Study of Volcanic Cinder Cone Evolution by Means of High Resolution DEMs

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EXTENDED ABSTRACT

Square-grid digital elevation models (DEMs) are widely used to calculate in an accurate way different morphologic parameters from the DEM surface. The digital terrain analysis allows defining primary attributes such as slope, aspect, plan and profile curvature, local fractal dimension, and secondary attributes more devoted to estimate the role played by topography in the distribution of soil water or on the susceptibility of landscapes to erosion, for instance.

High resolution DEMs can provide more precise results but require specific treatments related to the vertical accuracy. The present application concerns the study of different volcanic cinder cones of the Trans Mexican Volcanic Belt. Their evolution is directly related to erosion processes and partly to the human activity that develop on their flank gullies and local collapse structures.

Volcanic cinder cones formed by cinder and pyroclastic debris are generally considered as truncated cones with a crater located in the summit. Morphologic changes occur with time and can provide information about the age of the edifice using quantitative ratio between different parameters in order to characterize the volcanic shape: i.e., the ratio height of the cone versus the base diameter would be equal to 0.18 and the ratio between the crater diameter and the base diameter would remain at 0.40. Until now, numerous geomorphological studies concerning the geomorphic definition of the volcanic characteristics or the effect of the erosion process are based on these parameters and ratio.

In order to quantify the volume of removed material during the erosion process, an algorithm that reconstitutes the original volcanic shape has been applied in a first approach to a 5 m resolution DEM and new parameters characterizing the volcanic cones have been proposed.

In the present case, a combination of aircraft-based LIDAR and GPS has been used to enhance in the same region the former DEM resolution in such a way that the treatments presented here have been applied to a 1 m resolution DEM.

The process decomposes the studied zone in different altitude slices according to the hypsometric interval chosen; the corresponding contour line is then extracted. The convex zone of each slice is calculated in such a way that a volcanic cone without gullies can be created. The new position of the contour lines thus generated is taken into account to simulate the erosive regression inside the different actual gullies and calculate the volume of cinders removed during this process. For a given altitude, all the original DEM pixels that are equal or higher than this altitude are reported in an image and codified with the value 1000; on the contrary, all the convex DEM pixels that are lower than this altitude are codified with the value 500.

This procedure manages a free space codified with the value 10000 and where the intermediate position of the contour line has to be researched. This calculation depends on a dilation procedure used to fill progressively the free space. The new position of the contour line corresponds to the limit between the two dilated zones. This procedure is applied until reaching the position of the contour lines as observed in the original DEM.

The hypsometric difference between the original DEM and the successive reconstituted DEM provides an estimation of the volume of the eroded material at each step.

Actually, the present treatment illustrates the increasing of the gully depth and does not take into account its progressive formation from the volcanic base line until its present position. For this reason, further developments will simulate progressively the gully formation according to the time scale provided by terrain observations.

INTRODUCTION

Studies of the current changes of land cover make possible the characterization of erosion processes, desertification and biodiversity loss of a land portion. In the specific case of monogenetic volcanic fields, one can take advantage of the fragility of the constituent material (ash) to establish a relation between temporal and spatial changes of the land use/cover and the erosion of the volcanic structures. Landscapes under study are situated in the Chichinautzin Range Volcanic Field (ChRVF). This region is located in the central part of the Mexican Volcanic Belt (MVB), and it is characterized by the development of more than 200 volcanic centers of Quaternary age that cover a sector of 2400 km^2 (Figure 1). Mainly composed of volcanic ashes, the volcanic cones are submitted to erosion processes due to natural and, more recently, to anthropogenic factors. The erosion of the volcanic structures of this zone can partly be also explained by natural factors such as climate, ash composition and weathering.

