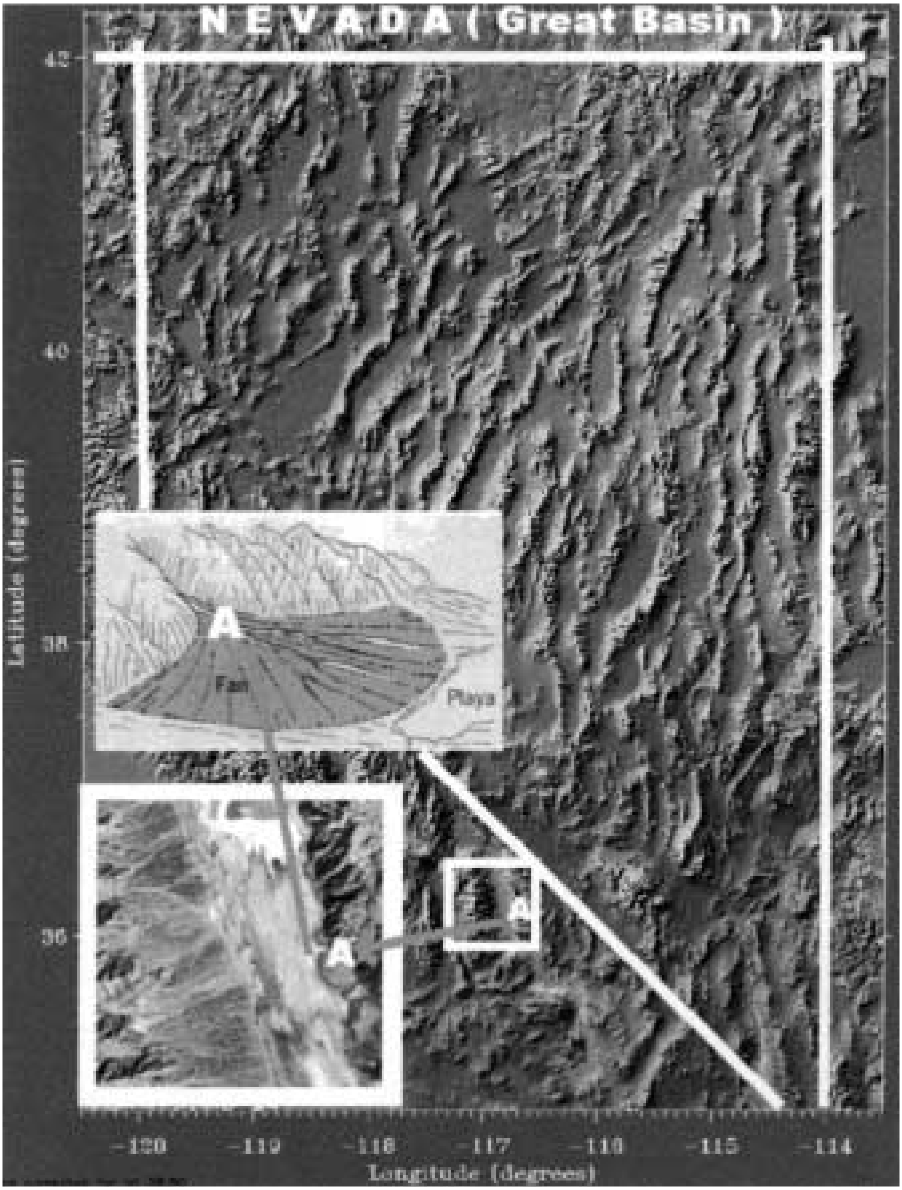

Figure 3.1 Study area. The state of Nevada as it appears in the color landform atlas of U.S. The Death Valley Intermontane Basin is pointed out and an enlarged view of the basin in a Landsat Thematic Mapper (TM) image is provided. A block diagram is included showing an alluvial fan (A). See color version of this figure in the color section following page 114. (From Sterner, R., 1999, http://fermi.jhvapl.edu/states/maps1/nv.gif. With permission.)

assisted the interpreter to infer the landform of a site through a step-by-step question-and-answer scenario. The user was queried for all pattern element values of a site and the degree of certainty ascribed to each value. Based on the user's responses, the system inferred the landform of the site, indicating also a certainty value for each decision (e.g., the inferred landform is sandstone with certainty, 0.95).

While the earlier developed landform interpretation procedures are still used, in this research effort knowledge related to the physiographic region of a site and to the spatial pattern of related landforms is also represented, formalized, and programmed.

Building this new physiographic expert system involved identifying, naming, describing, and organizing knowledge pertaining to physiographic regions (provinces and sections), and their component features in terms of their distinguishing indicators. The conception of the various indicators encompassed a study of physiographic books and reports and it was achieved through trial-and-error experimentation.[3] The compiled factual and structural descriptions were represented within an expert system tool by using appropriate definitions of classes, subclasses, hierarchies, spatial relations, and rule structures.[3,4,5]

The expert system representation has the drawback in that it employs mostly qualitative terrain indicators which occasionally can be vague and ambiguous to novice and inexperienced interpreters. There are three different approaches to partially assist in the representation of ambiguity of these terrain terms.

- The first is the use of a terrain visual vocabulary composed of definitions, diagrams, and aerial images describing each terrain term that can be used concurrently with the consultation of the expert system to enhance the perceptual and mental models of the novice. Such a terrain visual vocabulary was implemented through a hypermedia system.[6]
- The second approach, discussed in the following, is the computer-assisted segmentation of digital elevation models into discrete landforms through image processing operators and geomorphometric techniques and the subsequent quantification (parametric representation) of the discrete landforms and physiographic regions based on geomorphologic attributes.[16,17,24]
- The third approach, discussed also in the following, is using fuzzy sets[34] to handle the ambiguity or lexical uncertainty of terrain indicators. In particular, fuzzy sets are used as a calculus for the representation of a natural geomorphic language in the Great Basin geomorphologic context.[17,18]

Despite the common misconception that computer representation—symbolic or numerical—makes terrain interpretation "objective," it entails much human intervention and subjectivity. The resulting subjectivity affects (1) the symbolic representation of physiography within an expert system, (2) the surface parameterization into spatially discrete landforms, and (3) the fuzzy set representation of the physiographic indicators in the Great Basin context. Human factors and subjectivity are addressed throughout the chapter.

