Quantification of Terrain Processes

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Abstract

Terrain processes quantification requires an object terrain segmentation framework allowing the partition of the landscape to either a continuous framework (aspect regions) or a discontinuous framework (landforms). Each object is parametrically represented on the basis of its spatial 3-dimensional arrangement and mapped according to a terrain classification scheme in an attempt to identify regions that include objects with distinct parametric representation. Case studies are presented that include tectonic, fluvial and aeolian, and gravity (landslides) processes quantification in both the Earth and Mars.

Keywords: fluvial, morphotectonic, aeolian, terrain segmentation, terrain pattern recognition, spatial decision making.

1 Processes and Landforms

The Earth's surface is comprised of relief features of different scales. A scale dependent generalized classification assigns continents to the 1st relief order, mountain ranges and basins to the 2nd order, alluvial fans to the 3rd order, while sand dunes are assigned to the 4th order (Pandey 1987).

The relief features are the result of endogenic and exogenic processes that shape the Earth's surface. Exogenic processes include denudation (that is the downwasting of land surfaces due to erosion, gravity forces, weathering, etc.) and deposition (the filling up with sediments) (Summerfield 1996). Endogenic processes are associated with geotectonics and include volcanism, faulting, crustal warping, etc. (Summerfield 2000). The relief features recognized on the Earth's surface, often called landforms, could be the result of different kinds and intensities of processes. Landforms are defined as natural terrain units, which might be developed from the same soil and bedrock or deposited by a similar combination of processes and, under similar conditions of climate, weathering, and erosion, exhibit a distinct and predictable range of visual and physical characteristics (Lillesand and Kiefer 1987).

The study of landforms and the recognition of the various processes acting are of great importance in both geomorphologic and terrain analysis studies for site evaluation and site selection. This fact gave rise to geomorphometry, which involves subdividing a landscape into landforms based on a terrain segmentation methodology and measurement of their size, shape, and relation to each other (Evans 1981). During its initial stages, geomorphometry concentrated mainly on drainage basin analysis from topographic maps, since basins could be defined in a rather continuous way in the majority of geomorphologic landscapes evident in mid-latitudes. The historical steps in the development of geomorphometry involved:

- Orometry, the 19th-Century measurement of mountains was an attempt to interpret landscape evolution and physical process that reflect the interplay of mountain building and erosion in regions of active deformation. Today, the mountain topography (Miliaresis 2001a) is of great significance, not only in tectonic geomorphometry but also in terrain analysis, in navigation of airplanes, and in the InSAR processing chain.
- Physiography corresponds to the regional-scale geomorphologic studies (1st and 2nd order landforms) in the early part of the 20th century (Miliaresis and Argialas 1999). Physiographic analysis was based on the partition of terrain into physiographic units by taking into account the form and spatial distribution of their component features through fieldwork and visual interpretation of topographic maps. Today, physiography is being stimulated by the need to explain enigmatic landscapes, newly explored on the surfaces of other planets through remotely sensed data (Miliaresis and Kokkas 2004).
- Terrain analysis corresponds to large scale geomorphometry and it involves the systematic study of pattern elements relating to the origin, morphologic history and composition of the distinct terrain units, called 3rd and 4th order landforms (Way 1978). Typical pattern elements examined include topographic form, drainage texture and pattern, gully characteristics, soil tone variation and texture, land use, and vegetation cover (Lillesand and Kiefer 1987).

Nowadays, quantitative techniques (Pike 1995, 2000) have been developed and applied in order to automate the interpretation of terrain features from digital elevation models (DEMs) and various geomorphometric parameters were developed in an attempt to characterize the landscape and identify the various processes (Evans *et al.* 2003). This chapter aims to review the physical world terrain partition frameworks at various scales and present how terrain objects' parametric representation, classification, and mapping might be used for tectonic, fluvial, and aeolian processes quantification.

