Terrain Feature Recognition Through Structural Pattern Recognition, Knowledge-Based Systems, and Geomorphometric Techniques

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Abstract

This paper reports on various research efforts, each having produced an original, practical prototype computer system applied to terrain-related interpretation. The first is the computational description and identification of drainage patterns through structural pattern-recognition. The second uses a variety of expert-system methods and tools to address terrain knowledge-representation and to construct prototype expert-systems for inferring the landform or the physiographic region of a site from user observations of their indicators. The third effort develops a terrain visual vocabulary through a Macintosh-based hypermedia system consisting of interlinked definitions, graphics, and aerial images which can be used simultaneously with the expert systems to assist novice interpreters in the use of such systems. The fourth effort develops a geomorphometric methodology for the classification of the GTOPO30 digital elevation model to three classes of physiographic features and for the identification, representation and classification of mountain objects.

Introduction

Terrain analysis is the systematic study of image elements relating to the nature, origin, morphologic history and composition of distinct units called landforms ([1], [2], [3]). Landforms are natural terrain units which when developed under similar conditions of climate, weathering, and erosion exhibit a distinct and predictable range of visual and physical characteristics. The entity of landform is fundamental in representing and organizing topographic and geomorphic information through the pattern-element approach to terrain analysis. The pattern elements examined include topographic form, drainage pattern, gully characteristics, soil tone variation and texture, land use, vegetation, and special features. The landform is inferred from the pattern-elements of the site and then the parent material is inferred by its association with the landform. It has wide applications in civil engineering, soil sciences, environmental inventory and mapping, in agricultural engineering, in structural geology, and in hazard and risk modeling ([1], [4], [5]).

Terrain analysis can be time consuming, labor intensive and costly. Its skills are a product of lengthy and expensive training. Therefore, it could help to at least partially automate this process by developing computer-assisted interactive systems [6]. It should be noted that landforms and pattern elements, including drainage patterns, are a vital and poorly described component of the landscape and very few of these features can be extracted automatically by image analysis or geomorphometric techniques.

This paper reports on various research efforts, each having produced an original, practical prototype computer system applied to terrain-related interpretation. The first is the computational description and identification of drainage patterns through structural pattern-recognition. The second uses a variety of expert-system methods and tools to address terrain knowledge-representation and to construct prototype expert-systems for inferring the landform or the physiographic region of a site from user observations of their indicators. The third effort develops a terrain visual vocabulary through a Macintosh-based hypermedia system consisting of interlinked definitions, graphics, and aerial images which can be used simultaneously with the expert systems to assist novice interpreters in the use of such systems. The fourth effort develops a geomorphometric methodology for the classification of the GTOPO30 digital elevation model to three classes of physiographic features and for the identification, representation and classification of mountain objects.

Structural Drainage Pattern Recognition

Drainage pattern is the configuration or shape of a set of tributaries within a drainage network. Comprehensive empirical descriptions of more than thirty pattern configurations were discussed by

Howard [7]. Drainage patterns are associated with topographic form, land use, soil type, rock type, lithologic type and geologic structure. Therefore one could draw a number of inferences related to these terrain features upon the interpretation of the drainage patterns. Drainage patterns are used in geology, geomorphology, and remote sensing because they are useful for the recognition of landforms and structures of a region. Computer classification of drainage patterns is useful for formalizing and automating the classification of textures and structures appearing on remotely-sensed images.

Argialas [6] and Argialas and Roussos [8] developed a prototype software system for the identification of drainage patterns by a structural pattern-recognition approach. The Drainage Pattern Analysis (DPA) system was originally programmed in a main frame and later as DPA-PC, within the Microsoft Windows environment. Structural pattern-recognition for drainage patterns included the design of conceptual drainage pattern models, and their corresponding numerical hierarchical and relational models, selection and extraction of pattern attributes, and design of a classification strategy. Patterns were described and classified by modeling their topologic, geometric, and structural relationships among constituent streams. The drainage pattern hierarchy was composed of semantic objects, Strahler segments, reaches, and nodes. Nodes were aggregated to reaches, reaches to Strahler segments, and Strahler segments to semantic objects. An attribute list was designed and attached to each node of the object hierarchy, in the form of a relational table, to characterize the object of that node. Figure 1 shows examples of drainage pattern recognition through the DPA-PC system. Figure 2 shows the computed angle statistics (min, max, mean, standard deviation, range) in particular those related to the intermediate angles of a pinnate drainage pattern. It is concluded that structural pattern recognition provides a formal framework for describing the structure of drainage patterns.