Geomorphometric features such as the surface roughness provide information about regional geomorphology. Many parameters have been proposed with such a goal. Square-grid digital elevation models (DEMs) are nowadays widely used, as the possibility of storage and advances in computing technology increased strongly in recent years. The horizontal and vertical resolution is sufficient to calculate in an accurate way different parameters extracted from the DEM surface. The digital terrain analysis (Wilson and Gallant, 2000) allows defining primary attributes such as slope, aspect, plan and profile curvature and secondary attributes more devoted to estimate the role played by topography in the distribution of soil water or on the susceptibility of landscapes to erosion, for instance. Most of the primary attributes are computed directly with a finite difference scheme or by fitting an interpolation function $z = f(x, y)$ to the DEM in order to calculate the derivatives of this function. These different attributes provide numerous indicators about the geomorphology concerning the study region. They are used to describe the morphometry, catchment position, stream channels, and to compute topographic attributes.

Volcanic cinder cones formed by cinder and pyroclastic debris are generally considered as truncated cones with a crater located in the summit (McDonald, 1972). The first geomorphological studies have shown that morphologic changes occur with time and can provide information about the age of the edifice (Colton, 1967; Scott and Trask, 1971). Porter (1972) was the first to define quantitative ratio between different parameters in order to characterize the volcanic shape: i.e., the ratio height of the cone versus the base diameter would be equal to 0.18 and the ratio between the crater diameter and the base diameter would remain at 0.40. Bloomfield (1975), using radiometric age determinations, observed that the first ratio decreases from 0.21 until 0.10 with time, meanwhile the second one increases from 0.40 to 0.83. On the other hand, according to Settle (1979), the shape characteristics of the volcanic cones are related to the nature of the material involved in the eruptive process, and to the nature and duration of the erosion activity. Wood (1980a, 1980b) confirms and formalizes the morphometric parameters proposed by Porter (1972). Until now, numerous geomorphological studies concerning the geomorphic definition of the volcanic characteristics or the effect of the erosion processes, are based on these parameters and ratio (i.e. Dohrenwed *et al*., 1986; Hasenaka, 1994;; Hooper and Sheridan, 1998; Aranda-Gomez *et al*., 2003), even if their use remains problematic when the studied cone does not present a crater (Hasenaka and Carmichael, 1985).

The possibility to obtain more detailed geomorphic information has been explored by Garcia-Zuniga and Parrot (1998) who proposed to use a Digital Elevation Model (DEM) and to define pattern recognition parameters applied to hypsometric slices describing the volcanic cone, from its base line to its summit. This approach described as tomomorphometric analysis registers the morphologic changes taking into account parameters such as the convexity index, direction of the principal axis. This recent approach has been used to study the lithospheric motion of the Somalian and Arabian plates (Collet et al., 2000), the Anatolian volcanic massif (Adiyaman et al., 2003) and the Chichinautzin volcanic cinder cone field, Mexico (Noyola and Parrot, 2005).

More recently, Parrot (2007) used a five meter resolution square-grid DEM in order to obtain an automated parameterization of volcanic cones that is based on seven parameters: the volume of the volcanic cone, the volcanic base line radius and eventually its elongation, the total height of the cone from the base line until its summit, the crater radius when existing, the depth of this crater, the mean dipping angle outside the crater and the mean dipping angle inside the crater, parameters used to reconstitute the original volcanic cone shape. This paper was focused on two volcanic regions in Mexico. The first one comprises the Jocotitlan volcano, whereas the second is formed by two volcanoes from the Chichinautzin range (Fig. 2). The corresponding 5 m resolution DEM with a decimeter vertical resolution is produced by a multidirectional interpolation (Parrot and Ochoa-Tejeda, 2004) taking into account contour lines of 10 meters interval. Even if this high resolution DEM presents some artefacts inherent to this type of interpolation that over-estimates the number of pixels describing the contour lines, it was possible to obtain a good estimation of the material removed on the southern flanks of the El Aire volcano.