2 Data Analysis Techniques

The quantification of processes requires a partition framework, which transforms the DEM representation of the landscape to elementary objects (Miliaresis and Argialas 2000). Physical processes are scale dependent and define various continuous (Miliaresis and Kokkas 2004) or discontinuous (Miliaresis and Argialas 2002) terrain partition frameworks. A unified terrain partition framework is impossible to achieve; instead various physical processes-objects dependent terrain representation schemes might be established. Thus from the conceptual point of view, processes and scale determine the physical terrain partition framework that should be derived from the DEM data. The derived terrain partition framework defines the objects that are parametrically represented, classified, and mapped towards processes quantification.

2.1 Data

During the initial steps, studies were based on interpretation and measurement performed on topographic maps and imagery. Nowadays, DEMs that are freely available from the WEB represent the Earth's relief at regional to moderate scales (Pike 2002). More specifically:

- The GTOPO (GTOPO30 1996) and the Global land one-kilometre base elevation (GLOBE 2001) DEMs are available, providing a digital representation of the Earth's relief at a 30 arc-seconds sampling interval.
- The Shuttle Radar Topography Mission (SRTM) successfully collected Interferometric Synthetic Aperture Radar data over 80% of the landmass of the Earth between latitudes of 60 degrees North and 56 degrees South in February 2000 (Farr and Kobrick 2000). The Consortium for Spatial Information of the Consultative Group for International Agricultural Research is offering post-processed void-free 3 arc-second SRTM DEM data for the globe (SRTM 2006) that is suitable for 1:250,000 studies.
- A moderate-resolution DEM (500 m spacing) is available for Mars, acquired by the Mars Orbiter Laser Altimeter (MOLA), a 10-Hz pulsed infrared-ranging instrument, which operated in orbit around

the planet from 1997 to 2001 aboard the Mars Global Surveyor (MOLA 2004).

2.2 Terrain segmentation

Terrain segmentation is applied to either DEMs or to derivative products and so slope, aspect, or even curvature could be computed according to the methods proposed by Shary (1995) and Florinsky (1998). The terrain partition framework of the landscape is either continuous (Miliaresis *et al.* 2005) or discontinuous (Miliaresis 2001a).

2.2.1 Continuous segmentation framework

Aspect regions are a paradigm of a continuous terrain segmentation scheme (Miliaresis and Kokkas 2004). In this approach, aspect is computed for every DEM point (Figure 1a). Then aspect is standardized to the eight directions (N, NE, E, SE, S, SW, W, NW) defined in a raster image (Figure 1b). For example, points with aspect in the range 22.5^o to 67.5^o are considered to slope towards 45^o azimuth (NE) and they are labelled with the same integer identifier. Note that zero labels indicate flat terrain (if slope $< 2^o$, then aspect is undefined). Thus, the points of the resulting aspect image are labelled with 9 integer identifiers corresponding to eight geographic directions defined in a raster image and the aspect undefined label (Miliaresis *et al.* 2005).

The aspect regions are easily interpreted from Figure 1b, since they are formed from points having the same shade of grey. For aspect regions to be explicitly defined, a connected component-labelling algorithm (Pitas 1993) is applied. The algorithm scans the image and identifies the regions formed by adjacent points labelled with the same aspect label. Approximately 30,000 aspect regions were identified. In Figure 1c, each aspect region is assigned to one out of seven classes depending on the mean slope of the DEM points that form the aspect region. In Figure 1d, aspect regions with mean elevation and mean slope in a specific interval are mapped in an attempt to express the following geomorphometric rule: “landslide risk is high if aspect region elevation is low while aspect region slope is high” (Miliaresis *et al.* 2005). So the parametric representation of aspect regions expresses in a quantitative manner the qualitative knowledge that was acquired by domain experts (landslide engineers) (Argialas and Miliaresis 2001).