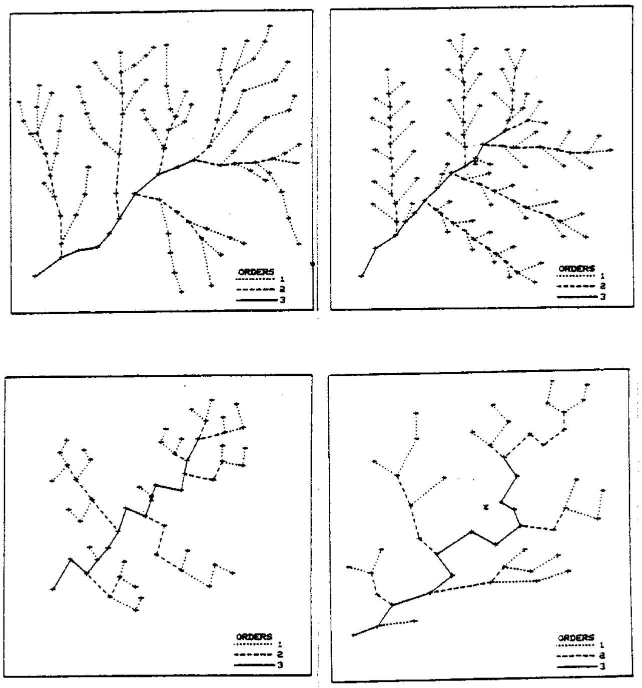
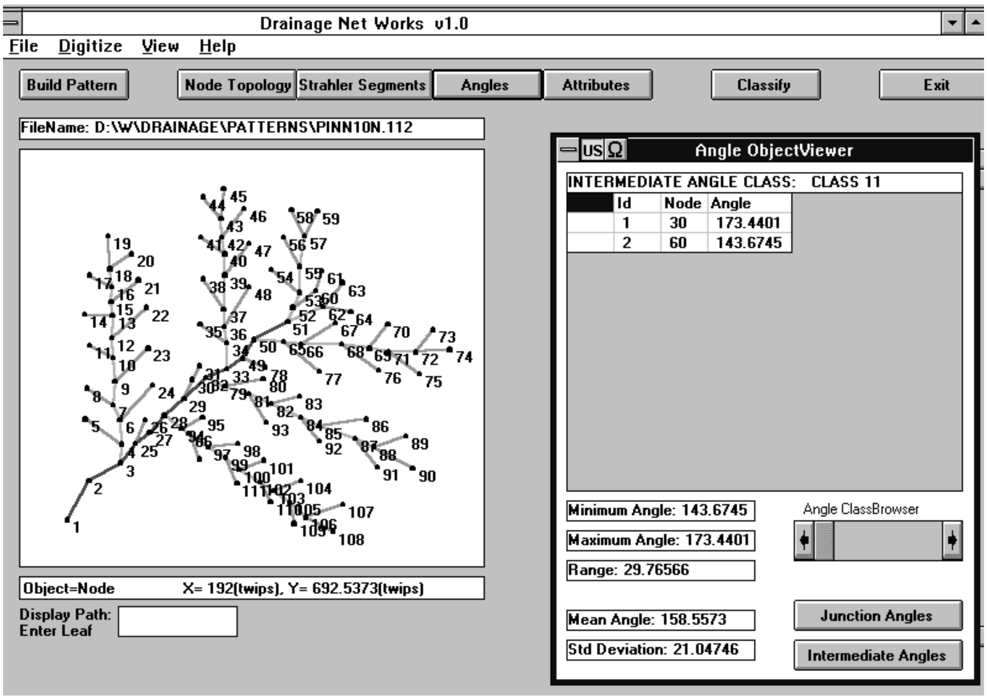


Figure 1. Drainage pattern recognition through the DPA-PC system. Clockwise from upper left a dendritic, pinnate, rectangular and angular patterns.

Knowledge-Based Landform Interpretation

Advances in expert systems have indicated that they can capture the knowledge structure underlying expertise in many fields and tasks in remote sensing [9]. The expert-system approach to terrain-analysis problem-solving was implemented with production rules involving inexact reasoning, frames and fuzzy sets ([3] [6]). The systems described were termed Terrain Analysis eXperts (TAX-1, 2, 3, 4, 5).