3.2 Knowledge-based physiographic interpretation

3.2.1 Study area

The methodology was implemented for the Basin and Range Province of the Southwest U.S. The province, centered principally in the state of Nevada (see Figure 3.1), is a large area, approximately one tenth of the U.S., occupied mostly by wide desert plains, generally almost level, interrupted by great, largely dissected, north trending, roughly parallel mountain ranges (see Table 3.1). The Province of Basin and Range is further subdivided to five sections, each at a different erosion stage, such as the Great Basin (mainly in the youthful erosion stage) and the Sonoran Desert (maturity erosion stage).[11] The Great Basin is known as such because its drainage waters do not reach the sea but evaporate in saline lakes on the plains between the mountain ranges. The space taken by the mountains is about half of the total. The Sonoran Desert has mountain ranges that are smaller and perhaps older, occupying one fifth of the space. Moreover, large areas are without concave basins of internal drainage and the section belongs to the maturity erosion cycle.

Each physiographic section was partitioned into its component physiographic features, and each physiographic feature into its component topographic forms, and each topographic form into its component landforms.[23] The physiographic features observed within the Basin and Range Province are (1) the mountain ranges, (2) the major desert valleys, and (3) the intermontane basins. Close intermontane basins are also called bolsons while open basins are also called semibolsons. The topographic forms observed within an intermontane basin are (1) the Piedmont slope, a gross topographic form, forming a gently sloping surface parallel to mountain front and surrounding the mountain belts, and (2) the basin floor. Figure 3.2 shows typical mountain ranges, intermontane basins, Piedmont slopes and basin floors. The common landforms expected within the Piedmont slope are the alluvial fan, pediment, and bahada, while the common landforms within the basin floor are the valley fill, the playa, and the saline lake. Death Valley is a typical (closed) intermontane basin of the Basin and Range Province. Figure 3.2(a) shows the landforms (LFs) and topographic forms (TFs) interpreted from a Landsat Thematic Mapper (TM) image,[30] and Figure 3.2(b) shows the relief and spatial relationships between these landforms and topographic forms.

Table 3.1 Physical and perceptible characteristics of the physiographic features in the Great Basin section. (From Fenneman, N., *Physiography of Western United States,* McGraw-Hill, N.Y., 1931. With permission.)

Mountain Range							
1. Size	**2. Shape**	**3. Elevation**	**4. Relief**	**5. Roughness**	**6. Process**	**Basin**	**Spatial arrangement**
Lengths of 80–110 km and widths of 10–24 km are common. The mountain ranges are of all sizes from mere hills or buttes up to ranges and *there are more small than larger ones.*	Ranges are elongated and oriented mainly in N–S direction.	Ranges' most frequent altitudes are 2000 to 3000 m above sea level.	The local relief of ranges is between 910–1500 m.	Within its length there is no great variation in height.	The mountains in the Great Basin are either in the first erosion cycle (youthful) or in the second erosion (maturity) cycle.	The average gradient of a basin is about 3%. Each basin has its own base level.	Roughly parallel mountain ranges separated by desert basins. The total area of the section is about evenly divided between mountains and basins. Piedmont slopes occupy narrow belts some miles in width surrounding the mountain ranges.

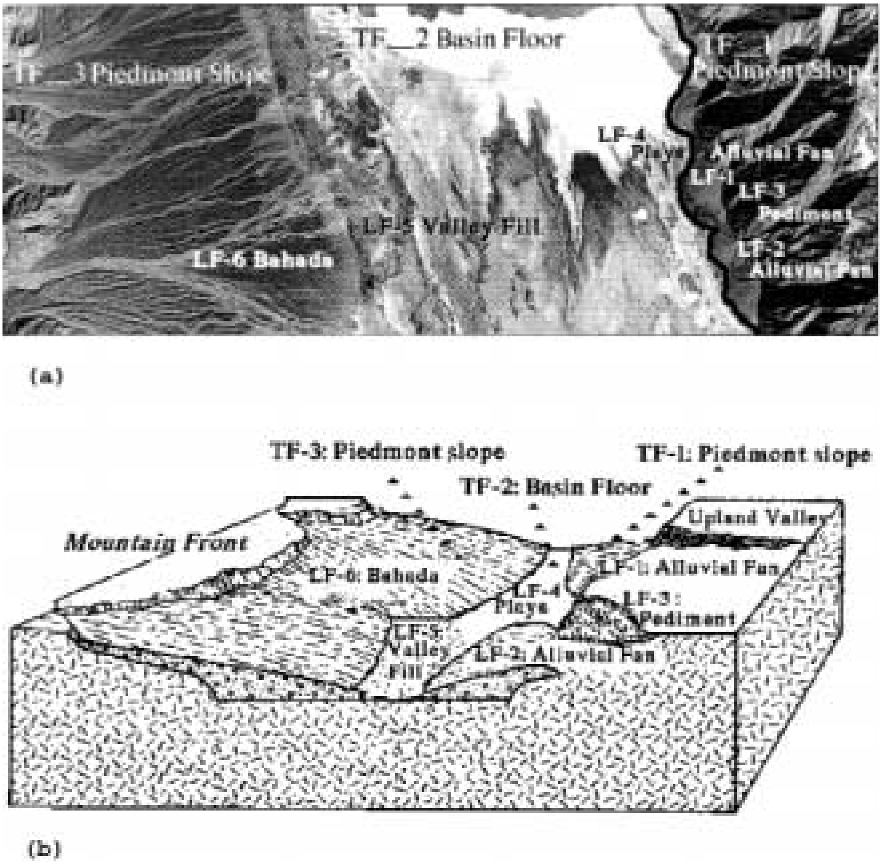

Figure 3.2 The Death Valley Intermontane Basin. **(a)** Landforms (LF) and topographic forms (TF) of Death Valley interpreted from a Landsat Thematic Mapper (TM) image. (From U.S. Geological Survey, *Landsat-Thematic Mapper Image of Death Valley,* Order: 0119612270019, 1884. With permission.) **(b)** Block-diagram simulating the 3-D representation of Figure 3.2(a).

A conceptual framework for the representation of factual, structural, inferential, and strategic knowledge is now presented.

3.2.2 Factual and structural knowledge representation

For the factual and structural representation of physiographic knowledge, an object-oriented representation structure was developed that uses frames as classes, subclasses, objects, subobjects, and slots as properties.