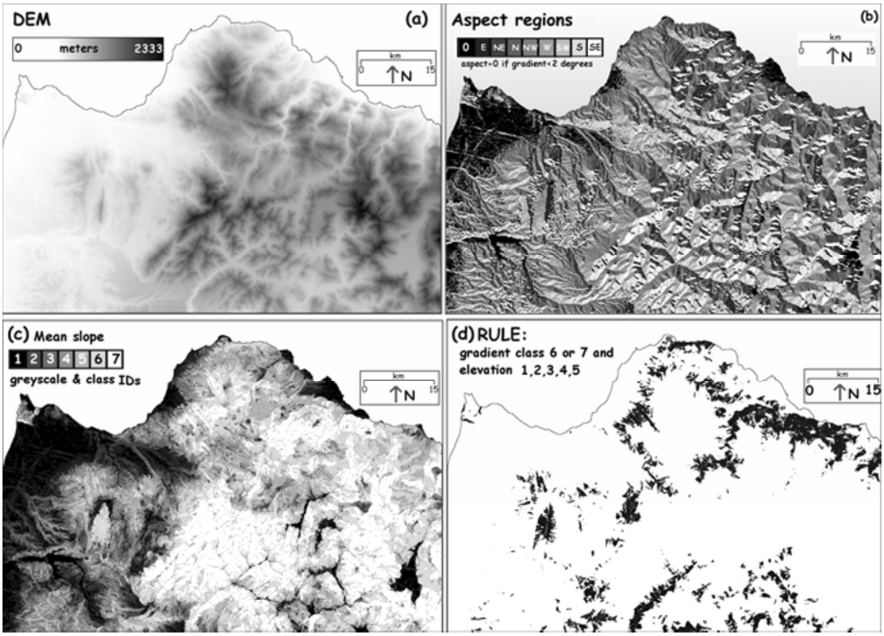

Figure 1. A continuous terrain partition framework (Miliaresis *et al.* 2005).

(a) DEM of the study area in SW Greece; the darker the point, the greater its elevation.
(b) The aspect regions are easily interpreted from the aspect image. Note that aspect was standardized to the 8 geographic directions defined in a raster representation, while an aspect region is formed by adjacent points with the same shade of grey.
(c) Each aspect region is assigned to one of seven classes depending on the mean slope of the DEM points that form the aspect region and mapped by a unique shade of grey.
(d) Aspect regions (black regions) with mean elevation and mean slope in a specific interval are mapped.

2.2.2 Discontinuous segmentation framework

Region growing segmentation is applied in order to isolated specific landforms from the geomorphologic background (Figure 2); thus a discontinuous terrain partition framework is created. This technique uses an initial set of points (seeds) and growing-stopping criteria (Miliaresis and Argialas 1999). The seeds are expanded during successive iterations by checking the neighbouring points. If the region growing criteria are fulfilled, then the neighbouring points are added to the initial set of points. The procedure is repeated until no more points are added.

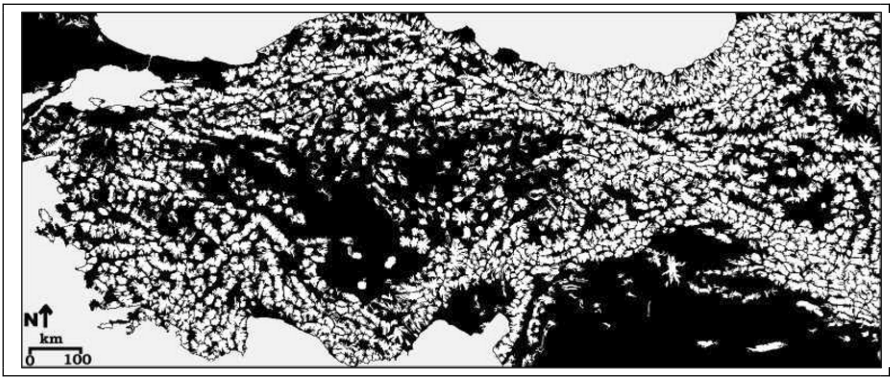

Figure 2. A discontinuous terrain partition framework (Miliaresis 2006) that identifies mountains (white pixels) from the surrounding basins (black pixels) in Asia Minor (SW Asia).

