Available online at www.sciencedirect.com

SCIENCE DIRECT®

Geomorphology 67 (2005) 407–422

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Geomorphometric analysis for characterizing landforms in Morelos State, Mexico

Andrea Bolongaro-Crevenna[a,b,*], Vicente Torres-Rodríguez[a], Valentino Sorani[c], Dawn Frame[d], Mario Arturo Ortiz[e]

[a]*Academia Nacional de Investigación y Desarrollo., Wimbledon 31-B, Fracc. Junto al Río, Temixco, Morelos, 62580, México*
[b]*Facultad de Ciencias Biológicas, Universidad Autónoma del Estado de Morelos, Av. Universidad 1001, Col. Chamilpa C.P. 62210, México*
[c]*Laboratorio Interdisciplinario de Sistemas de Información Geográfica, Centro de Educación Ambiental e Investigación Sierra de Huautla, Universidad Autónoma del Estado de Morelos, Av. Universidad 1001, Col. Chamilpa C.P. 62210, México*
[d]*Institut de Botanique, 163, rue A. Broussonnet 34090 Montpellier, France*
[e]*Instituto de Geografía, Universidad Nacional Autónoma de México, México, D.F., 04510, México*

Received 20 August 2002; received in revised form 1 November 2004; accepted 5 November 2004
Available online 2 December 2004

Abstract

Landforms can be described and quantified into simple relief elements by parametrization of digital elevation model (DEM). In this research, we investigate the use of morphometric parameters and a new classification scheme to characterize selected elemental forms associated with landforms. We apply and test this methodology on a geomorphologically diverse region located in Central Mexico. These simple elements are known as morphometric classes and include ridge, plane, channel, pit, peak, and pass. These classes correspond to real entities and are of practical significance. The morphometric classes were grouped according to their areal parameters (ridge, plane, and channel) and pointed parameters (pit, peak, and pass), which can be used to form the basis of a system of characterization and classification of landforms. Landform elements display statistically significant compositional differences with respect to their proportions of morphometric classes. This, in turn, can be plotted onto a diagram of characterization and classification known as a double ternary diagram (DTD), which comprises both areal and pointed parameters and any combination thereof. The DTD is useful for studying geomorphological processes wherein areal and point values and properties have expressions which are topographically quantifiable.

Keywords: DEM; Geomorphometry; Relief analysis

1. Introduction

Landforms are the result of geologic and geomorphologic processes that occur on the earth's surface. The term "landform" as used by geoscientific

* Corresponding author. Academia Nacional de Investigación y Desarrollo., Wimbledon 31-B, Fracc. Junto al Río, Temixco, Morelos, 62580, México.
E-mail address: andreabc@prodigy.net.mx (A. Bolongaro-Crevenna).

0169-555X/$ - see front matter
doi:10.1016/j.geomorph.2004.11.007

modelers denotes a portion of the earth that unites the qualities of homogeneous and continuous relief due to the action of common geological and geomorphological processes. This concept of landform is essentially an idealized one, it follows then that the closer the study landform conforms to its definition, the greater the accuracy of the obtained model. Geomorphometry, a subdiscipline of geomorphology, has for its object the quantitative and qualitative description and measurement of landform (Pike and Dikau, 1995; Dehn et al., 2001; Pike, 2002) and is based principally on the analysis of variations in elevation as a function of distance. A basic principal underlying geomorphometrics is that there exists a relationship between relief form and the numerical parameters used to describe it, as well as to the processes related to its genesis and evolution. This is to say that landforms are not chaotic, they are structured by geologic and geomorphic processes over time. One aim of geomorphologists working with landform models is to obtain better and better approximations of physical reality.

Derivation of landform units can be carried using various approaches, including classification of morphometric parameters, filter techniques, cluster analysis, and multivariate statistics (Dikau et al., 1995; Dikau, 1989; Sulebak et al., 1997; Etzelmüller and Sulebak, 2000; Adediran et al., 2004). A common focus of the study of landforms is to consider them as formed by small and simple elements topologically and structurally related. Morphometric studies usually begin with the extraction of basic components of relief, such as elevation, slope, and aspect; a more complete description of the landform may be achieved by using spatial derivatives of these initial descriptors, as well as useful indicators, e.g., the topographic wetness index (Moore and Nieber, 1989), stream power index (Moore et al., 1993a), and aggradation and degradation index (Moore et al., 1993b). Currently, geomorphology frequently relies on digital elevation models (DEM) as the information base from which both the basic components and indicators are extracted.

The great number and easy availability of DEM allows researchers to obtain geometric characteristics, including numerical descriptions of topographic forms of the Earth at several scales. Parametrization of relief is a method of spatial analysis, whereby there are rules of correspondence between real and numerical forms. Wood (1996) proposed a group of algorithms for numerically describing relief as forming a reduced number of classes of simple forms or morphometric classes. The rules defining each morphometric class are based on the values of slope and convexity as calculated from a DEM. Wood's approach is based on Evan's hypothesis (1972) that the land's surface may be conceptualized as a continuous surface, and as such, may be represented analytically by a second-degree polynomial function, such as: $z=Ax^2+By^2+Cxy+Dx+Ey+F$, wherein x and y are geographical coordinates, and the letters A through F are coefficients of the polynomial that contain information on relief attributes.

The morphometric classes proposed by Wood were ridge, channel, plane, peak, pit, and pass (Fig. 1), numerical representations which are considered to represent the name of real forms (Fig. 2). Additional numerical forms, such as cliff and ramp, were suggested by Felicísimo (1999).

The use of morphometric parameters represents an advance in the characterization of each DEM element, i.e., pixel, but cannot fully describe a group of more complex forms such as landforms. The goal of this study is to demonstrate that landforms can be characterized by an assembly of morphometric classes, a positive result will open the way for structural and textural landform studies. In addition, if it can be shown that a strict relationship exists between these morphometric classes and geomorphologic processes, we will be able to propose a landform classification system. In this research, we propose the use of morphometric parameters and a new classification scheme to characterize selected numeric elementary forms associated with landforms. This methodology is currently tested and applied on a geomorphologically diverse region located in Central Mexico.