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INTERMEDIATE ANGLE CLASS: CLASS 11

Id	Node	Angle
1	30	173.4401
2	60	143.6745

Minimum Angle: 143.6745
Maximum Angle: 173.4401
Range: 29.76566
Mean Angle: 158.5573
Std Deviation: 21.04746

Object=Node X= 192(twips), Y= 692.5373(twips)

Figure 2. In this output of the DPA-PC system, the user has selected to view the computed angle statistics (min, max, mean, standard deviation, range) in particular those related to the intermediate angles of this pinnate drainage pattern. This pattern has been recognized as pinnate by the system.

In TAX-1 factual knowledge described the landforms in relation to their pattern elements and the physiographic sections in relation to their expected landforms. Strategic knowledge (problem-solving decisions) were represented by inexact production rules through a Bayesian formalism [6]. Based on user response for the query of the physiographic section of the site, the system constructed a set of candidate landforms of the site and estimated their a priori probabilities. TAX then chose the landforms in this candidate list, one by one, and attempted to establish each one of them, by matching the user-supplied pattern-elements of the site with those expected for each landform. A typical consultation script generated with the terrain analysis expert system TAX-1 is shown below. The numeric responses of the user, between -3 and 3, indicate the user's certainty for the presence of the specific pattern-element value in the study area.

Please provide the following information about the site.
To which Physiographic-section does the site belong?
Cumberland-plateau
Is the "gully-amount" of the site "none" ? -3
Is the "gully-amount" of the site "few" ? 1
Is the "gully-type" of the site "v-shaped" ? 3
Is the "landuse-valleys" of the site "cultivated" ? -1
Is the "landuse-valleys" of the site "forested" ? 3
Is the "landuse-slopes" of the site "cultivated" ? -3
Is the "landuse-slopes" of the site "forested" ? 3
Is the "soil-tone" of the site "medium" ? 1
Is the "soil-tone" of the site "light" ? 0
Is the "soil-tone" of the site "dark" ? 0
Is the "drainage-texture" of the site "coarse" ? 3
Is the "drainage-type" of the site "internal" ? -2
Is the "drainage-type" of the site "angular" ? 2
Is the "topography" of the site "steep-slopes" ? 3
Is the "gully-amount" of the site "many" ? -2
The site appears to be "sandstone-humid"
The certainty associated with this result is "0.99"

The Terrain Analysis Expert-2 (TAX-2) system was designed in the Intelligence Compiler, a frame and rule based expert-system tool. TAX-2 demonstrated the representation and reasoning capabilities of frames, backward and forward chaining rules, and inexact reasoning for landform interpretation [6].

The Terrain Analysis Expert-3 (TAX-3) system was designed so that to represent the vagueness and imprecision that is inherent in the qualitative descriptions of terrain terms by fuzzy sets [6]. Fuzzy set approaches provide a way for dealing with vague linguistic descriptions such as "gentle relief", and "partly dendritic, partly rectangular drainage pattern". For example, a linguistic label such as Gentle Relief may be construed as a fuzzy restriction on the values of the base variable "Relief in feet". Thus a flat plain or a site having a Relief of 0 m would be definitely called Gentle Relief, a Relief of 100 m could be called Gentle or Moderate Relief. When Relief equals 100 m, the membership in Gentle Relief is 0.5 and so is the membership in Moderate Relief.

Knowledge-based Physiographic Analysis

In all earlier efforts in constructing prototype expert terrain-related systems, knowledge related to the physiographic region of a site was not explicitly represented and used. It is however evident that the photointerpreter in deciding the landform of a site is studying first, among other things, the physiography of a region and performs a kind of physiographic analysis and reasoning so that to create reasonable hypotheses of the possible landforms of the site ([1], [2], [3], [4], [5], [16]). This type of reasoning is termed here physiographic context reasoning. On the other hand if the photointerpreter has already identified a landform, then she or he is in a position to create physiographic region hypotheses and consequently to be guided to interpret additional landforms by their spatial associations to the already interpreted landforms. Physiographic context and spatial reasoning are informal tasks at present since they are not described explicitly in a formal manner in books and guides.

Argialas and Miliaresis ([10], [11], [12]) developed a formal conceptual framework for the representation of physiographic and spatial context reasoning within an expert system. Emphasis was placed in the definition of the subproblems and subtasks through domain-dependent concepts, hypotheses and observations. The presented case study concerns typical terrain of the Basin and Range Province of Southwest USA. The knowledge representation encompasses the typical physiographic sections of the Basin and Range province (Great Basin and Sonoran Desert) and the typical landforms of the piedmont slope and basin floor of the Basin and Range province. The developed conceptual schemes are being used in the Terrain Analysis eXpert -4 (TAX-4) and -5 (TAX-5) systems which guide the user to establish tentative hypotheses about the types of physiographic regions based on observed evidences of their indicators and suggests reasonable landform hypotheses to be investigated. The role of landform spatial knowledge was developed both in helping the user to identify logical neighbors of an interpreted landform and to test the adjacency relations among interpreted landforms. In the design of TAX-4 and -5 the Nexpert Object (by Neuron Data) expert system tool, recently renamed to Smart Elements was used [12].