First, we named and described by their properties (see Table 3.1), and organized into class-subclass hierarchies the following terrain classes (see Figure 3.3):

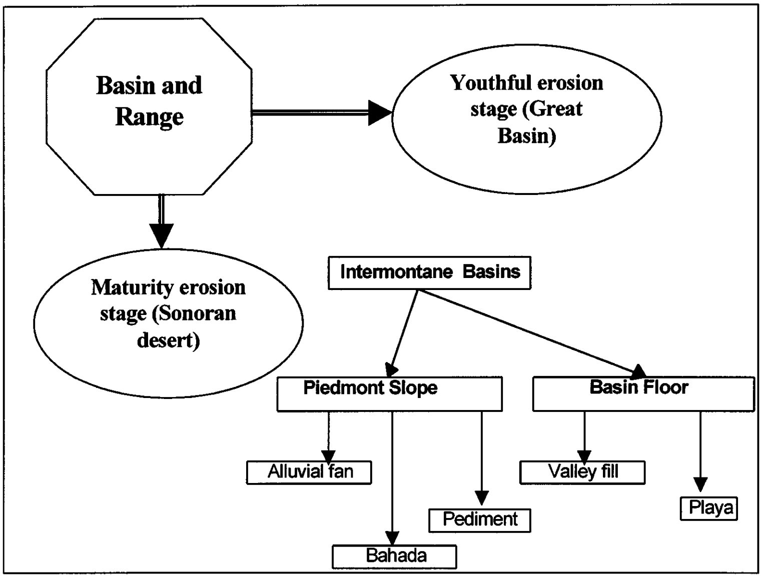

Figure 3.3 Organization and spatial relationships of physiographic provinces and features, topographic forms, and landforms for Basin and Range.

- Class of physiographic provinces and sections; subclass of basin and range; sub-subclasses: basin and range youthful stage, basin and range maturity erosion stage
- Class of physiographic features; subclass of intermontane basins; sub-subclasses of bolson and semibolson
- Class of topographic forms; subclasses of Piedmont slope, basin floor
- Class of landforms with subclasses alluvial fan, playa, etc.

Through the class-subclass hierarchy, properties are inherited down each hierarchy so as to be shared by all the members of each class.

Then, we defined an object-subobject or whole-part hierarchy thus defining the "whole-part terrain organization" (see Figure 3.3). For example, each topographic form is composed of a set of landforms and conversely each landform is part of a topographic form.

Finally, we defined class members or *instances* of each class or subclass so that the expert system to use them for symbols inferred features of each class during our consultation. These instances are dynamic objects generated during the consultation of the expert system. Thus when a topographic form is inferred, the system creates an instance TF1 belonging to the proper topographic form class and when a landform is inferred, the system creates an instance LF1 belonging to the proper landform class.

3.2.3 *Inferential and strategic knowledge representation*

Having defined the classes, subclasses, objects, and component objects, we use them now to describe the inferential and strategic knowledge through a rule-based formalism.

We have conceived four distinct aspects of strategic physiographic reasoning:

1. Physiographic province and section inferencing and refining to either youthful or maturity erosion stage by specific physiographic indicators,
   - Rules were developed inferencing physiographic regions (provinces and sections) from their physiographic indicators (see Figure 3.4). Rules were also developed which refined the concept of the province to that of a physiographic section of that province. In the case of the basin and range concept, the refinement rules inferred the concept of a youthful (Great Basin) or mature erosion stage (Sonoran Desert).
2. Physiographic feature inferencing by their indicators,
   - Once a physiographic province or section was inferred and/or refined by physiographic indicators, the system queries the user for the identification of the possible physiographic features that could be evident in the study area.
3. Topographic form inferencing by spatial association,
   - Once a physiographic feature (e.g., an intermontane basin) was inferred based on the user's input of the relevant indicators, the

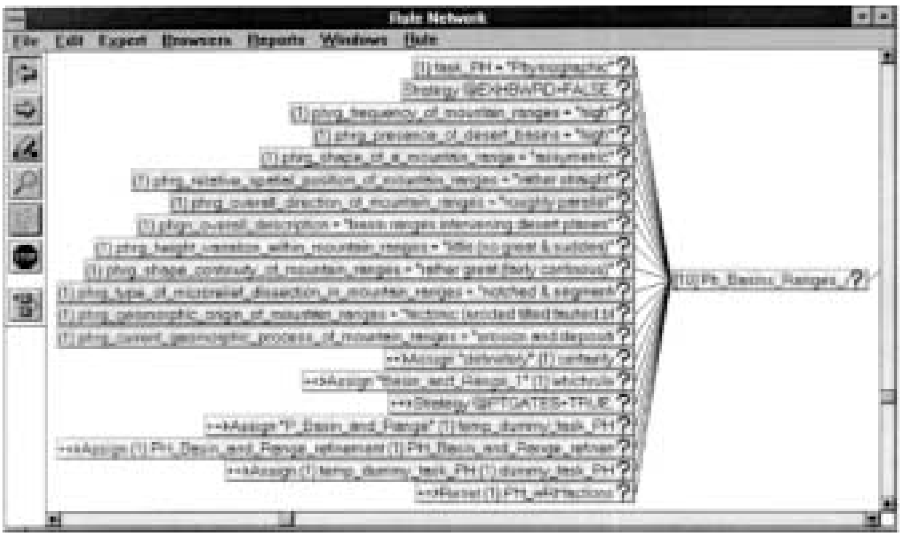

Figure 3.4 Physiographic rule inferring the Basin and Range Province. Indicators like "frequency of mountain ranges," "shape of mountain ranges," etc., as used by Fenneman in his physiographic descriptions (see Table 3.1) could be inferred from the shaded relief map of Figure 3.1 or from Landsat Thematic Mapper images such as the one shown in Figure 3.2.

possible types of topographic forms that could be evident within that physiographic feature would be posed for examination to the user.

4. Landform inferencing by pattern elements, geomorphologic indicators, and spatial association to interpreted landforms,
   - Once a topographic form was inferred, then the user was guided for the identification of the expected landforms within that topographic form according to user-specified pattern elements and spatial constraints.

3.2.4 Formalization of physiographic knowledge with NEXPERT OBJECT

The earlier developed object oriented representation structure and the associated inference rules were programmed in the expert system tool NEXPERT OBJECT (recently renamed SMART ELEMENTS).[22]

NEXPERT OBJECT provides a graphical representation of the object and rule structure as it exists before the program execution or as it unfolds during the dynamic consultation of the expert system. These graphical networks are more declarative than the alternative textual representations and therefore they are used in the figures to demonstrate the system operation. Classes and subclasses are shown in circles while the class-subclass relationships are shown with links (lines) connecting a class (circle) with another class. Class properties are indicated with the little squares, while inherited properties are shown replicated in the subclasses as they appear in the parent class. Dynamic class instances (objects) are shown as little triangles and they are created during consultation. They are assigned (linked) to the proper class they belong to based on the inference process.