2. Study area

The study region, Morelos state, Mexico, is located in the centre of Mexico between 19°07′N and 18°19′ latitudes, 99°29′W and 98°37′W longitudes (Fig. 3) and comprises an area of 4960 km2 (Aguilar, 1989). The state is characterized by three physiographical provinces: the northern zone dominated by the

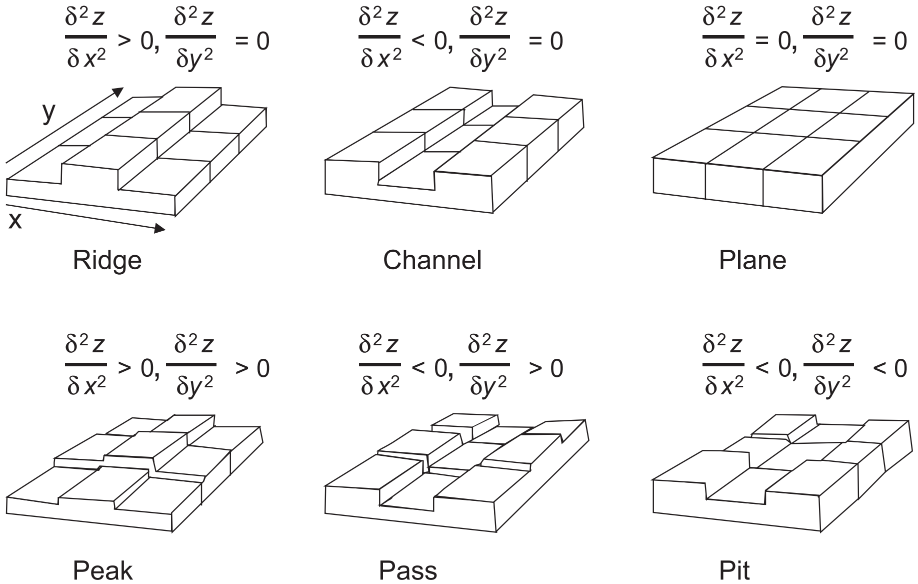

Fig. 1. Morphometric classes that can be obtained from the numeric analysis of the change in gradient of a central point in relation to its neighbors (modified from Wood, 1996).

Transmexican Volcanic Belt of the Plio-Quaternary, the central zone readily recognizable by its valleys and sedimentary Mesozoic mountain ranges, and the southern zone with its folded Mesozoic mountain ranges covered by predominantly acidic volcanic rock (Morán-Zenteno, 1990; Morán-Zenteno et al., 2002).

The geomorphological classification map of Morelos state, which serves as the basis for this study, recognizes 11 landforms (Table 1; Fig. 4). This map was obtained with traditional manual methods and published by the Social Development Ministry (SEDESOL, 2000).

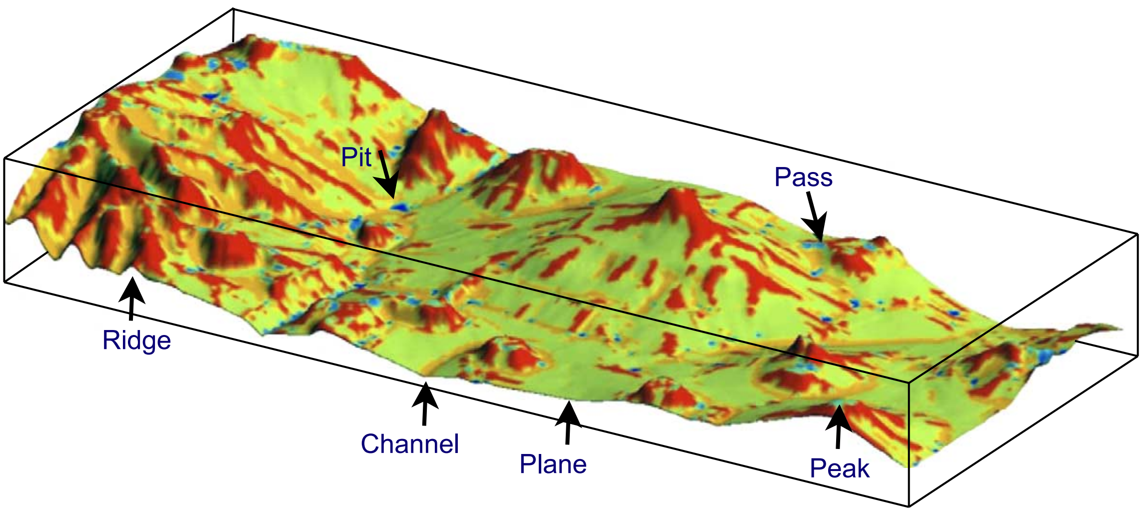

Fig. 2. Profile scheme of six morphometric classes.

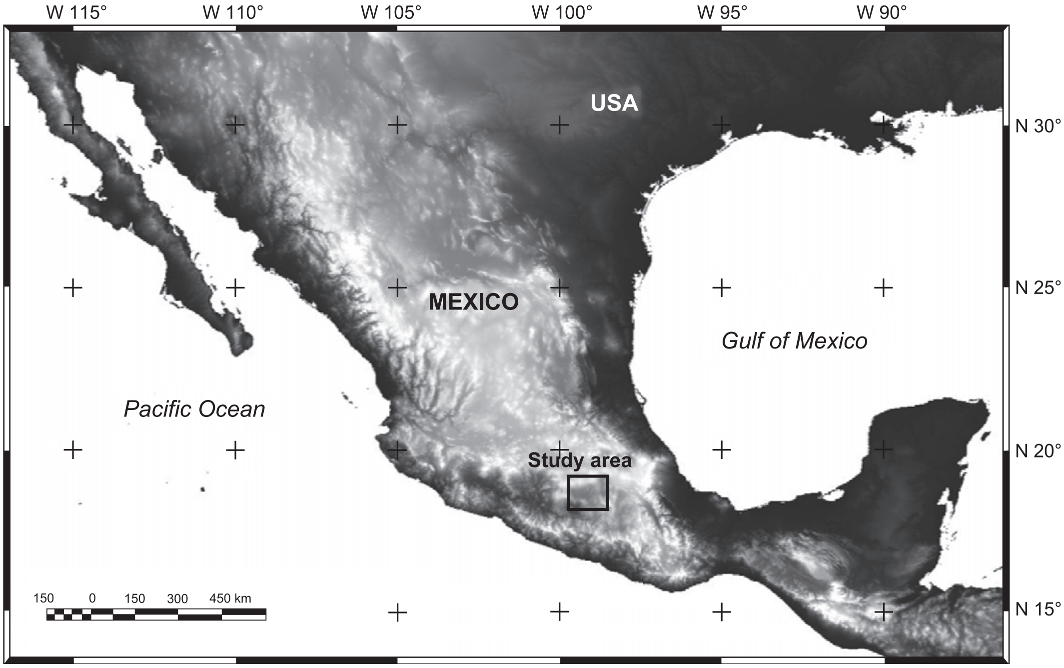

Fig. 3. Map of the study area location.

In the Morelos state, the most common relief forms are ramps and accumulative plains, which together account for more than 40.4% of the land cover. Next, in order of land cover importance is volcanic relief, mostly made up of recently accumulated volcanic rocks (16.6%) and eroded explosive rocks (15.9%).

3. Methodology

3.1. Data sources

Our approach was to overlay a traditional landform map with a DEM, both at a scale of 1:250,000. The landform map was created by interpretation of topographical and geological maps from the National Institute of Statistics, Geography and Informatics (INEGI, 1996) and defines the principal morphostructures, composition of the parent rock, type of deposition, and its corresponding morphogenetic processes. This traditional landform map was subsequently digitalized using an ESRI Arcview® interface, so that polygons were formed for each landform, then integrated into a commercial Geographical Information System (GIS). The DEM was generated based on 90-m equidistant contour lines to obtain a grid of 1115× 1119 pixels.