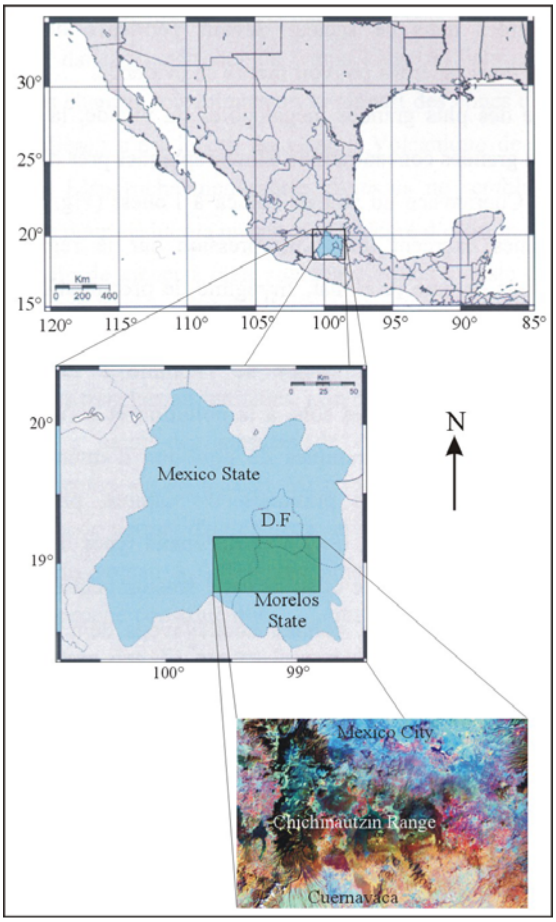

Figure 1. Chichinautzin Range localisation.

A pedologic and geomorphologic study of this edifice is presently engaged (see the aerial photograph of figure 3). The main purpose is to quantify the volume of removed material. For this reason, a high resolution DEM is required. A combination of aircraft-based LIDAR and GPS has been used to enhance the DEM resolution. Thus, the treatments presented here have been applied to a 1 m resolution DEM of the same region.

The methodology applied is described in the following section and the results obtained are presented in the third section.

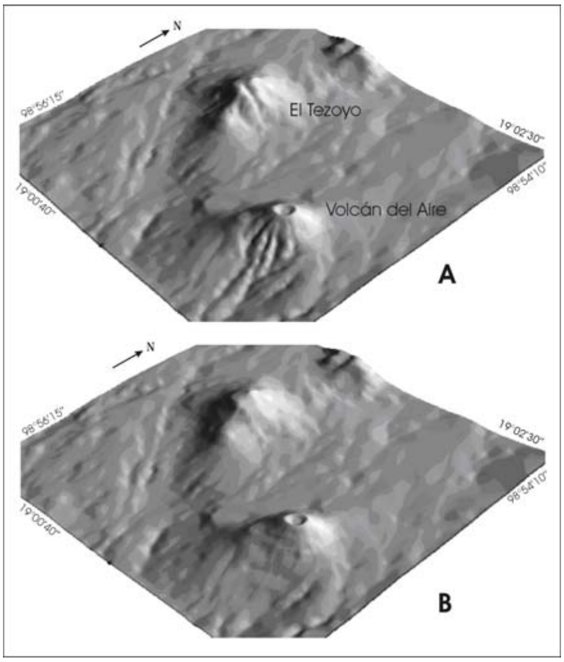

Figure 2. 3D diagram of El Tezoyo and Volcan del Aire volcanoes. A. Original shape. B. Reconstituted volcanoes.

Figure 3. Aircraft photograph of the El Aire volcano.

METHODOLOGY

An accurate DEM provides us information by means of tomomorphometric and volumetric approaches. The first one decomposes each volcanic cone in various slices of altitude. Pattern Recognition parameters such as the convex index, the length-width ratio, or the orientation of the principal axis, are used in order to discriminate and characterized each volcanic slice and then to follow the morphologic evolution according to the altitude. The volumetric approach takes into account field observation and theoretical models in order to reconstitute the original volcanic cone before the erosion process occurred. This first method provides for each cone an estimation of its degree of erosion.

In the present case, as shown in figure 4, the main erosive process occurred on the southern flank of the volcano. Thus, the treatment was only applied to this last zone.

The process consists to decompose the studied zone in different altitude slices according to the hypsometric interval chosen; the corresponding contour line is then extracted. Using the Jarvis march (Fig. 5), the convex zone of each slice is calculated in such a way that a volcanic cone without gullies can be created (Akl and Toussaint, 1978).

Figure 4. Aspect. Technique of the pallet of the painter (Parrot, 2006). Red = 0°; Yellow = 120°; Blue = 240°.