The inferential knowledge for determining the physiographic context of the Basin and Range Province was expressed in rules. Figure 3.4 shows a graphical representation of a typical rule for establishing the Basin and Range Province. Any rule like this in NEXPERT OBJECT is composed of three parts: the hypothesis to be established or rejected (PH_Basin_and_Range) in the right, the physiographic conditions (indicators) in the left to be asked to the user in order to prove / disprove the hypothesis (e.g., frequency of mountain ranges, presence of desert basins), and the "then" actions of the rule, shown to the left with the prefix "+=>", executed if and only if the rule fires. Once the hypothesis of the basin and range is verified, a rule is triggered by the hypothesis PH_Basin_and_Range_Refinement that refines the basin and range context to either maturity (Great Basin) or youthful (Sonoran Desert) stage.

The outcome of a hypothesis that was proved true is the creation of a dynamic object (e.g., an instance of the relevant class established during execution). For example, in Figure 3.5A we observe the dynamic object PH_1 derived by the rule in Figure 3.4 that was assigned to the class Basin and Range. In Figure 3.5B we see that the dynamic objects are linked with part-of

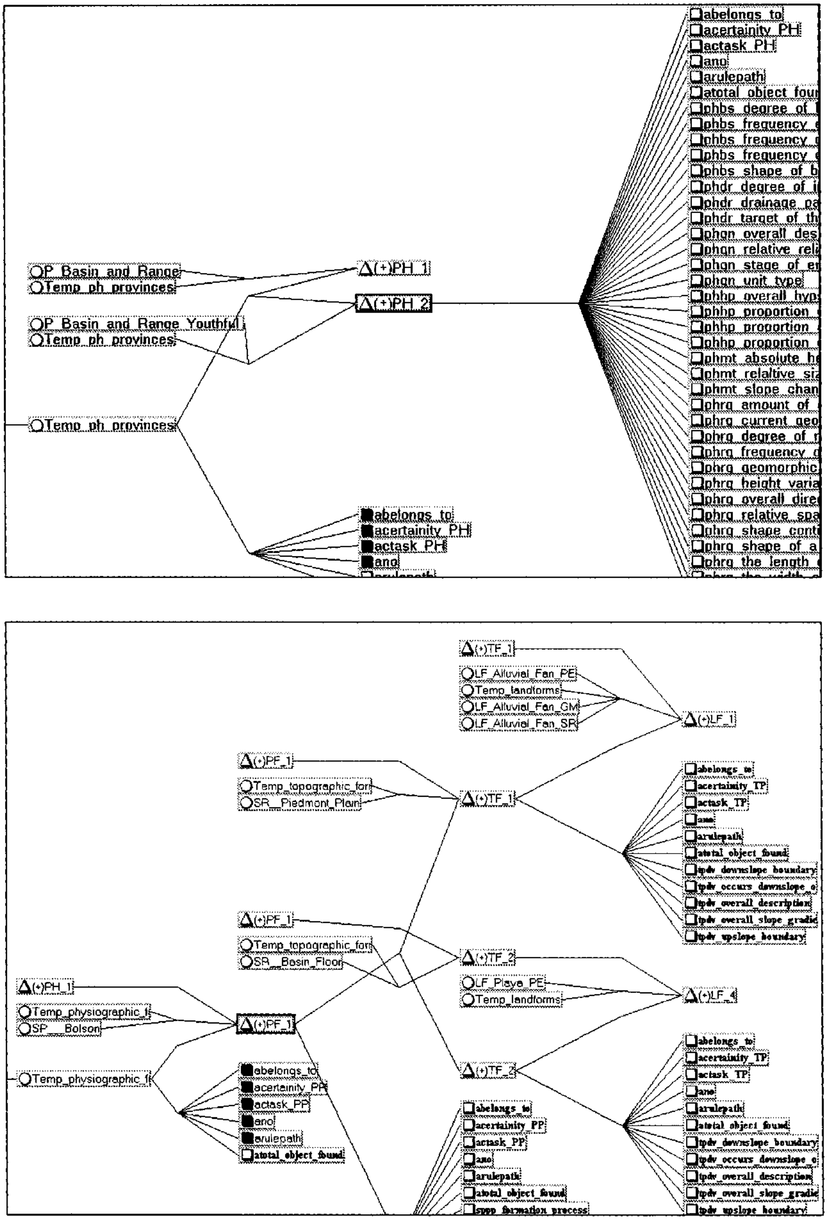

Figure 3.5 Dynamically created objects. Top: Inferred objects PH_1 and PH_2 are members of the basin and range physiographic class. Object PH_2 was further refined and assigned to the youthful erosion stage class. Bottom: The landform object LF_1 is an alluvial fan inferred from pattern elements (PEs), geomorphologic criteria (GMs) and spatial associations (SPs) while LF_4 is a playa inferred only from pattern elements. LF_1 is a part-of a Piedmont plain object (TF_1) while LF_4 is a part-of a basin floor object (TF_2). Both objects TF_2 and TF_1 are parts of the physiographic feature PF_1 that is a kind-of closed intermontane basin (bolson).

relationships to each other based on their spatial association. So the dynamic object LF_1 is a kind-of alluvial fan established from pattern elements (LF_Alluvial_Fan_PE), geomorphologic criteria (LF_Alluvial_Fan_GM), and spatial association criteria (LF_Alluvial_Fan_SR). At the same time LF_1 is part-of the topographic form TF_1 which is a kind-of Piedmont plain. TF_1 and TF_2 (basin floor) are part-of of the physiographic feature PF_1 that is a kind-of intermontane basin of bolson type.

3.2.5 Testing and evaluation

The lack of a detailed published procedure used by experts conducting physiographic analysis precludes the comparison of our own research prototype to such a source. We have tested the developed system for a number of interpretation scenaria mostly in the Basin and Range Province. For the cases tested, the system's reasoning was satisfactory and conformed to our interpretations. Further testing with other users needs to be conducted to evaluate the features of the system.

3.2.6 Human factors in building the physiographic expert system

The developed landform and physiographic interpretation expert systems are characterized as *research prototypes* in the sense that they are exploratory tools of the potential of the expert system paradigm in the typology, structuring, and formalization of photointerpretation knowledge. The formalized knowledge of the physiographic expert system was compiled from examples and case studies found in engineering, physiographic, and geomorphologic books[3,4,5] and mainly from Fenneman,[11] and Peterson.[23] Our own education, experience, expertise, trial-and-error experimentation, heuristics, and intuition have also greatly contributed to the developed representations. We did not generate any new knowledge; instead, we have turned the "implicit knowledge" available in books and in our mental models into "explicit knowledge" formalized through terrain classes and hierarchies, and inferential and strategic rules. These formal representations were implemented in an expert system tool and the resulting prototype expert system guides the novice interpreters in a step-by-step question and answer procedure to investigate various strategic interpretation scenarios and inferential paths for physiographic reasoning. We have captured within the rule system what we conceived as reasonable stages in terrain interpretation and have made available this interactive consultation guidance to novice users through the physiographic expert system. Despite this subjectivity, the physiographic expert system prototype contains a partial formal backbone object and rule structure for experimentation, evaluation, revision, improvement, and extension. What is important is that this backbone structure contains explicit and declarative terrain knowledge in the form of classes, objects, and rules and as such it is easier to be inspected, criticized, expanded, transferred, and understood than if it was available in textual form.