3.2. Parametrization

The morphometric analysis began by extracting three relief basic components: altitude, slope, and aspect from DEM. By using Ermapper® (version 6.3), a commercially image processing software, the DEM was parametrized using the algorithm proposed by Wood (1996). The algorithm calculated the topographic slope pixel by pixel and the maximum and minimum convexity values. For each pixel, the variation of these parameters was quantified with respect to neighboring pixels (in orthogonal directions), and then, based on a set of tolerance rules, each pixel was assigned to one of six possible elemental forms or morphometric classes: ridge, channel, plane, peak, pit, or pass. The resultant morphometric classes were color-coded and visualized (Fig. 2). Better visualization was achieved by draping the color-coded

Table 1
Description of landforms in Morelos state, Mexico

Landform code	Landform name	Area (%)	Description
1	Recently accumulated volcanoes	16.6	Basaltic and andesitic lava flows, fields of cinder cones, and stratovolcanoes
2	Folded sedimentary structures with gulches	11.0	Folded mountain ranges, mesozoic limestone, and shales
3	Intrusive bodies	0.6	Isolated granitic and granodioritic elevations
4	Erosion hills	2.9	Elevations and/or hills formed by denudation and erosion of mesozoic shales
5	Ramps and accumulative plains	40.4	Piedmont ramps (slopes of <12°) and structural plains of mesomorphic relief, such as plateaux, terraces, and tablelands
6	Water bodies	0.2	Lakes
7	Dissected volcanic relief	3.1	Highly dissected lahars
8	Volcanoes with eroded slopes	2.6	Mantle-like denuded basaltic lava
9	Eroded explosive volcanoes with gulches	15.9	Barely consolidated Tertiary ignimbrites and tuffs product of caldera explosion
10	Alluvial plain valleys	1.5	Found along the main rivers
11	Gullies	5.2	Ramps dissected, with steps and falls

morphometric classes over a three-dimensional (3D) map formed by the fusion of an altitudinal map with orthophotographic and Landsat images.

3.3. Calibration

Wood's algorithm offers the option of parametrizing the relief on the basis of changes in tolerance of topographic slope and convexity for assignation to morphometric classes. Slope change tolerance values are used to decide if a pixel qualifies as a peak or a pit, whereas convexity tolerance values are used to determine if a pixel has enough curvature to qualify as a channel or a ridge. Thus, the basic model was calibrated by running Wood's algorithm with slope tolerance values between 3° and 9° and convexity tolerance values from 1×10^{-4} to 10×10^{-4}. Each calculated morphometric class was compared with the relief visualized on an altitudinal 3D-DEM. The best fit occurred with slope tolerance values of 6° and convexity tolerance values of 1.0×10^{-4} (Fig. 5).

3.4. Superposition of maps

To examine the difference between the calculated forms (pixels) and those derived from traditional landform analysis (polygons), the two map types were superposed, then the number of pixels coincident between each morphometric class and each polygon were calculated with the result expressed as a percentage (Table 2).

3.5. Double ternary diagram (DTD) for characterization of landforms

A DTD was designed based on two triangles which graphically represent the proportions of areal and pointed morphometric parameters. Using the percentages obtained from the superposition of maps, the DTD was constructed to characterize the landforms based on morphometric class proportion (Fig. 6). In the first triangle, the morphometric classes related to areal parameters: ridge, channel, and plane were displayed; the second, shows the morphometric classes related to pointed parameters: peak, pass, and pit. When the two ternary diagrams are placed side by side at a slight distance, a diamond may be drawn above them, the whole creating one large equilateral triangle. The diamond field was designed to show both areal and pointed parameters. For each landform, a line was projected from its location in the areal and pointed ternary diagrams, into the upper (diamond) region. Where the lines intersect, a symbol was plotted. Thus, it is possible to visualize, within the diamond field, the composition of each landform with respect to its percentage of morphometric classes; this in turn became the basis of the landform classification scheme here proposed.

3.6. Statistical analysis

To determine if there exists significant differences between landforms with respect to their morphometric