For mountains (Miliaresis 2001a, 2006), seeds correspond to ridge points and the region growing criteria are defined on the basis of slope/elevation range and pixels that belong to the valley network. For alluvial fans (Miliaresis and Argialas 2000), drainage outlet points determine the seeds and the region growing criterion is based on slope (Figure 3). For bajadas (coalescent fans), streams emerging on the basin floor form the set of seeds (Figure 4), while the region growing criterion is based on slope combined with size dependent objects filtering and drainage pixel removal after the first iteration (Miliaresis 2001b).

2.3 Object representation, terrain classification and mapping

The representation of the segmented objects is performed by a set of parameters that are associated either with their planimetric shape (size, elongation, etc.) or their 3-D arrangement (mean elevation, local relief, roughness, mean slope, hypsometric integral, etc.). For example:

- The area of the region occupied by the object is computed as the aggregate of the pixels constituting the object region multiplied by the area extent of each pixel.
- The mean elevation of objects is computed as the average elevation of the pixels that belong to an object's region.
- Roughness corresponds to the standard deviation of elevation and it is a stable measure of the vertical variability of the terrain within an object.

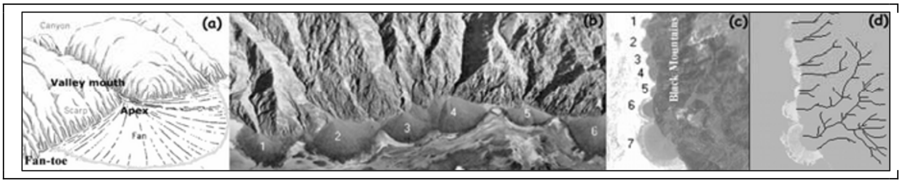

Figure 3. Alluvial fans in Death Valley, California (Miliaresis and Argialas 2000).

(a) Block diagram of an alluvial fan deposited in front of a valley mouth.
(b) 3D view of the study area.
(c) Landsat image of the study area.
(d) Region growing segmentation of alluvial fans on the basis of drainage outlet points.

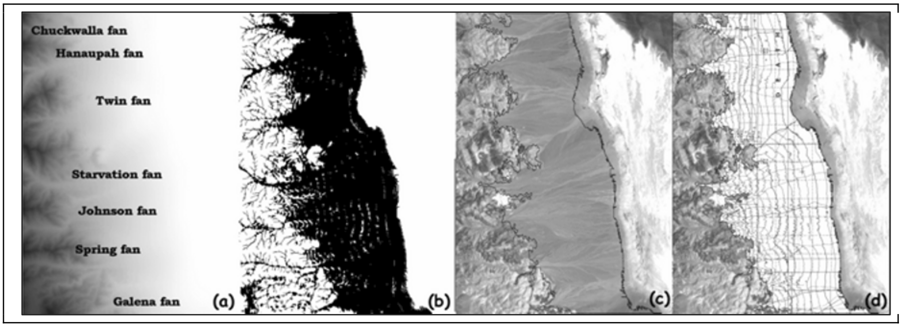

Figure 4. Bajadas segmentation in Death Valley (Miliaresis 2001b).

(a) The DEM of the study area. The elevation values (-86 to 1,904 m) were rescaled to the interval 255 to 0 (the brightest pixels have lowest elevation).
(b) Region growing segmentation (first iteration).
(c) The borderline of the segmented bajadas object superimposed on the TM image (band 5).
(d) Hybrid image. TM band 5 in the background while the map is shown through the segmented bajadas polygon.

These parameters quantify the physical processes since they indicate the elevation and slope variability within the object. The hypsometric integral reflects the stage of landscape development, while the mean slope is associated with the intensity of both erosion and tectonic processes (Miliaresis and Argialas 2002).