Terrain representation with an expert system paradigm entails much human intervention and subjectivity. At the level of terrain, problem identification is subjective in the selection of the geographic scale of the problem studied, the terrain features to be reasoned with, the tasks, subtasks, and hypotheses that the system considers, the choices given to the user, and the assumptions made within the problem solving space. At the level of conceptualization, identification is subjective in the selection of the hypotheses and reasoning paths to be investigated, the class-subclass and whole-part relations adopted, and the approach for handling uncertainty and inexactness. At the level of knowledge formalization, it is subjective in the selection of a specific tool chosen for programming the developed representations.

The developed physiographic expert system representation has a drawback in that it employs mostly qualitative terrain indicators, such as those appearing in Table 3.1, which occasionally can be vague and ambiguous[26,32] to novice and inexperienced interpreters. The next section presents surface parameterization into spatially discrete mountain ranges, and a fuzzy set representation for the natural geomorphic language used in the expert system. The application was made for the Great Basin section of the Basin and Range Province.

3.3 Physiographic feature quantification

According to Hoffman and Pike[13] the task of automating all parts of the terrain analysis process requires (1) an analysis of the language used to describe terrain, and (2) an analysis of the optical information about terrain that is available to the perceiver. In this particular study, the language that describes the mountain ranges in the Great Basin Section was related to a set of attributes concerning their size, shape, and geomorphologic characteristics.[11] These attributes were used earlier for the representation of physiographic reasoning within an expert system.

The symbolic representations are quite vague and ambiguous although interpreters communicate successfully.[26] In addition, the imprecision that is inherent in most words (“lexical uncertainty”) is context dependent.[1] For example, in the expression of Fenneman, “there are more small than larger ones (mountain ranges)” the words “small” and “large” are both perceived in a specific physiographic context, that of the Great Basin physiographic section.[11] In a different province, it is possible for the largest mountain ranges observed in the Great Basin to be comparatively small. Thus, there is the need for capturing a geomorphometric terrain description (perceived optical information) and relate it to the symbolic representation (language). That is achieved by the use of fuzzy sets that relate the symbolic representations to the numeric representations and thus producing “digital words” that can be used for reasoning in a computer system.[32]

In order to quantify the natural geomorphologic language in the Great Basin context, the mountain features will be interpreted from digital elevation models[17] and will be numerically represented by a set of attribute values.[16] These values will specify the fuzzy set representation of the Fenneman's attributes in the Great Basin's physiographic context.[18,19]

3.3.1 Mountain feature extraction

The basis used for the extraction of mountain features was the GTOPO30[31] Digital Elevation Model (DEM) with spacing 30 arc-s since it provides a digital global representation of the earth's relief appropriate for regional scale (1:1,000,000) comparative studies. In a mountain, two parts are often distinctive: (1) the gently sloping summit, and (2) the steep mountainsides.[10] The process for the identification of mountains is based on the assumption that the summit or ridge pixels form the initial set of mountain pixels which needs to be expanded downslope taking into account the gradient values present in their neighborhood. The employed algorithms first identify the summits and then label the pixels around the summits as mountain pixels as long as their gradients were greater than a certain threshold[17]:

- The summits were extracted and labeled by imlementing runoff simulation. In this approach, a single water unit is imported in every cell of the DEM and travels according to the upslope aspect pointing direction. The water units imported in each cell are counted and finally, the derived values represent the runoff per cell. The cells with runoff values greater than a certain threshold should belong to the ridge network. Human expertise is required in order to judge whether the resulting ridge network resembles the usual ridge network observed on maps in the current physiographic context. In this case study, it was learned that the threshold should be equal to nine.[17] The resulting ridge pixels are given in Figure 3.6(a).
- Then the gradient was computed (see Figure 3.6(b)). The gradient value depends on (1) the computation method, and (2) the accuracy specification and grid size of the DEM. Due to the accuracy specification of the GTOPO30[31] a kernel of size 9×9 was selected for gradient computation. The gradient values represented in Figure 3.6(b) differ to a degree from the values an interpreter observes in the field and additional expertise should be developed by landform specialists in order to deal with this kind of computer derived image. Statistical analysis of training areas indicated that the gradient of the mountainsides should be greater than 6º.[17] Note that if the gradient threshold chosen was greater than 6º, then the resulting mountains would have been smaller in size; while if it was less than 6º, then the resulting mountains would have been larger in size. This threshold is by no means applicable to other physiographic regions since their mountainsides could be less or more steep than the mountainsides observed in the Great Basin. Additionally, if a different relief representation and/or a