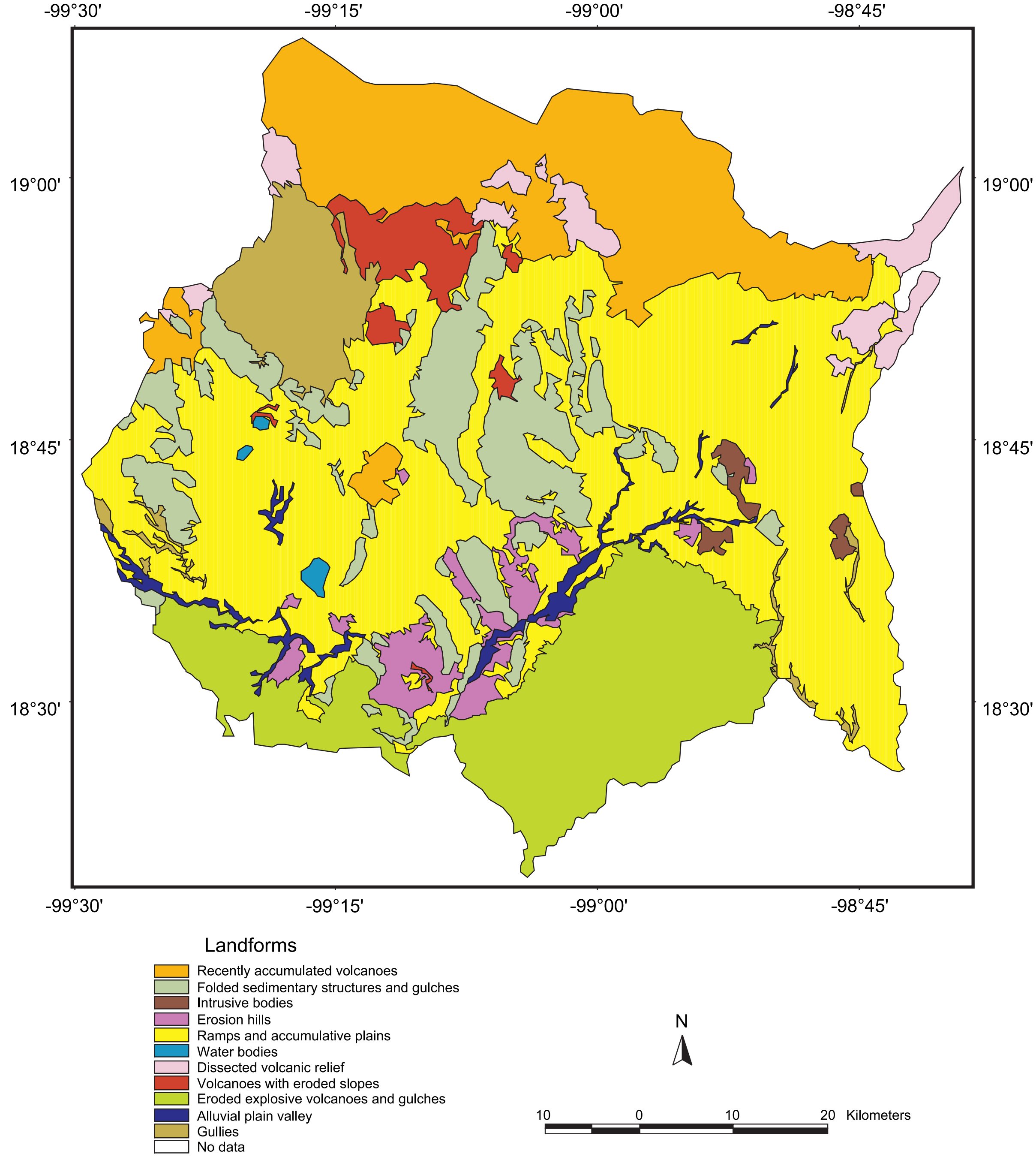

Fig. 4. Map of the landforms of Morelos State.

class composition, an analysis of similarities (ANOSIM) was conducted using the statistical program PRIMER® version 5 (Clarke, 1993).

A similarity matrix was created from a digital random sample containing 30 sites for each landform. The samples were 10×10 pixel squares equivalent to

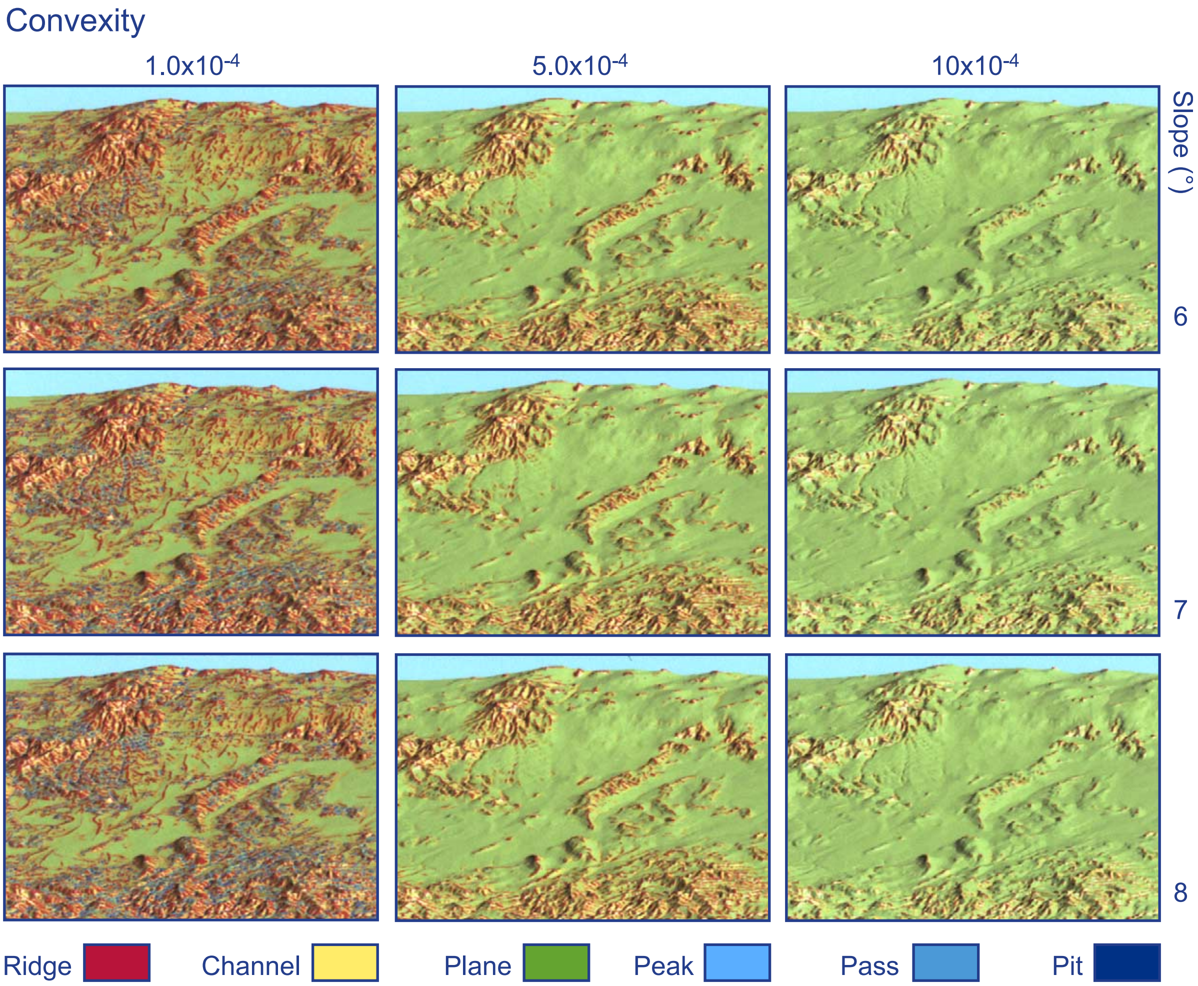

Fig. 5. Calibration of the basic model by running the algorithm with slope tolerance values between 3° and 9° and convexity tolerance values from 1.0×10^{-4} to 10×10^{-4}. The chosen solution was the top left image.

900×900 m areas. In the case of comparatively small dimension systems (i.e., water bodies, intrusive bodies, erosion hills, and alluvial plain valleys), we used 3×3 pixel squares, equivalent to 270×270 m areas. For each square, the number of pixels belonging to each morphometric class was calculated and their percentage was obtained.

ANOSIM calculates the statistic R, which is based on the difference of mean ranks between groups (Rb) and within groups (Rw): $R=(\mathrm{Rb}-\mathrm{Rw})/(N/(N-1)/4)$.

The divisor is chosen such that R will be in the interval $-1\ldots+1$; the value 0 indicates a completely random grouping. The statistical significance of observed R is assessed by permuting the grouping vector to obtain the empirical distribution of R under the null-hypothesis.