The new position of the contour lines thus generated is taken into account to simulate the erosive regression inside the different actual gullies and calculate the volume of cinders removed during this process.

The procedure consists of extracting a sequence of contour lines having the same altitude in the two DEMs: the original and the DEM resulting from an interpolation using the contour lines provided by the former treatment. Thus, for a given altitude, all the original DEM pixels that are equal or higher than this altitude are reported in an image and codified with the value 1000. All the convex DEM pixels that are lower than this altitude are codified with the value 500.

This procedure manages a free space codified with the value 10 000 and where the intermediate position of the contour line has to be researched. This calculation depends on a dilation procedure used to progressively fill the free space. A combination of two morphological structural elements that provides a quite isotropic dilation (Fig. 6) is applied until the disappearance of null points codified with the value 10 000.

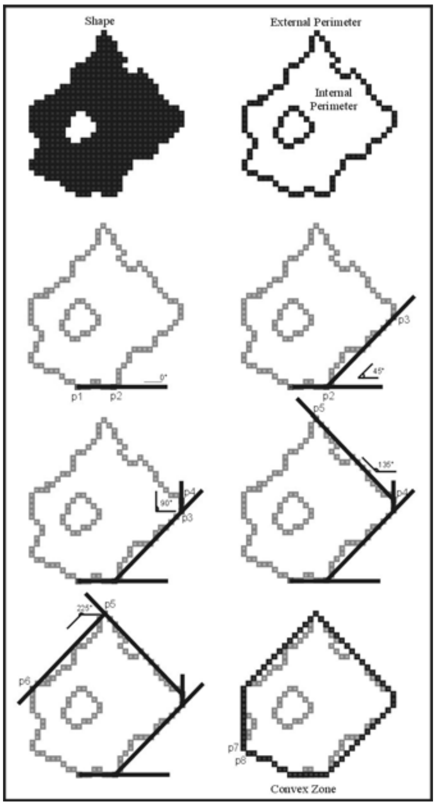

Figure 5. Jarvis's march.

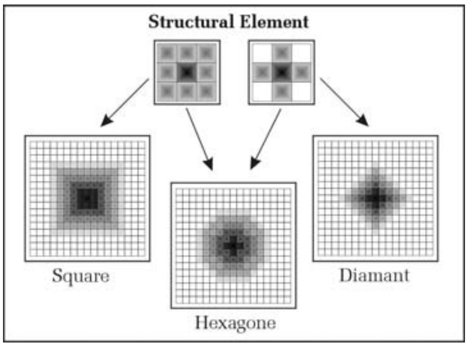

Figure 6. Structural elements used to dilate the free space borders.

The new position of the contour line corresponds to the limit between the two dilated zones (Taud *et al.*, 1999). When all the contour lines have been transformed in such a way, the former multidirectional interpolation (Parrot and Ochoa-Tejeda, 2004) is applied generating a new DEM used to calculate the volume difference and define the following treatment. This procedure is applied until reaching the position of the contour lines as observed in the original DEM. Figure 7 illustrates the displacement of the contour lines inside a gully from the position they have in the convex DEM until the original one. Figure 8 shows the increase of the distance between the first convex contour line and the successive contour lines that define the gully is reported (distance versus 2^{step}); this distance is calculated according to the drainage network.