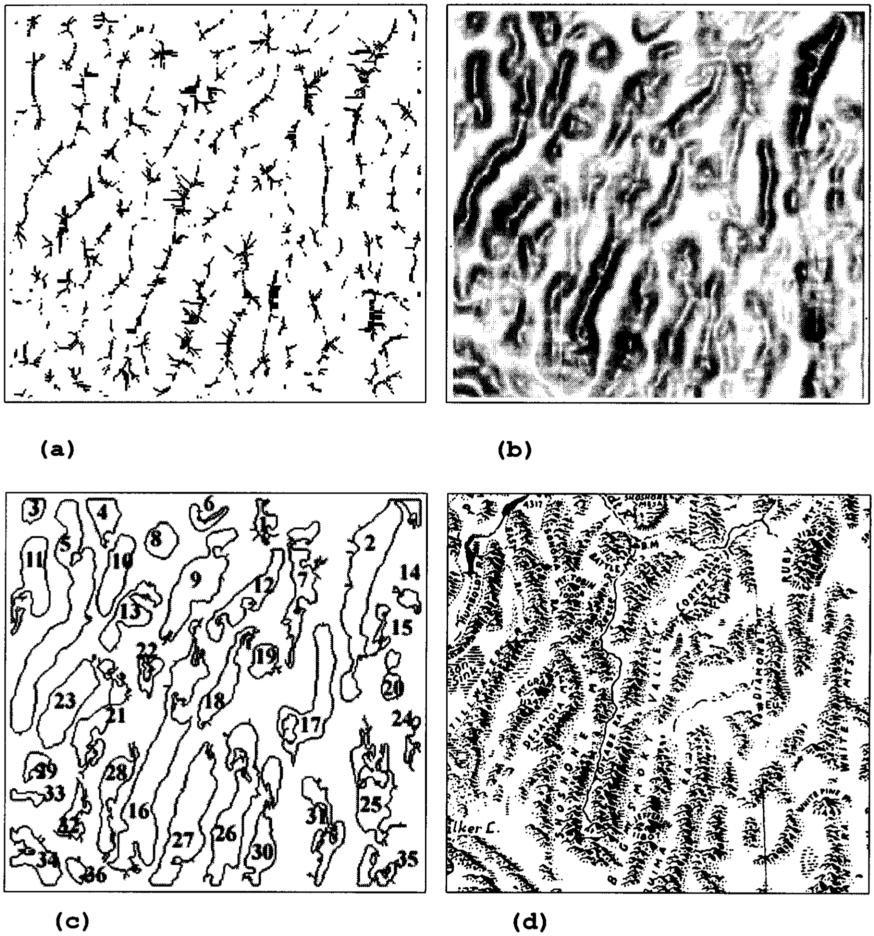

Figure 3.6 Extraction of Mountains. **(a)** Initial set of mountain seeds generated by runoff simulation in the upslope direction. **(b)** Gradient derived from the GTOPO30 DEM. Gradient values (minimum is 0 and maximum is 35°) were rescaled to the interval 255 to 0 (the lighter a pixel is the lower its gradient is). **(c)** Boundary and label identification of mountain objects in the study area. (From Miliaresis, G. Ch. and Argialas, D. P., in *Comput. Geoscience*, 25(7), 715–728, 1999. With permission from Elsevier Science.) **(d)** Shaded relief map of the study area. (From Atwood, W. W., *Map of the Landforms of California and Nevada*, Ginn and Co., Boston, 1895. With permission.)

different algorithm for gradient computation were going to be used, then a different gradient threshold would have been derived even for the Great Basin.

- Then, an iterative region growing segmentation algorithm was applied to label the mountain pixels,[17] the boundary of the mountain features was delineated, and a unique integer identifier was assigned to each mountain (see Figure 3.6(c)).

Visually comparing the extracted mountain features to the mountain ranges compiled by Atwood[8] that could also be interpreted from the shaded relief map of the study area shown in Figure 3.6(d), it is observed that there is a fairly good correspondence between them (e.g., for each of the Atwood ranges there is at least one range in the map of extracted mountain ranges). It is, however, observed that some of the mountain ranges of Atwood appear rather broken in the map of extracted mountains. This discrepancy could be explained either by the level of generalization induced by human and machine or by the intrinsic nature of the mountain ranges in Great Basin.[11] Atwood could have used human expertise and fieldwork and thus, he might have connected isolated mountains and adjacent mountain ranges applying a generalization process.[8]

The mountain feature extraction techniques are subjective to a degree. Human expertise is needed in order to deal with the discrete representation of the terrain at various scales and select the most suitable algorithms that could deal with the elevation and positioning errors of the available datasets. Usually one has to use a specific dataset that is available and thus a particular expertise should be developed in order to deal with the derived images and models. The selection of thresholds for gradient or for runoff is performed through a trial-and-error procedure and through comparison of the derived images to our mental images and models for this particular physiographic context. In the next section quantitative attributes for the mountains will be defined.

3.3.2 Mountain feature parametric representation

To create a parametric representation of the extracted mountain features, one first needs to select their attributes. We have selected such attributes for the Great Basin mountain ranges based on the descriptions of Fenneman[11], some of which appear briefly in Table 3.1. The selected attributes were then defined quantitatively after study of published geomorphometric parameters[9] and image processing operators:[16]

1. *Size.* The natural logarithm of the object's "diameter" was used for the quantification of size
2. *Elongation*. Eccentricity (E) was used for the quantification of elongation
3. *Orientation* (Φ)
4. *Mean elevation* (H)
5. *Roughness* (R). The standard deviation of elevation
6. *Local relief* (LR). The difference between the highest and the lowest elevation occurring in a mountain feature
7. *Hypsometric integral* (HI). Pike and Wilson[25] defined it as the ratio of Mean Altitude-Lowest Altitude to Local Relief. HI reflects the stage of landscape development. Areas with HI values above 0.6 are in the youthful erosion phase, values below 0.35 correspond to the monadnock phase while HI values in the range 0.6 to 0.35 correspond to equilibrium[28]
8. *Mean gradient* (G)

Table 3.2. Parametric representation of some of the mountain features (see Figure 3.6(c)) in the Great Basin. (From Miliaresis, G. Ch. and Argialas, D. P., *Proc. Inter. Conf. Assoc. Math. Geol.*, International Association for Mathematical Geology, 1998, 892–897. With permission.)

	Ln D	**E**	**Φ**	**H**	**R**	**LR**	**HI**	**G**
No	**Km²**	**0..1**	**Deg**	**M**	**m**	**m**	**0..1**	**Deg**
1	3.60	0.32	58.3	1769	172	852	0.37	9.1
2	5.02	0.57	68.6	2231	355	1625	0.32	15.7
3	3.16	0.08	48.2	1601	221	954	0.33	13.2
4	3.73	0.24	54.9	1817	296	1415	0.34	13.2
5	5.16	0.60	70.2	1634	292	1445	0.43	14.0
6	3.48	0.26	34.6	1671	217	762	0.39	12.1
7	4.68	0.66	72.9	1954	185	1065	0.37	9.3
8	3.53	0.05	47.2	1797	254	1034	0.38	12.7
9	4.58	0.29	56.6	1841	248	1491	0.29	11.0
10	4.15	0.48	64.9	1778	306	1679	0.36	14.9

Table 3.2 shows the attribute values computed for a subset of the mountain features extracted. The presented parametric representation as a computed abstraction of reality simplifies their shape and morphologic complexity while at the same time it leads to their numeric representation which allows the use of (1) statistics, and (2) algorithms to further process and analyze them. Furthermore mountain feature parametric representation techniques are subjective in many respects. First, human expertise is needed in the selection of an attribute (e.g., elongation and size). The attributes selected are by no means universally applicable to other physiographic contexts. For example, elongation is a well-accepted attribute for the Great Basin physiographic context but it might be meaningless for a context with eroded, almost circular mountain remnants. In the next section, an effort will be made to use the parametric representation for the quantification of the geomorphologic words for the Great Basin.