Detailed, "book-level" knowledge pertaining to physiographic regions and landform spatial associations was identified, named, described and organized. For the structural representation of physiographic and spatial reasoning knowledge an object-oriented representation structure was introduced that uses frames as classes, subclasses, objects, subobjects, and slot frames as properties. The following terrain classes were named and described by their properties: physiographic regions, the Basin and Range concept, the Basin and Range youthful stage concept, the Basin and Range maturity erosion stage and many others.

Physiographic, topographic, and landform classes were organized into class-subclass hierarchies. Classes included sub-classes so that additional levels of detail were described only in the subclasses. Describing classes through subclasses gave access to a hierarchical representation of concepts and objects. Figure 3 shows the landform class-subclass hierarchy where the landform class (Landform Top) is the root under which are linked the subclasses containing various aspects of landforms: landform pattern elements (LF_PE), spatial reasoning indicators (LF_SR), engineering property indicators (LF_Engineering), suitability indicators (LF_Suitability), and military suitability indicators (LF_Military). Figure 4 shows the physiographic province hierarchy. The root superclass name is Physiographic Provinces and has as subclasses all the provinces. The subclass Basin and Range is linked to this superclass. The Basin and Range Youthful Stage and Basin and Range Maturity Stage are subclasses of the Basin and Range class.

While classes were useful in representing a concept as a whole, it was necessary to define individual (static or dynamic) class members or object instances of each class or subclass so that to use them for symbols for the interpreted features of each class on an image. Figure 5 shows a variety of class-instances for the classes of landform, topographic forms, and physiographic regions.

Each class was defined by a set of properties indicating their distinguishing characteristics. Objects and subclasses can obtain their properties dynamically from a particular class through a mechanism called inheritance. Thus through the class-subclass or class-instance hierarchy these properties are inherited down each hierarchy so that to be shared by all the members and instances of each class (Figure 5). An object-subobject or whole-part hierarchy was also defined in order to capture the whole-part terrain organization. In particular, a physiographic region (PH-1) was partitioned to its component physiographic features (PF-1), a physiographic feature to its component topographic forms (TF1), and a topographic form to its component landforms (LF-1, LF2) (Figure 5).

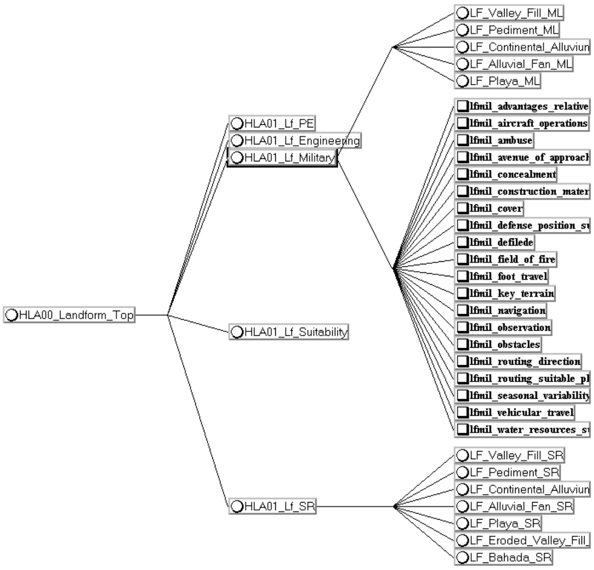


Figure 3. The class-subclass landform hierarchy.