Terrain classification is achieved by cluster analysis of the parametric representation of objects. It is based on measurement of the Euclidean distance, which is calculated in a c-dimensional space, where c represents the number of attributes used in the clustering process (Miliaresis and Iliopoulou

2004). Terrain mapping and interpretation of the spatial distribution of clusters will be presented in the following case studies.

2.4 Software for terrain segmentation

Connected components labelling, object filtering, and region growing segmentation can be implemented with Geologic Shell (2001). This software package is freely available for download on the internet from the WEB site of the International Society for Mathematical Geology, and a newer version will be available soon (Miliaresis and Kokkas 2007).

Drainage basins, ridge and valley networks, as well as general geomorphometric parameters could be determined with TAS software (Lindsay 2005) that is available free through the WEB (TAS 2004).

3 Terrain Processes Recognition

3.1 Asia Minor versus Zagros Ranges

In the Zagros Ranges, the collision of the Arabian Shield with Iran has shortened and thickened the crust to produce a spectacular mountainous physiography. The linear topographic highs represent huge folds (NW–SE anticlines), marked by SW facing topographic escarpments, while the geometry of asymmetrical anticlines indicates the existence of basement reverse faults (Berberian 1995). In Asia Minor, horizontal expulsion is taking place and most of the area is extruding westward away from the Arabian-Eurasian collision and towards the small remnant of oceanic crust underlying the Aegean Sea (Miliaresis 2006).

Having decomposed the terrain into the mount and non-mount terrain classes, elevation frequency histograms are computed for each class of Asia Minor and the Zagros Ranges. The underlying idea is that mountains are usually under a different (kind or intensity) physical process than the surrounding basins. These differences should be revealed in the frequency distributions used to describe each class (Miliaresis 2001a).

The elevation frequency histogram of the non-mount terrain class looks very similar to the overall frequency histogram of the study area (Figure 5), both including three major peaks. The resemblance of the two histograms is explained by the fact that the non-mount terrain class occupies 64% of the study area, forcing the histogram of the study area to fit the histogram of the non-mount terrain class. The three major peaks at elevations of 0, 420, and 1,045 m observed in the histogram of the non-mount terrain class indicate the existence of three major peneplains at regional scale. The elevation frequency histogram of the mount terrain class preserves one peak at an elevation of 1,260 m, with the elevation frequency declining gradually away from it.

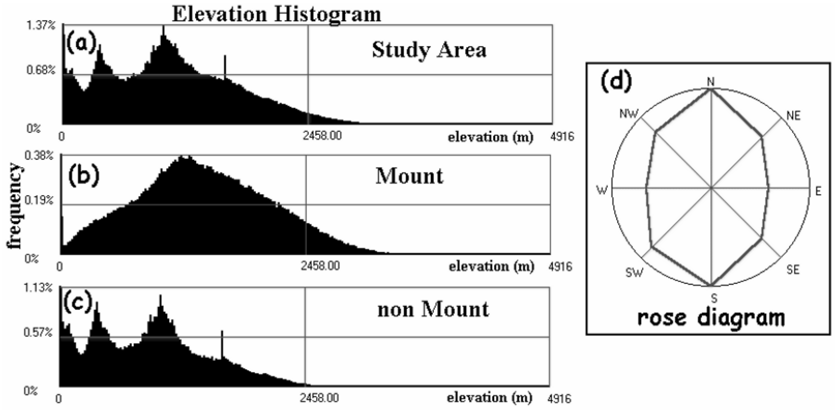

Figure 5. Descriptive statistics of Asia Minor (Miliaresis 2006). Elevation frequency histograms of the decomposed terrain classes of the study area. (a) study area, (b) mount, (c) non-mount, (d) a rose-diagram of the aspect vector (pointing downslope) standardized to 8 geographic directions defined in a raster image.

The aspect vector rose diagram (Figure 5d) indicates that the landscape flows equally in the North and South directions at right angles to the main axes of the mountain ranges (Figure 2).