3.3.3 Fuzzy set representation of mountains

Fuzzy sets have been developed as a calculus for the representation of natural language in various domains and are being used in the following for representation of the imprecision of the qualitative mountain attributes (linguistic variables) used in our knowledge base. A variable is called linguistic if it can take words in a natural language as its values.[26] The words are represented by fuzzy sets defined in the domain of the linguistic variable. More specifically, a linguistic variable is characterized by:

1. The name of the variable (e.g., Local Relief)
2. The set of linguistic labels that the variable takes (e.g., low, moderate, high)

3. The actual physical domain in which the linguistic variable takes its quantitative values (e.g., {300, 1200})
4. A semantic rule that relates each linguistic label of a variable with a fuzzy set in the actual physical domain[34]

Thus, in order to quantify the natural geomorphologic language, all four elements should be determined. The names of the linguistic variables and their labels were determined directly by physiographic descriptions (see Table 3.1). The quantitative values of the actual physical measurements were computed through the geomorphometric parameterization of each extracted mountain feature to a set of attribute values (see Table 3.2).

A fuzzy partition of the physical domain was next implemented and a sub-domain for each linguistic label was derived. This was achieved based on geomorphological knowledge and trial-and-error experimentation.

The semantic rules that relate each linguistic label with a fuzzy set in the actual physical domain were expressed through membership functions.[34] For a continuous variable (x), the "membership function" (MBF) describes the compatibility between the linguistic label and the degree of membership (DMB), that is [DMB = MBF (x)]. The DMB and its values are in the interval 0 to 1. The membership function of a linguistic label is (1) subjective, (2) context-dependent, and (3) influenced by new numerical data and knowledge.[32] There is no general method to determine an MBF.[1] Its specification is a matter of definition, rather than of objective analysis.[32]

Many different shapes of MBFs have been proposed in the literature and the most practical implementations use the so-called standard MBFs[1] that are normalized (maximum is always 1 and minimum 0). The definition of a standard MBF includes the following steps:

- Define the value of the domain that best fits to the meaning of the label and assign DMB equal to 1
- Define the rightmost and the leftmost values (DMB = 0) of each linguistic label assuming that adjacent labels have usually 60% overlap[1]

For example, the fuzzy sets that correspond to each label of the linguistic variable "Size of the mountain Ranges in the Great Basin physiographic context"[18] are given in Figure 3.7.

The fuzzy sets allowed the fuzzy partitioning of the domain of geomorphic variables in the Great Basin and the quantitative representation of the geomorphic language in that physiographic context. Their definition was based on both (1) well-accepted physiographic knowledge, and (2) the geomorphometric data acquired for the study area (physical domain).

Thus, the geomorphic language describing the mountain ranges was quantified for the Great Basin context.[18] So a user of a computer system could be assisted during the interpretation process by recalling the knowledge base of Great Basin and by using it to interpret the numeric data acquired from

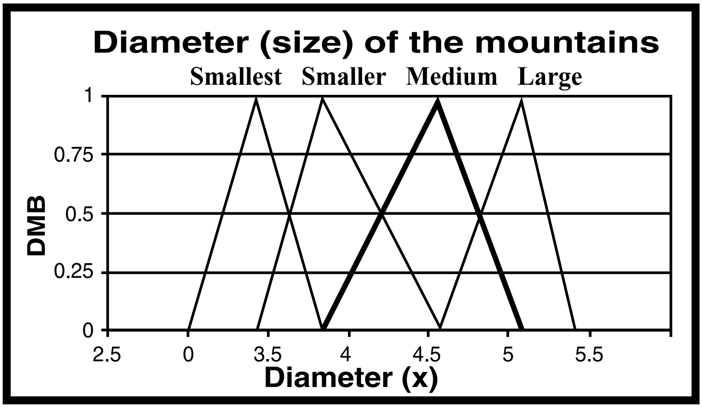

Figure 3.7 Fuzzy set representation of the linguistic variable Diameter (size) of the Mountains in the Great Basin physiographic context. (From Miliaresis, G. Ch. and Argialas, D. P., *Proc. 25th Conf. Remote Sensing Soc.*, 1999. With permission.)

aerial photographs and digital elevation models. The computer system projects the values he gave to the domain of the Great Basin digital words and would give responses like, "This mountain feature is small in size and elongated in a Great Basin physiographic context."[19]

Human factors are crucial for the fuzzy partition of the domain and for the selection of the MBF types. The last selection influences the interpretation process and is performed by a trial-and-error procedure on the basis of human expertise and the derived quantitative data (domain). Although there is degree of subjectivity, a novice interpreter could be assisted and make judgements on the basis of the relative (context-dependent) knowledge base of "digital words." In the future, when perhaps a more complete and tested knowledge base can be made available for various physiographic regions, it will lead to the creation of an absolute definition (noncontext dependent) of the geomorphic words and terms.

3.4 Conclusion

This chapter has demonstrated some of the lessons learned in attempting to conceptualize, represent, interpret, segment, and quantify terrain features from DEM and satellite imagery through expert systems and geomorphometry. All the procedures employed involved judgement calls.

The hardest part of conceptualization—and quite subjective in nature—is the identification of terrain-related objects, their organization, their relations, and their combinations in creating inference and strategic rules. Identification of this conceptual structure involves both discovery and invention of the key abstractions and mechanisms that form the vocabulary of terrain analysis problem solving, and it strongly depends on the bibliographic sources and mental models of the knowledge engineers and the terrain analysis experts. We have made an extra effort in capturing a number of "intermediate-level concepts" in physiographic reasoning which are perhaps the most important tools available for organizing knowledge bases, both conceptually and computationally.

The numerical description of mountain features involves subjectivity in (1) the discrete representation of the earth surface (DEM) including methods of preprocessing and generalizing, (2) the segmentation of the DEM into mountain ranges through selected algorithms and associated thresholds, (3) the selection of parameters of 3-D form, and (4) the computation of these parameters through selected geomorphometric and image processing operators.

The subsequent fuzzy set representation resulted in the quantification of geomorphologic words and concepts, by assigning to each numeric representation a linguistic label that interpreters easily conceive and computer systems are able to process. Subjectivity is also induced, however, since in the fuzzy partitioning of the physical domain, the linguistic labels and the membership functions are also subjective and context dependent. Their specification is a matter of *definition*, rather than of objective analysis. "Definition" indicates human expertise and evaluation by trial-and-error procedures.

Quantification involves subjectivity. Expertise is needed in order to deal with geomorphometric descriptions. The main advantage of quantification is that (1) it approaches the complexity of the real world while at the same time simplifies it to a degree, and (2) it provides numerical representations that can be used for statistical comparisons.

We thank the Editors, Professors Hoffman and Markman, for their kind and extensive reviews. They contributed greatly to the improvement of the original manuscript both in style and in the emphasis on human factors.