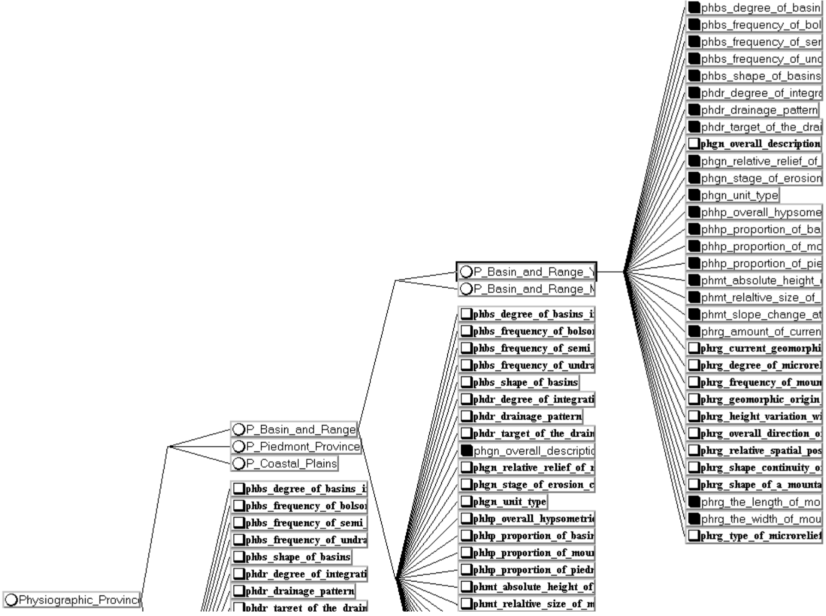


Figure 4. The conceptual physiographic provinces hierarchy.

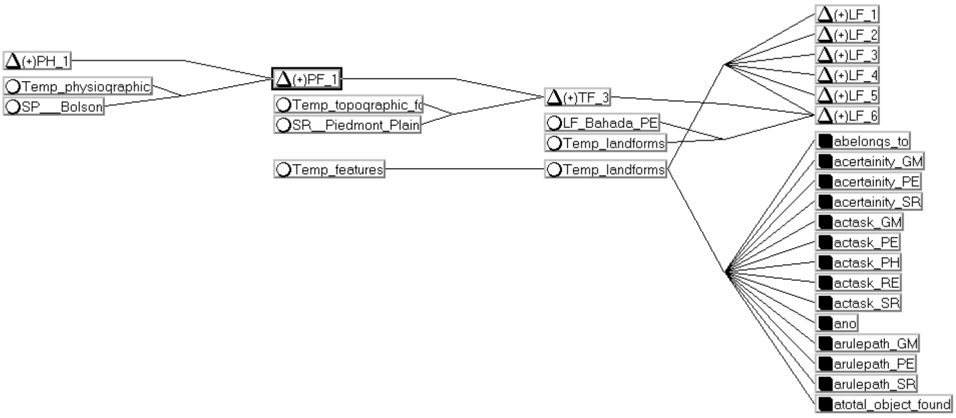


Figure 5. Object-subobject and class-instance relations.

A rule-base was developed for representing the strategic knowledge needed for inferring a physiographic region (province and section) from its own indicators ([10], [11], [12]). In the case of the Basin and Range concept, refinement rules inferred the concept of either a youthful or mature erosion stage the first corresponding to the Great Basin and the second to the Sonoran Desert section. One of the rules that infers the Maturity Erosion Stage concept follows.

IF relative_relief_of_region is "low" and
relaltive_size_of_mountains is "small" and
slope_change_at_piedmont_angle is "not abrupt" and
shape_of_basins is "rather plain than concave" and
overall_hypsometric_distribution_within_the_section is "more than 1/2 of the surface is below 2000 ft" and
proportion_of_Mountain_Ranges_versus_Piedmont_Plains_versus_Basins is "20% : 40% : 40%" and
amount_of_observed_tectonic_evidences_in_mountain_ranges is "low (the minority has a fault origin)" and
degree_of_basin_integration is "high" and
stage_of_erosion_cycle is "maturity (advanced,late)" and
frequency_of_bolsons is "low (less prelevant)" and
frequency_of_semi_bolsons is "high (more prelevant)" and
degree_of_integration_of_drainage_pattern is "high" and
outlet_of_the_drainage_network is "usually to another drainage basin"
Then Basin_and_Range_Maturity_Stage is true and certainty is medium

A rule-base was also developed for representing the strategic (inferential) knowledge needed for spatial reasoning which included three distinct aspects a) landform identification by spatial association, b) landform verification by spatial association, and c) landform hypotheses-formulation by spatial association ([10], [11], [12]). The landform identification by spatial association was developed in order to identify a landform by using its relevant spatial indicators (pattern elements). The landform verification by spatial association was developed so that to test if two or more landforms, identified by the pattern element approach, were satisfying the required regional spatial constraints as these are determined by geomorphologic and physiographic considerations. The landform hypotheses-formulation by spatial association, was developed so that once a landform was identified by pattern elements, the landform spatial knowledge rule-base suggested a small set of candidate landform hypotheses to be investigated by the user as being the most promising neighboring landforms according to geomorphologic constraints. Figure 6 shows the reasoning behind the Landform Hypotheses Formulation by Spatial Association.