In the Zagros Ranges, the frequency histograms of elevation (Figure 6) indicate that the extracted mountain objects are developed almost equally on all levels in the elevation domain (Miliaresis 2001a). The greatest frequencies were observed in the range 1,500 m to 2,500 m. The frequency histogram of the non-mount terrain class looks very similar to the overall elevation frequency histogram of the study area because both include the extensive NW coastal plains (Figure 8).

The rose diagram of aspect pointing downslope (Figure 6C) indicates that much of the surface is sloping away from the mountains in a NW to SE direction. This direction is at right angles (Figure 8) to the collision of the Arabian Shield with the Iranian Plateau and verifies the asymmetry of the mountain ranges (huge asymmetrical anticlines).

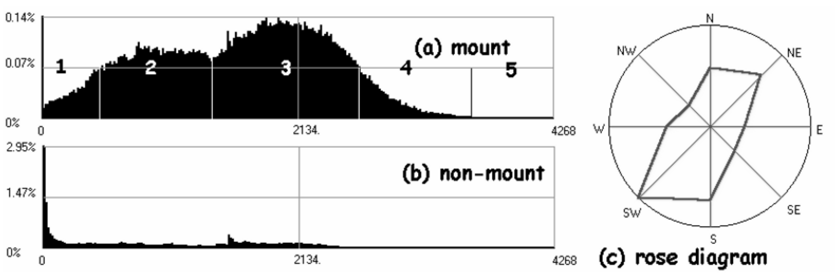

Figure 6. Descriptive statistics of Zagros Ranges (Miliaresis 2001a). Elevation frequency histograms of the decomposed terrain classes of the study area. (a) mount, (b) non-mount, (c) a rose-diagram of the aspect vector (pointing downslope) standardized to 8 geographic directions defined in a raster image.

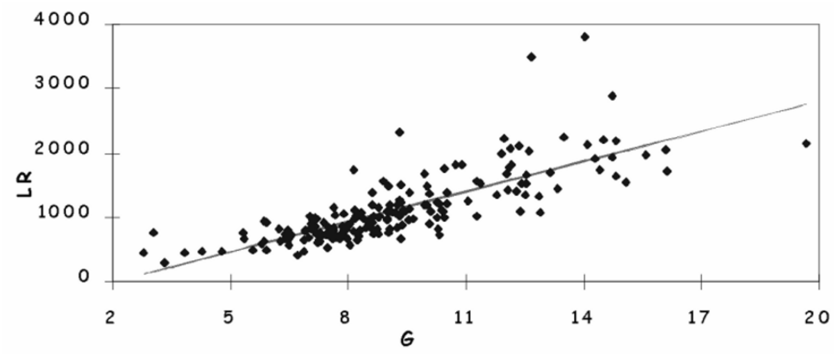

Figure 7. Linear regression of local relief (LR) versus slope (G) for the mountain objects identified in Zagros Ranges (Miliaresis and Iliopoulou 2004).

The correlation between the attributes of the mountain objects is of great significance and might be explored either by computing correlation coefficients, or by assuming the linear regression model (Miliaresis and Iliopoulou 2004). In the case study of the Zagros Ranges, the correlation between Local Relief ($LR = H_{maximun} - H_{minimum}$, within a mountain object) and slope (G) is expressed by the equation (Figure 7):

$$LR = -316.+156.1*G$$

Such models are of great significance since they might prove to be quantitative indicators of landscape development and tools for estimating the intensity of processes.

Figure 8. Spatial arrangement of the clusters derived by the centroid method in Zagros Ranges (Miliaresis and Iliopoulou 2004).

3.2 Clustering of Zagros Ranges

The mountain objects segmentation and parametric representation (Miliaresis 2001a) followed by the centroid clustering method revealed clearly the SE–NW stair-step topography observed in the Zagros Ranges, while the steepest and more massive mountains were also observed along this direction (Figure 8).

The zones derived by the mapping of clusters were associated with the existing morphotectonic zones of the study area, while geomorphometric processing proved capable of segmenting morphotectonic zones to subregions with different geomorphometry (Miliaresis and Iliopoulou 2004).