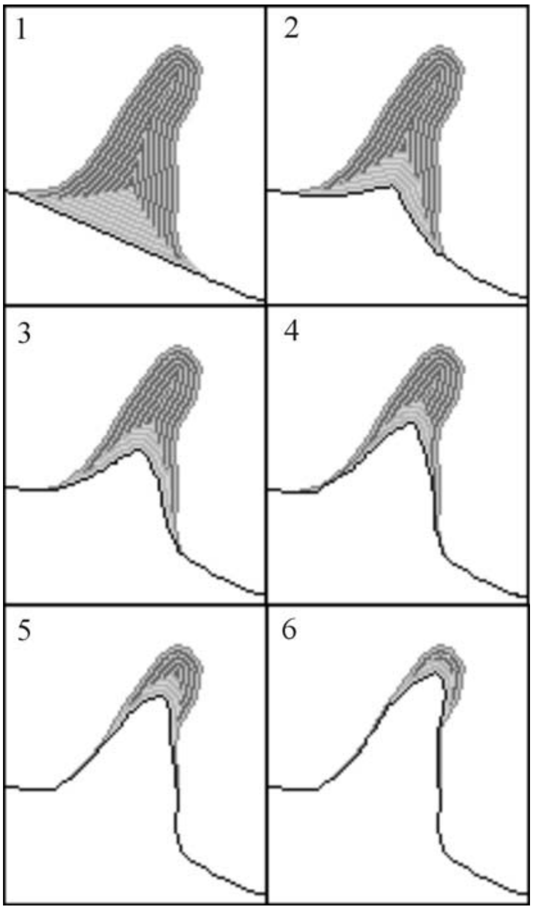

Figure 7. Successive positions of a contour line inside a gully.

RESULTS AND DISCUSSION

Treatments applied to high resolution DEM allow us to calculate in an accurate manner different geomorphic parameters, to simulate the evolution of a given shape and then to estimate the volume of removed material during an erosive process.

The applied treatment in the case of the southern side of the studied volcano is illustrated in figure 9. The hypsometric difference between the original DEM and the successive reconstituted DEM (Fig. 12) provides an estimation of the volume of the eroded material at each step (Fig. 10 and Fig. 11).

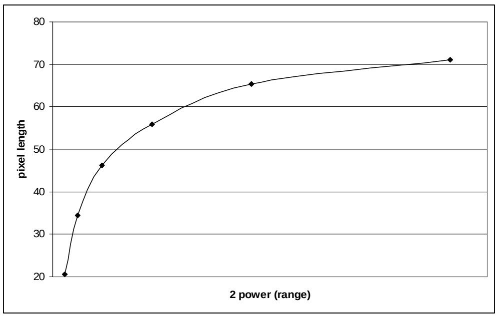

Figure 8. Length evolution.

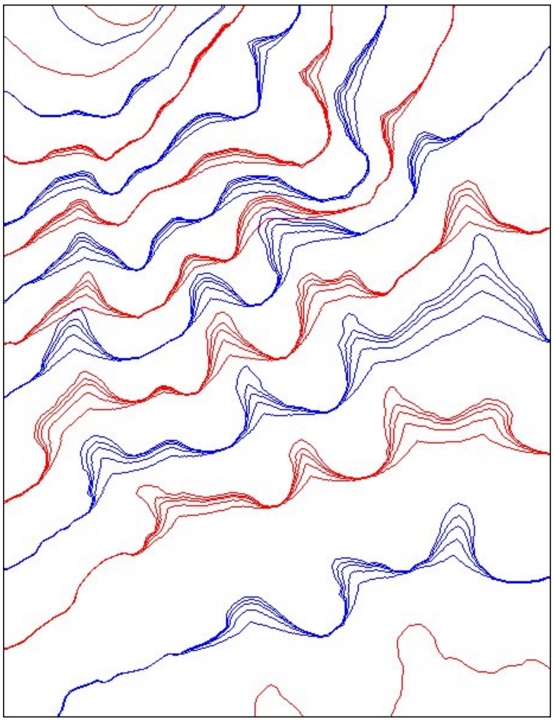

Figure 9. Contour line (each 20 meters) displacement in the studied zone.

The first figure (Fig. 10) shows the distribution of the frequency of the sediment thickness according to the different steps. The number of pixels corresponding to a thickness of 1 decimeter increases from step 1 until step 4 and the number of pixels corresponding to one meter decreases rapidly. This behavior is related with the regular increase of the depth of the gullies that progressively reach its equilibrium profile. Correlatively, the value of the volume removed at each step decreases from 15 714 m2 to 5 056 m2 (Fig. 10).

But actually, at the present step of this research, the computation takes into account all the different contour lines that are moving at the same time. For this reason, this procedure does not illustrate the regressive erosion that has to start from the volcanic base line until reaching the border of the crater, but only emphasizes the depth increasing of the gully bottom.