4. Results and interpretation

4.1. Composition of landforms on the basis of morphometric classes

By superposing the morphometric classes map, calculated by Wood's method (op. cit.), onto a traditional landform map, the percentages of each morphometric class per landform were obtained (Table 2). For example, the *ramps* and *accumulative*

Table 2
Percentages of each morphometric class per landform

Landform code	Landform name	Areal parameters			Pointed parameters			% Areal	% Pointed
		Ridge	Channel	Plane	Peak	Pass	Pit		
1	Recently accumulated volcanoes	18.0	18.3	60.4	1.0	1.5	0.8	96.7	3.3
2	Folded sedimentary structures with gulches	36.3	23.6	31.7	3.1	3.9	1.4	91.6	8.4
3	Intrusive bodies	40.0	25.5	26.2	2.5	4.6	1.1	91.7	8.3
4	Erosion hills	22.7	29.9	38.4	2.6	3.8	2.7	91.0	9.0
5	Ramps and accumulative plains	8.4	11.2	78.3	0.7	0.8	0.6	97.9	2.1
6	Water bodies	0.5	1.3	97.7	0.2	0.4	0.0	99.4	0.6
7	Dissected volcanic relief	38.3	33.3	22.7	1.8	2.8	1.0	94.4	5.6
8	Volcanoes with eroded slopes	7.6	9.4	81.6	0.5	0.4	0.5	98.6	1.4
9	Eroded explosive volcanoes with gulches	35.1	32.8	22.6	2.7	4.7	2.2	90.4	9.6
10	Alluvial plain valley	14.6	37.9	38.3	1.7	3.8	3.8	90.7	9.3
11	Gullies	23.1	22.2	47.7	1.9	2.3	2.9	93.0	7.0

plains landform is formed mainly by the plane morphometric class (78.3%) and to a lesser extent by the channel (11.2%) and ridge (8.4%) classes. These percentages reflect the actual dominant morphological types in that relief, which is characterized by piedmont ramps (slopes less than 12°) and plateau relief structural plains, such as highlands, terraces, and mesas.

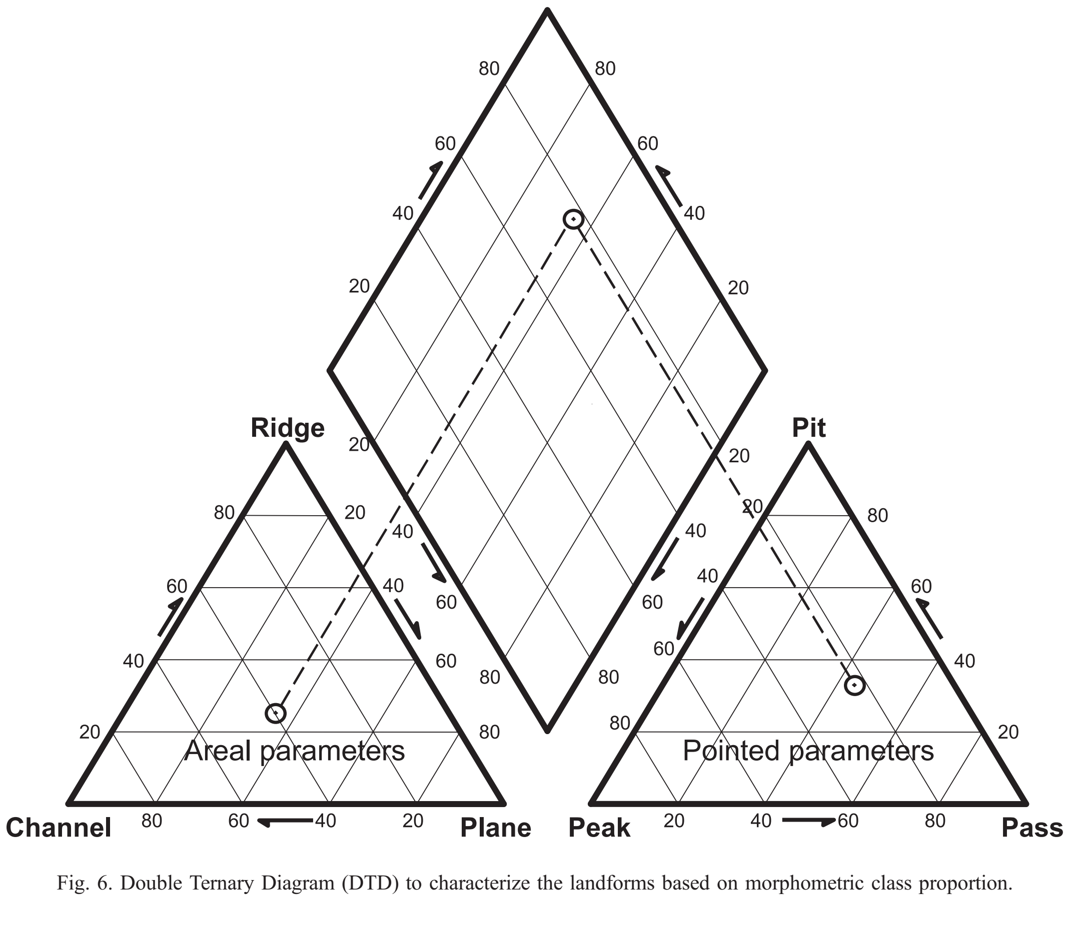

Fig. 6. Double Ternary Diagram (DTD) to characterize the landforms based on morphometric class proportion.

In contrast to the *ramps and accumulative plains* landform, the second most common landform in the study area, the *recently accumulated volcanoes* landform, is marked by reduced percentages of the morphometric class plane (60.4%), but elevated percentages of ridge (18.0%), and channel (18.3%) classes. In this case, the abundance of plain surfaces is explained by the presence of basaltic lava flows, which tend to build flat surfaces, as is visible at the study scale (1:250,000). In similar manner, the ridge and channel morphometric classes correspond to lava lobes and fronts. When we compare this last landform with *eroded explosive volcanoes with gulches*, another volcanic landform differences become apparent. This last system is formed by rhyolites, ignimbrites, and tuffs; albeit significantly altered and strongly dissected, these characteristics substantially modify the percentages of the morphometric classes, such that in this system, there is a more equitable distribution of the three common morphometric classes, plane (22.6%), ridge (35.1%), and channel (32.8%).

One outstanding feature is that the areal parameters of landforms represent more than 95% of the composition of landforms, as opposed to less than 5% for pointed parameters. Notwithstanding, the pointed parameters are of special interest, and as we shall see further on, this can be a key item for differentiating between landforms having similar proportions of areal parameters. For example, in