The Terrain Visual Vocabulary (TVV)

The TAX knowledge bases described earlier use many terrain indicators, each of which may have multiple values. For the most rudimentary knowledge base, the user must be familiar with more than a hundred different terrain indicators. Many more terrain features are needed for knowledge bases of significant size and detail. A novice user is unlikely to have unambiguous mental and visual models of all these terrain indicators. Accordingly, an interactive computer system could provide a terrain visual vocabulary (lexicon, or encyclopedia), which could incorporate explicit definitions, diagrams and photographic illustrations of each terrain indicator to be used by novice users of expert systems like TAX. The prototype Terrain Visual Vocabulary (TVV) system was designed to include three components to define and graphically depict landform features: (1) definitions, (2) diagrams (line drawings), and (3) scanned aerial images. The system was built in Hypercard, the authoring software environment of the Apple Macintosh computer. In the TVV, each landform indicator value was considered as a node and was represented by a card (Figure 7). The set of all cards describing this prototype vocabulary was stored in one HyperCard stack. Each card contains a definition of the corresponding term in a text field, diagrams (profile and block diagram) of the vocabulary term, and aerial photographs exemplifying landforms for each term. The links between associated ideas (terms) were implemented by constructing buttons or anchors, showing as boldface or underlined expressions in the definition field, and then associating a certain Hypertalk language script to them.

Physiographic Feature Extraction, Representation, and Classification from Moderate Resolution Digital Elevation Models

The knowledge-based representation of the physiographic analysis process for the Basin and Range Province, presented earlier, has indicated the need for the extraction and classification of the common physiographic features such as mountain ranges, basins, and piedmont slopes from digital elevation models and/or satellite images. To address this need, Miliaresis and Argialas ([13, [14]) developed a methodology (a) for the classification of the GTOPO30 digital elevation model [15] to three classes of physiographic features (Mountains, Piedmont Slopes and Basins) and (b) for the identification, representation, and classification of mountain objects. The terrain classification methodology was applied to the Great Basin section of the SW U.S.A. where more than hundred narrow mountain ranges separated by almost level desert basins have been observed [16].

After the rectification and resampling of the GTOPO30 digital elevation model, the Z operator, adjusted in a 9*9 neighbourhood, was first applied so that the elevation value of the DEM points were averaged over a 3*3 neighbourhood and then the partial derivatives were determined by the SOBEL operator and the Z operator. Finally, the gradient and aspect at each DEM point were computed. For the computation of region growing criteria, training areas were selected and gradient statistics were computed and analysed to yield the following criteria: a) gradient less than 3 degrees for basins and b) gradient greater than 6 degrees for mountains.

The runoff simulation technique was used for the selection of an initial set of mount and basin points since DEM points with large runoff belong either to the drainage network (downslope flow) or to the ridge network (upslope flow). An iterative region growing segmentation algorithm [17] was applied to the initial set of mount points so that if a point with gradient greater than 6 degrees, was an 8-connected neighbour to the set of mountain points then it was flagged as a mount point. An 8-connected component labelling algorithm [17] was applied and the regions formed by 8-connected pixels of either mount or non-mount points were identified. Then the erogenous regions were recognised, on the basis of their size and spatial conditions, and they were reclassified. Finally, 36 distinct mountain objects were identified and a unique label identifier was assigned to every point belonging to a certain object (Figure 8a). Similar region-growing procedures were applied for the basin point classification. The points that were neither classified as mount points nor as basin points were assigned to the piedmont slope class.