3.3 Tectonic processes identification in Mars

The DEM to Mountain transformation of Valles Marineris in Mars (Miliaresis and Kokkas 2004) revealed numerous tributary valleys originated from the plateau that cross the chasma sides and the mountain features extending to the basin floor (Figure 9).

The observation of segmented chasma downslope borders (fronts) indicates that they are rectilinear. A tentative interpretation is that uplift along front-faults produced the mountain fronts that are relatively straight, since they have not had time to be dissected and embayed by streams. As the range front is eroded, major drainage embays the front and causes it to retreat, depending on the width of the ranges and the length of the steams. This process might be accelerated by landslides that cause the occasional concave in plan hillslope forms (Figure 9).

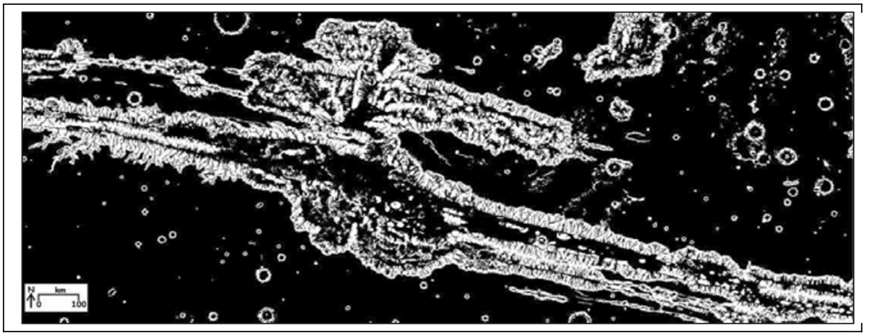

Figure 9. The mountain terrain class in Valles Marineris (Mars). The white pixels represent the pixels labelled by the DEM-to-Mountain transformation (Miliaresis and Kokkas 2004).

Additionally, the segmentation to aspect regions and their representation on the basis of mean elevation and mean gradient revealed the chasma terrain structure, proving that the basin floors of the elementary chasmata are interrupted by regions with higher mean elevation and gradient, due possibly to vertical tectonic movements (Miliaresis and Kokkas 2004).

3.4 Prospects: aeolian landforms segmentation

Desert environments are dominated by dunes that are accumulations of sediment blown by the wind into a mound or ridge. Dunes have gentle upwind slopes on the wind-facing side. The downwind portion of the dune is commonly a steep avalanche slope referred to as a slipface (Bullard 2006). The slipface stands at the angle of repose, which is the maximum angle (30° to 34° for sand) at which loose material is stable.

Dune typical heights and wavelengths (spacing) are in the range of 5 to 30 m and 50 to 300 m, respectively. Linear megadunes, in the Western Desert in between Egypt and Libya (Figure 10) and in the Namib Sand Sea (Namibia), attain even greater dimensions with heights of up to 400 m and wavelengths up to 4 km; the most significant factors determining their morphology are wind regime and sand supply (Summerfield 1996). Megadunes must take hundreds of years to attain an equilibrium form and thus are key landforms in the study of possible severe climatic change that will possibly be expressed by change in the direction and intensity of winds in desert regions.

Towards this end, linear megadune segmentation might be performed from SRTM DEMs (SRTM 2006) acquired in February 2000, while topographic information might be acquired from LANDSAT-SRTM imagery (Levin *et al.* 2004) for the period 1980–2000 and from ASTER imagery for the period 2001–2007. A multi-temporal analysis and change detection of their morphology might provide answers for the global climatic change in desert environments.