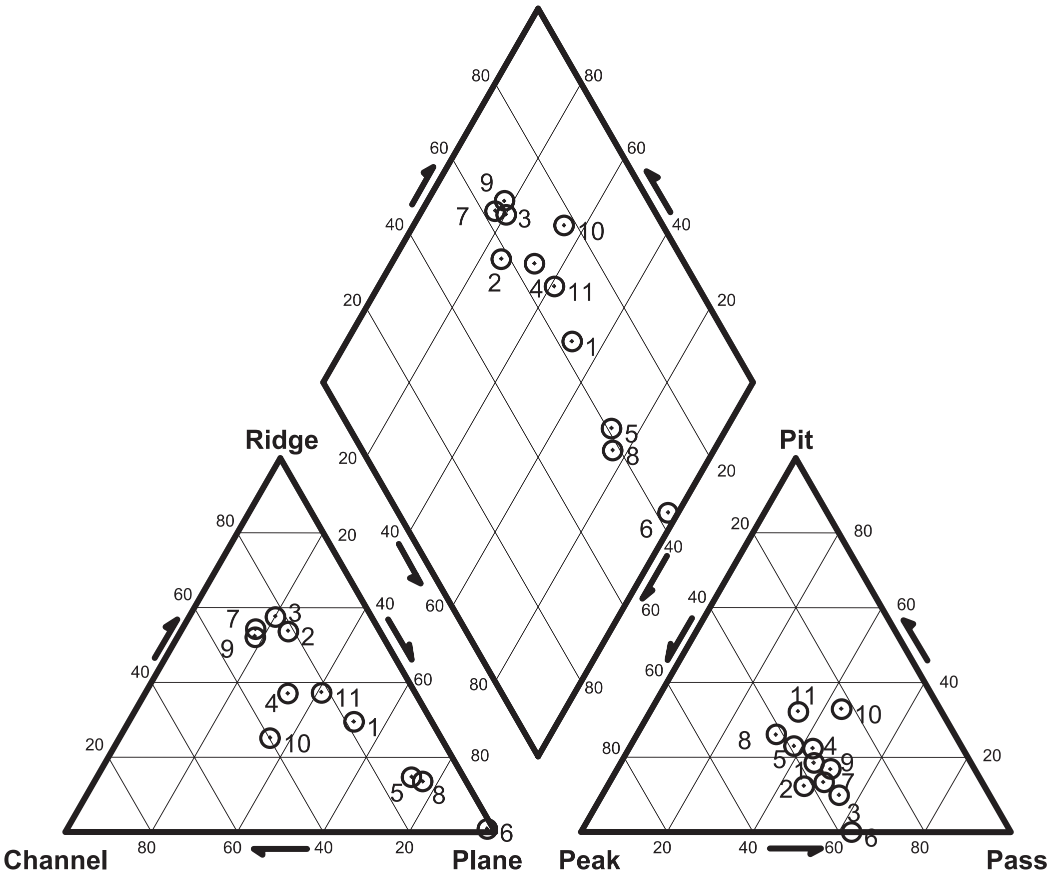

Fig. 7. Double ternary diagram (DTD) characterization of landforms calculated from the geomorphologic map. 1: Recently accumulated volcanoes; 2: folded sedimentary structures with gulches; 3: intrusive bodies; 4: erosion hills; 5: ramps and accumulative plains; 6: water bodies; 7: dissected volcanic relief; 8: volcanoes with eroded slopes; 9: eroded explosive volcanoes with gulches; 10: alluvial plain valleys; and 11: gullies.

volcanic applications, the pointed parameters are useful for distinguishing between a recent uneroded volcanic cinder cone and that of an older eroded one. The first structure will exhibit comparatively high values for the pit morphometric class (a pointed parameter) because of the presence of a crater on the summit, whereas the second will have peak as the predominant element type because erosion tends to destroy the crater leaving a hill on its place.

4.2. Double ternary diagram for characterization and classification of landforms

When we charted the landforms defined for the study area onto our ternary diagrams, we observed that they fall into localized regions of the triangles; this means that among the morphometric variables employed, there are elements that discriminate between classes. For example, in the DTD presented in Fig. 7, the morphometric classes that represent landforms dominated by planar surfaces, such as water bodies, *ramps and accumulative plains*, and *volcanoes with eroded slopes*, are clustered near the diagram's vertex named plane. Similarly, the morphometric classes representing landforms, such as *folded sedimentary structures* and gulches, *intrusive bodies*, and *dissected volcanic relief*, are located near the named vertex ridge.

4.3. Statistical analysis

To quantify the similarity between landforms, an ANOSIM statistical analysis or similarity analysis was conducted. Using the 11 landforms, 55 commutations were computed. Of these, 53 showed statistically significant differences as denoted by the positive value of the R statistic (R global=0.399, P<0.02; Table 3). The results of this analysis demonstrate that it is possible to discriminate between landforms on the basis of their morphometric composition.

Only in two cases, the pairwise test did not discriminate. The first case was observed between the pair *ramps and accumulative plains* and *water bodies* (R=−0.017, P>0.05), in the second, between *ramps and accumulative plain* and *volcanoes with eroded slopes* (R=0.033, P>0.05). The first result is explained by the fact that the algorithm used for calculating the morphometric classes has a 6° topographic slope tolerance, which means that water bodies and ramps will fall within this same slope range and hence we cannot discriminate between them. In the second, the similarity between the pair *ramps and accumulative plains* and *volcanoes with eroded slopes* is explained by the fact that this volcanic formation is the result of basalt flows which deposit material on ramps (covering them) in such a manner as to conserve their underlying ramp morphology.

It is evident from both the ANOSIM similarity and DTD analyses that good discrimination between landforms was achieved by means of the constituent areal and pointed computed parameters; this method may be useful for solving problems associated with mapping and advanced geomorphometric modeling.

Table 3
Pairwise tests of ANOSIM

Landforms[a]	R statistic	Significance level (%)	Landforms	R statistic	Significance level (%)
1,2	0.275	0	4, 5	0.546	0
1,3	0.528	0	4,6	0.95	0
1,4	0.31	0	4,7	0.209	0
1,5	0.123	0.4	4,8	0.734	0
1,6	0.386	0	4,9	0.05	2.7
1,7	0.477	0	4,10	0.45	0
1,8	0.138	0.2	4,11	0.315	0
1,9	0.503	0	5,6[b]	−0.017	56.2
1,10	0.45	0	5,7	0.705	0
1,11	0.078	2.6	5,8[b]	0.033	8.2
2,3	0.489	0	5,9	0.697	0
2,4	0.12	0.1	5,10	0.513	0
2,5	0.544	0	5,11	0.185	0.2
2,6	0.894	0	6,7	1	0
2,7	0.14	0	6,8	0.182	0.3
2,8	0.718	0	6,9	1	0
2,9	0.21	0	6,10	0.699	0
2,10	0.605	0	6,11	0.379	0
2,11	0.337	0	7,8	0.901	0
3,4	0.536	0	7,9	0.201	0
3,5	0.661	0	7,10	0.598	0
3,6	0.832	0	7,11	0.417	0
3,7	0.49	0	8,9	0.898	0
3,8	0.79	0	8,10	0.653	0
3,9	0.634	0	8,11	0.28	0
3,10	0.308	0	9,10	0.659	0
3,11	0.262	0	9,11	0.528	0
			10,11	0.148	0.5

[a] For landform code see Table 1.

[b] Landforms exhibiting no significant differences (p>0.05).

5. Discussion

5.1. DTD for landform classification

In the foregoing paragraphs, we demonstrate that a landform can be graphically and quantitatively represented on the basis of the proportions of morphometric classes which comprise it. This, in turn, raises the question whether there exists a combination of morphometric classes which could characterize and possibly be used to classify each landform.

Each landform within the DTD exhibits a characteristic location. The two triangles that describe entirely different properties, one areal and the other pointed, makes the DTD a useful tool for landform classification systems. As demonstrated by the ANOSIM statistical analysis, the composition of each landform is different, and when DTD are drawn, those landforms which share characteristics cluster in similar locations.