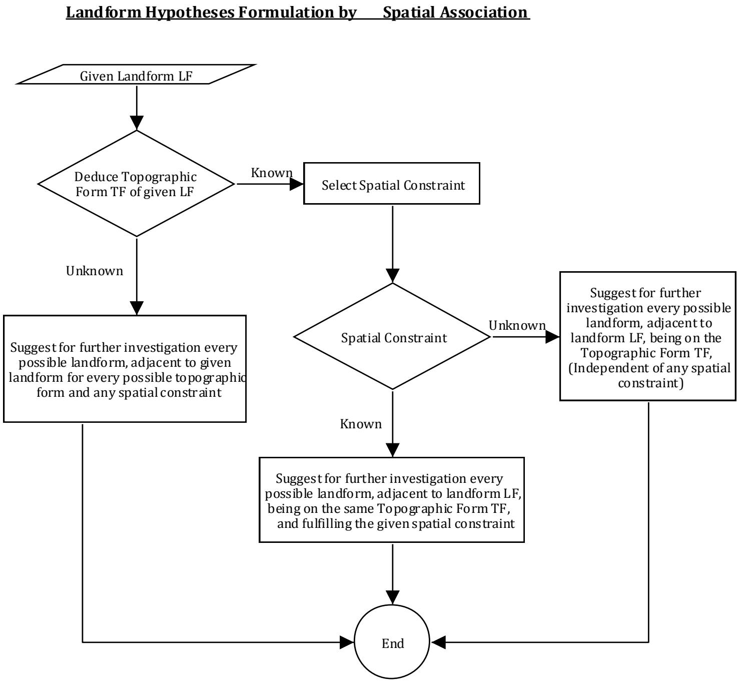
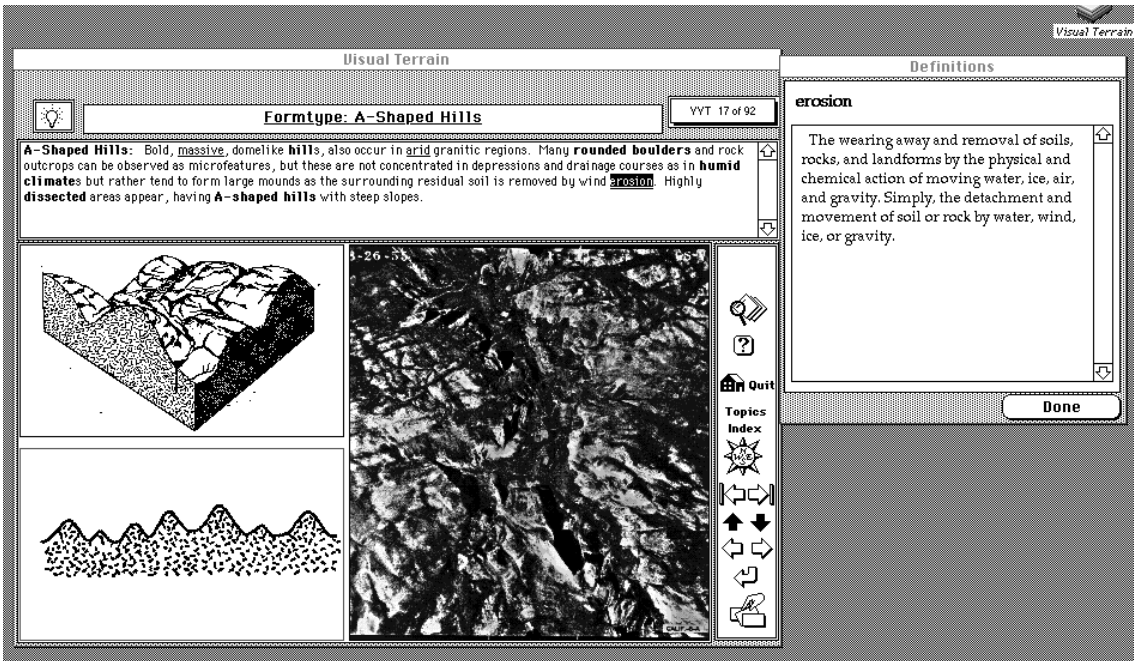


Figure 6. Landform Hypotheses Formulation by Spatial Association



Formtype: A-Shaped Hills

A-Shaped Hills: Bold, massive, domelike **hill**s, also occur in arid granitic regions. Many **rounded boulders** and rock outcrops can be observed as microfeatures, but these are not concentrated in depressions and drainage courses as in **humid climate**s but rather tend to form large mounds as the surrounding residual soil is removed by wind erosion. Highly **dissected** areas appear, having **A-shaped hills** with steep slopes.