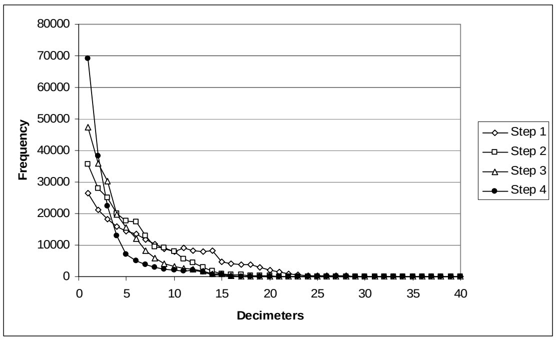

Figure 10. Frequency versus thickness of the sediment in decimeters.

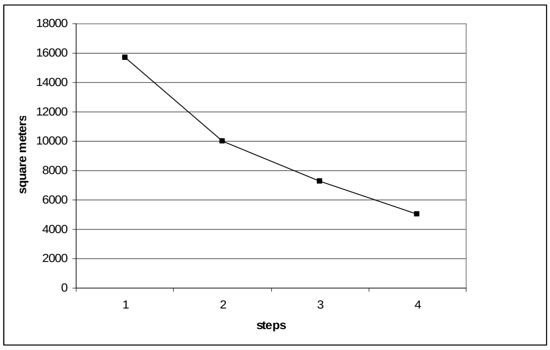

Figure 11. Volume removed in function of the different steps.

A further approach will concern the simulation of the regressive erosion process that implies a progressive development of local creeps affecting the cinder deposits upstream the gully segments formerly created. In this case, it will be necessary to displace in a first time the first lower contour line until its actual position, before to compute in a same way the displacement of the following upper contour lines. This procedure has to be applied until reaching the present gully development.

On the other hand, in order to integrate these results in the pedologic and geomorphologic study previously mentioned, we need to establish a close relationship between the simulated formation and the process timing taking into account field observation.

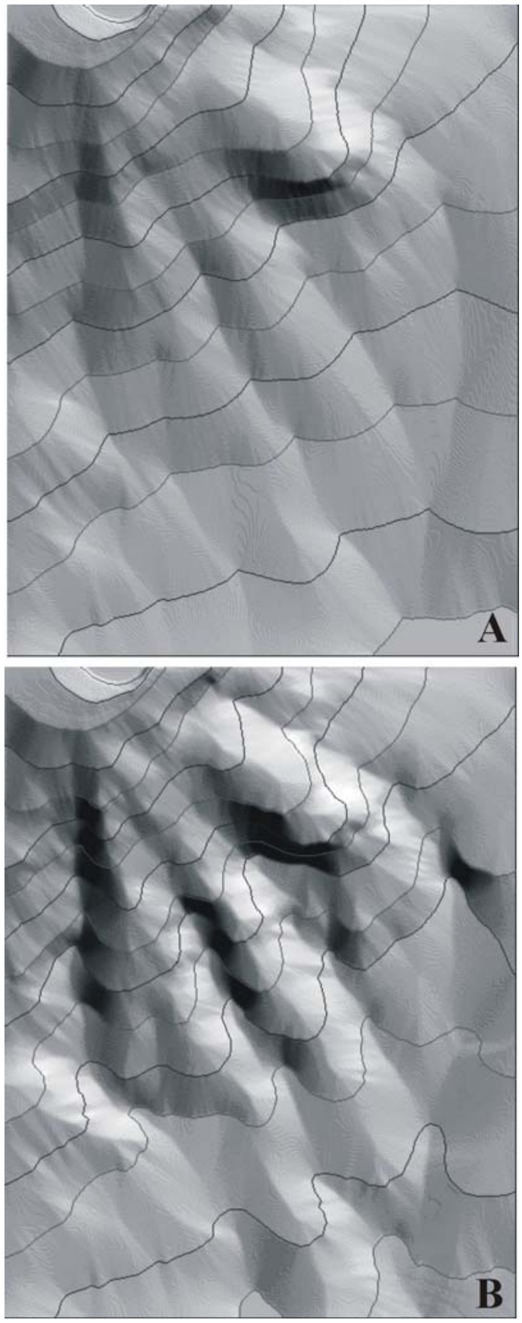

Figure 12. Treatment steps. A First Step; B Final Step.

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