In some cases, the evident similarities in the DTDs reflect homologous formation processes, but not always, they may also be the product of superficial resemblance and hence be analogous.

The potential use of DTD for landform classification is illustrated in Fig. 8. Several digital clips in diverse geomorphologic settings were obtained in the study area, then their respective DTDs were obtained. Various size clips (windows) were tested depending on the structure size. For example, in large *recent accumulative volcanic relief*, the windows size was 10×10 km, whereas in *gullies* zones, the windows size was 2×2 km. In the first (Fig. 8A), it can be observed that in spite of the abrupt topography of this zone, the plotted points into the DTD showed scarce dispersion. Similar results were obtained in the other geomorphologic environments (Fig. 8B, C, D, and F), except for alluvial plains (Fig. 8E) which will be discussed further on.

Mean values of digital clips described previously were plotted into a DTD (Fig. 9). In the left triangle, landforms composed in large proportion by flat surfaces, such as *bodies of water, ramps and accumulative plains*, among others, are located near the plane vertex. It is important to note that the morphometric class plane corresponds to a smooth surface independent of its inclination; this explains why the composition, for instance, of *volcanoes with eroded slopes* and *recently accumulated volcanoes* landforms, which have a fundamentally conical shape, evince a relatively high proportion of the plane morphometric class. In contrast, the other volcano landform elements, i.e., *eroded explosive volcanoes with gulches* and *dissected volcanic relief* are characterized by ridges, hence having a lower planar composition and are located near the ridge vertex.

5.2. DTD for geomorphologic processes

Morphographic landform information is essential for the modeling and understanding of many physical processes (Blaschke and Strobl, 2003). In a certain sense, this study is a refinement of Pike's (1988, 2000), Pike et al. (1989), who described landforms by means of geometric signatures. Working from the geomorphometric principle that there exists a close relationship between geomorphologic processes and characteristic morphometric parameters of landforms so formed, the morphometric units defined in our research not only describe landforms but should also provide clues to bear a close relationship with the predominant geomorphologic processes related to their formation. In this manner, the position of each landform within the DTD allows us to distinguish certain geomorphologic processes. For example, in the morphometric analysis of the *alluvial plain valley* landform, the pointed components, which appear in the right triangle (Fig. 8E) exhibit a conspicuous distribution along the triangle side defined by the peak and pit vertices. In this triangle, we find diverse proportions of peaks, pits, and passes, which coincide with the physical presence of promontories (explained by peaks) and terraces (explained by pits and passes) along the river bed. The presence of promontories and terraces in rivers indicates that these rivers are in distinct geodynamic phases or that they are made up of different substrates (not discussed here). In either case, our morphometric characterization reveals the presence of certain geomorphologic processes.

Based on principles of analytical geometry, the distance of each landform to the triangle vertices provides information about the predominant geomorphometric class or combinations thereof. General geomorphologic processes, such as planar denudation and lineal denudation, will produce distinctive forms

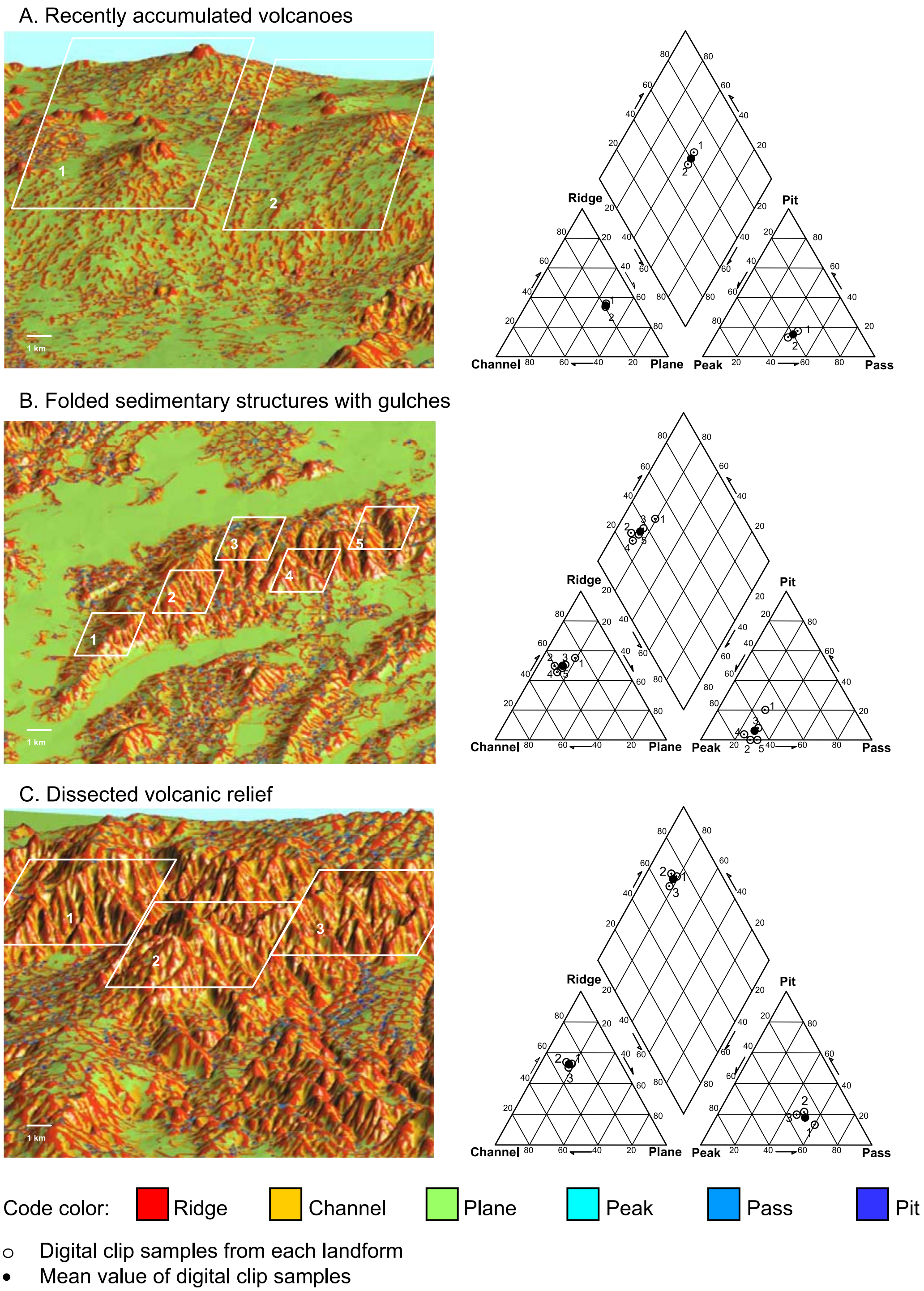

Fig. 8. Three-dimensional representation of certain landforms and their respective DTD. Left side shows color-coded morphometric classes. The right side shows DTD of each landform.