erosion

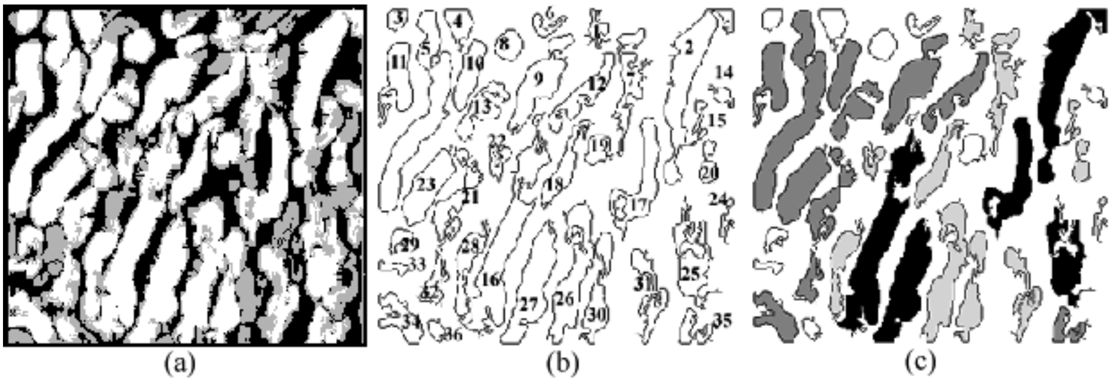
The wearing away and removal of soils, rocks, and landforms by the physical and chemical action of moving water, ice, air, and gravity. Simply, the detachment and movement of soil or rock by water, wind, ice, or gravity.

Figure 7. A typical card from the Hypermedia Terrain Visual Vocabulary presenting the landform A-shaped Hills.

The boundary of each one of the 36 distinct mountain objects was delineated and skeletonized [18] to one–pixel wide line segment (Figure 8b). A set of attributes were defined so that to carry sufficient physiographic information in order to be useful for the classification of mountain objects. The attributes included the area of the region occupied by the object, the object diameter, the mean polar radius, the eccentricity, the compactness, the polar index, the orientation, the asymmetry in orientation, the elevation, the roughness, the local relief, the relative massiveness, the elevation uniformity, and the slope. These attributes were used as descriptors for the parametric representation of mountain objects.

The classification of mountain objects was achieved through the implementation of a K-means clustering algorithm applied to the parametric representation of mountain objects. The mountain object clusters were analysed and interpreted in terms of their characteristic properties, e.g., size, slope, elevation, relief, elongation, and orientation. The members of each cluster were depicted with a unique shade of gray in order to detect any spatial arrangement of the cluster members (Figure 8c). The mountain objects were grouped into four clusters that appeared to be spatially arranged to distinct geographic regions.

For evaluation purposes, the boundaries of the extracted mountain objects were delineated and superimposed to the digital elevation model of the study area and it was observed that they enclosed the elevated features observed on the digital elevation model. The mountain features detected were also compared with the physiographic map of Atwood [19] and a good match was evident. The parametric representation of mountain objects, on the basis of the proposed geomorphometric and shape attributes, and their classification into four clusters, spatially arranged to distinct geographic regions, found to be in accordance with existing physiographic descriptions and physiographic maps of the study area.



(a) (b) (c)

Figure 8. (a) DEM classification to mountain (white), piedmont slope (gray), and basin (black) points, (b) Identified and labelled mountain objects, (c) Spatial distribution of the four classes of mountain objects.

Conclusions and Prospects

The structural drainage-pattern system successfully recognized eight drainage pattern types. It needs to be extended to include more types of drainage patterns, to get integrated with a network extraction system (DEM-to-watershed transformation), to incorporate 3-D geomorphometric attributes derived from the DEM, and to get integrated with the terrain-analysis expert-system for mutual support of both systems.

The Terrain Analysis Expert system prototypes involved the identification, conceptualization, and representation of knowledge related to landforms, topographic forms, physiographic features, and physiographic regions. They succeeded to capture a number of "intermediate-level concepts" which are perhaps the most important tools available for organizing knowledge bases, both conceptually and computationally. The TAX systems need to be expanded so that to represent knowledge related to additional auxiliary information, including existing maps, often used during terrain interpretation, e.g., regional geologic setting, structural and tectonic geology, soil data and maps, land cover/use maps, and relevant world knowledge.

Major types of links or associations need to be identified and represented between terrain related objects within the TVV system. Indeed, good links could help to categorize terrain related concepts into semantically and perceptually related units which will be linked and accessed by association, much as a human does. The challenge in choosing nodes and links is to structure the terrain related knowledge to reflect the mental models that experts create when they reason about landforms. The marriage of hypermedia and expert systems is also inevitable as hypermedia systems can help to build less ambiguous decision support systems and knowledge-bases and thus make expert interpretation systems more intuitive.

The geomorphometric processing of the digital elevation models to extract physiographic features and represent and classify mountain objects was successful as it was indicated by the evaluation process.

Integrating geomorphometric, spectral, and semantic aspects of terrain analysis problem solving could lead to improved systems.

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