References

1. Altrock, C., *Fuzzy Logic and Neurofuzzy Applications Explained,* Prentice-Hall, Upper Saddle River, NJ, 1995.
2. Argialas, D. P., Towards structured knowledge models for landform representation, *Z. f. Geomorphologie N.F. Supple.-Bd.*, 101, 85–108, 1995.
3. Argialas, D. P. and Miliaresis, G. Ch., Physiographic knowledge acquisition: identification, conceptualization and representation, *Proc. Am. Soc. Photogrammetry and Remote Sensing,* American Society for Photogrammetry and Remote Sensing, Baltimore, MD, 3, 311–320, 1996.
4. Argialas, D. P. and Miliaresis, G. CH., Landform spatial knowledge acquisition: identification, conceptualization and representation, *Proc. Am. Soc. Photogrammetry and Remote Sensing,* American Society for Photogrammetry and Remote Sensing, Seattle, WA, 3, 733–740, 1997.
5. Argialas, D. P. and Miliaresis, G. CH., An object oriented representation model for the landforms of an arid climate intermontane basin: case study of Death Valley, CA, *Proc. 23rd Conf. Remote Sensing Soc.*, The Remote Sensing Society, Reading, U.K., 1997, 199–205.

6. Argialas, D. P., and Mintzer, O., The potential of hypermedia to photointerpretation education and training, in *Proc. XVII ISPRS Cong.* (Part B), Fritz, L. and Lucas, J., Eds., International Archives of Photogrammetry and Remote Sensing, Washington, D.C., 1992, 375–381.
7. Argialas, D. P., and Narasimhan, R., TAX: a prototype expert system for terrain analysis, *J. Aerosp. Eng.*, l, 151–170, 1988.
8. Atwood, W. W., *Map of the Landforms of California and Nevada,* Ginn and Co., Boston, 1895.
9. Baker, V. R., Regional landform analysis, in *Geomorphology from Space, a Global Overview of Regional Landforms,* Short, N. M. and Blair, R. W., Eds., NASA SP–486, Washington, D.C., 1986, 1–22.
10. Bates, R. L. and Jackson, J. A., Eds., *Glossary of Geology*. American Geological Institute, Alexandria, VA, 1987.
11. Fenneman, N., *Physiography of Western United States,* McGraw-Hill, New York, 1931.
12. Hayes-Roth, F., Waterman, D., and Lenat, D., *Building Expert Systems,* Addison-Wesley, Reading, MA, 1983.
13. Hoffman, R. R. and Pike, R. J., On the specification of the information available for the perception and description of the natural terrain, in *Local Applications of the Ecological Approach to Human-Machine Systems,* Hancock, P., Flach, J., Caird, J., and K. Vincente, Eds., Erlbaum, Mahwah, NJ, 1995, 285–323.
14. Jackson, P., *Introduction to Expert Systems,* Addison-Wesley, Reading, MA, 1986.
15. Lillelsand, T. and Kiefer, R., *Remote Sensing and Image Interpretation,* 2nd ed., John Wiley & Sons, New York, 1979.
16. Miliaresis, G. CH. and Argialas, D. P. (1998). Parametric representation and classification of mountain objects extracted from moderate resolution digital elevation data. *Proceedings of 4th International Conference of the Association for Mathematical Geology* (pp. 892–897). Ischia, Italy: International Association for Mathematical Geology.
17. Miliaresis, G. CH. and Argialas, D. P., Segmentation of physiographic features from the global digital elevation model / GTOPO30, *Comput. Geosciences,* 25 (7), 715–728, 1999.
18. Miliaresis, G. CH. and Argialas, D. P., Formalization of the photo-interpretation process by a fuzzy set representation of mountain objects in the geomorphic context of the Great Basin section, *Proc. 25th Conf. Remote Sensing Soc.,* The Remote Sensing Society, Cardiff, U.K., 1999, 745–750.
19. Miliaresis, G. CH. and Argialas, D. P., Fuzzy pattern recognition of compressional mountain ranges in Iran, *Proc. 5th Inter. Conf. Assoc. Math. Geo.,* International Association for Mathematical Geology, Trondheim, Norway, 1999, 227–233.
20. Mintzer, O. and Messmore, J., *Terrain Analysis Procedural Guide for Surface Configuration* (Technical Report ETL-0352), U.S. Army Corps of Engineers, Engineer Topographic Laboratory, Fort Belvoir, Virginia, 1984.
21. Narasimhan, R. and Argialas, D., Computational approaches for handling uncertainties in terrain analysis, *Proc. Annu. Conv. Am. Soc. Photogrammetry and Remote Sensing,* American Society for Photogrammetry and Remote Sensing, Baltimore, MD, 3, 302–310, 1989.
22. Neuron Data, *SMART ELEMENTS (User Guide),* Neuron Data, Palo Alto, CA, 1993.
23. Peterson, F., *Landforms of the Basin and Range Province Defined for Soil Survey,* Technical Bulletin 28, Agricultural Experiment Station, Nevada, 1981.

24. Pike, R. J., Geomorphometry-process, practice and prospects, in *Z. f. Geomorphologie N.F. Supple. Bd.*, Pike, R. J. and Dikau, R., Eds., 101, 221–238, 1995.
25. Pike, R. J., and Wilson, S. E., Elevation-relief ratio, hypsometric integral and geomorphic area-altitude analysis, *Geol. Soc. Am. Bull.*, 82, 1079–1084, 1971.
26. Ross, T. J., *Fuzzy Logic with Engineering Applications*, McGraw-Hill, New York, 1995.
27. Sterner R., Shaded relief map of Nevada, 1999, http://fermi.jhuapl.edu/states/maps1/nv.gif
28. Strahler, A. N., Hypsometric (area-altitude) analysis of erosional topography, *Geol. Soc. Am. Bull.*, 63, 1117–1142, 1952.
29. Swift, J., *Gulliver's Travels* (A voyage to Brobdingnag, Chapter I) 1726, http://www.jaffebros.com/lee/gulliver
30. U.S. Geological Survey, *Landsat-Thematic Mapper Image of Death Valley,* Order: 0119612270019, 1984.
31. U.S. Geological Survey, *GTOPO30: 30 Arc Seconds Global Digital Elevation Model,* 1998, http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html
32. Wang, P., The interpretation of fuzziness, *IEEE Trans. Syst. Man Cybernetics*, 26(2), 321–326, 1996.
33. Way, D., *Terrain Analysis,* McGraw-Hill, New York, 1978.
34. Zadeh, L. A., The concept of a linguistic variable and its application to approximate reasoning I, II, III. *Inf. Sci.*, 8, (I) 199–251; 8, (II) 301–357; 9, (III) 43–80, 1975.