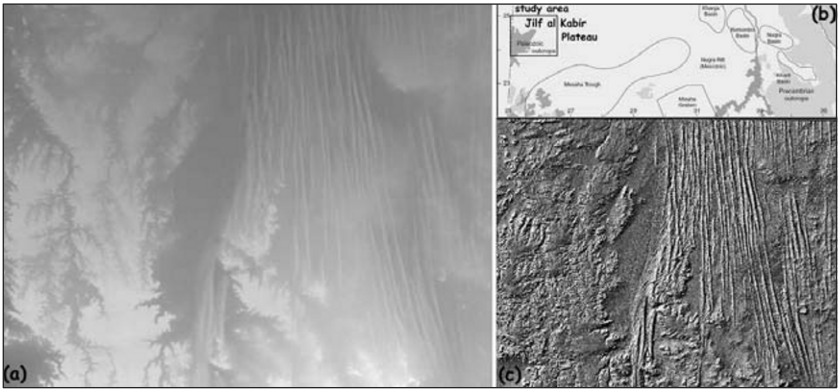

Figure 10. Mega-dunes (aeolian landforms).

(a) The SRTM DEM of the study area (the brighter the pixel, the greater its elevation)
(b) A physiographic map and the location of the study area in SW Egypt.
(c) Shaded relief map of the SRTM DEM of the study area.

An initial experiment on the delineation of megadunes is presented in Figure 11. Slope (Figure 11b) was derived from the DEM (Figure 11a). The initial set of seed points (Figure 11c) was defined by thresholding the upslope runoff image, while region growing criteria were based on both the slope and the valley network (Figure 11d).

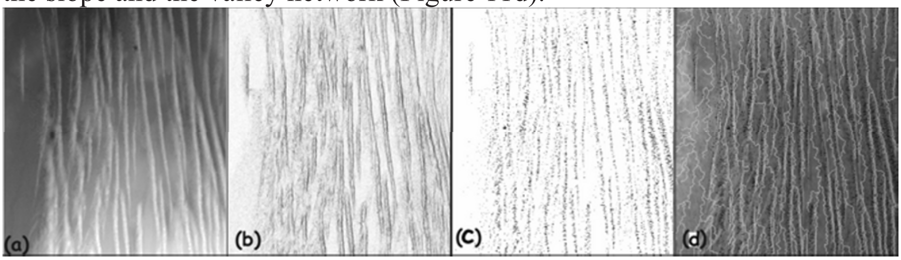

Figure 11. Towards the delineation of sand-dunes from SRTM DEM.

(a) DEM of the study area (the brighter the pixel, the greater its elevation).
(b) Slope image (the darker the pixel, the greater its slope).
(c) Seeds that correspond to points with upslope runoff greater than a threshold.
(d) Valley network extracted by runoff simulation and the seeds superimposed on the Landsat image.

4 Conclusion

Global digital elevation models of earth and other planets have fostered geomorphometric and terrain modelling at broad spatial scales. The broad-scale quantification of topography and the DEM-based analyses transformed geomorphometry into one of the most active and exciting fields in the Earth sciences. Segmentation techniques allowed the partition of the terrain into continuous and discontinuous schemes. The parametric representation of the derived objects combined by object classification schemes allowed the mapping and the quantification of various processes.

More specifically, tectonic processes were quantified on the basis of the discontinuous partition framework based on mountains. The quantification was based on the spatial distribution of the mountain pattern, on the linear regression of mountain attributes, and on the hypsometric and frequency distributions of elevation and aspect. Fluvial landforms (alluvial fans and bajadas) forming zones that are subject to frequent flash flooding were delineated from DEMs.

The aspect regions continuous terrain partition framework allowed the identification of regions with high landslide hazards on the basis of aspect regions parametric representation and knowledge-based rules acquired by domain experts, while in Mars aspect regions modelling revealed the tectonic processes. SRTM DEMs seem to be capable of capturing aeolian processes on the basis of the morphometry of linear megadunes in desert regions.

Geomorphometric analysis provides a quantitative way to compare developed and developing landscapes in areas of both differing and similar geologic structure. Additionally, experience with the Earth's landscape assists the exploration and interpretation of various landscapes in inaccessible areas on other planets from digital elevation data.

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