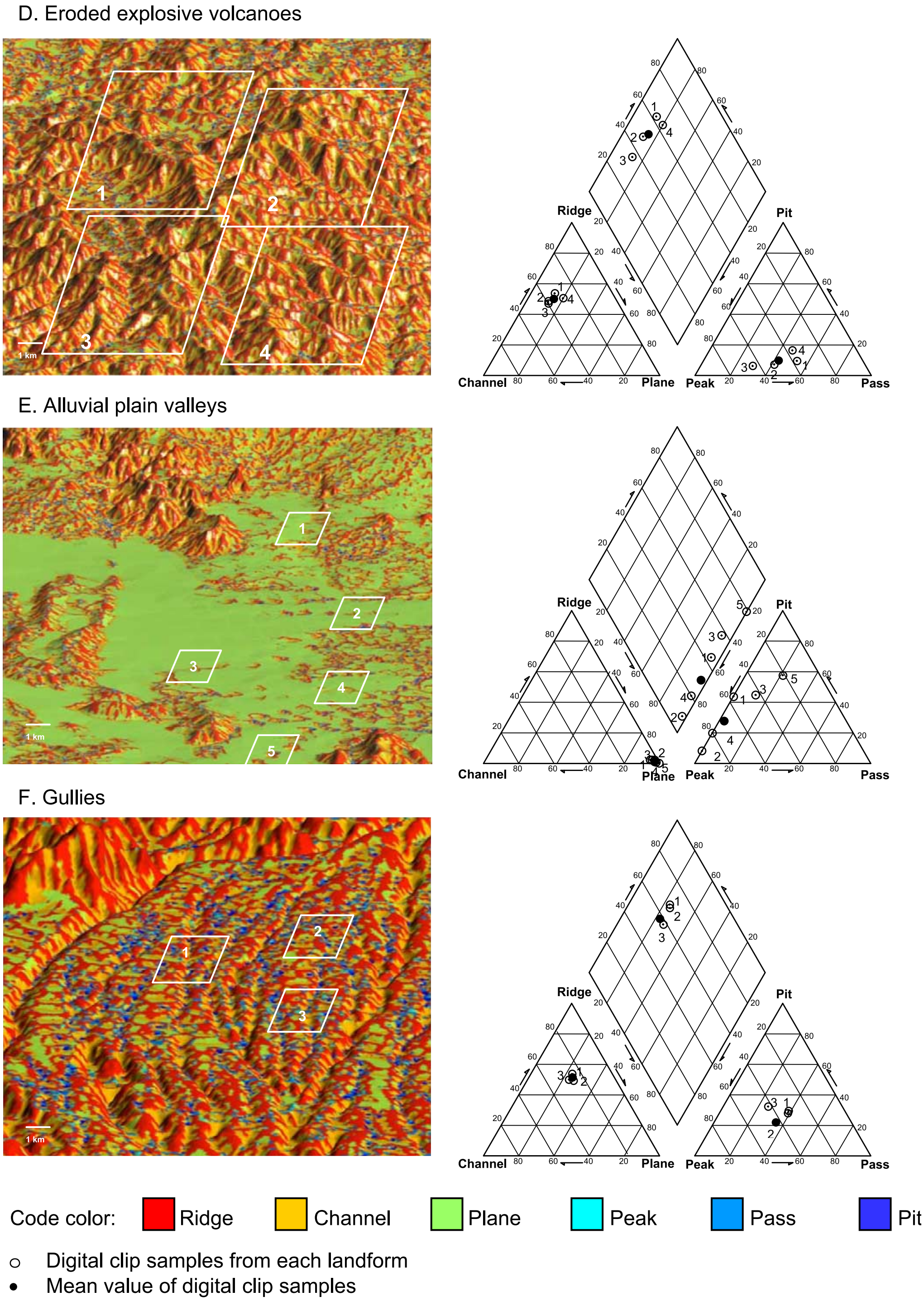

Fig. 8 (*continued*).

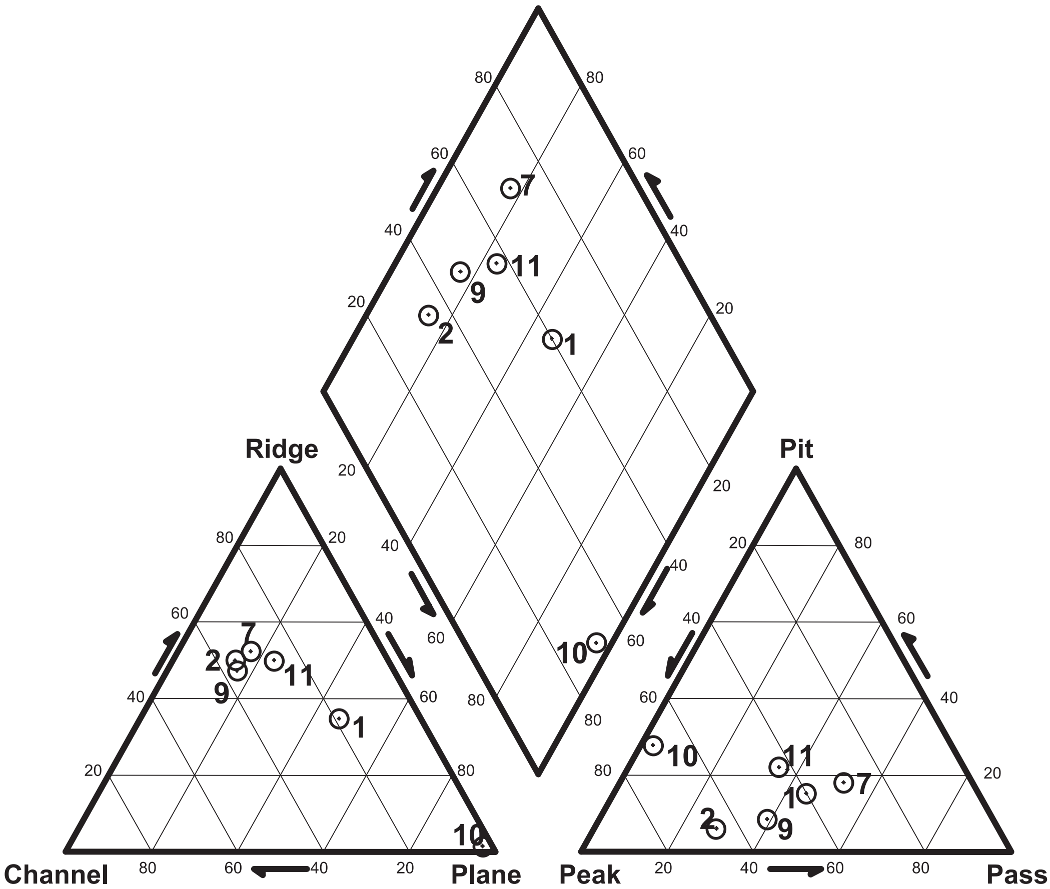

Fig. 9. DTD of mean value of digital clips samples calculated from Fig. 8. 1: Recently accumulated volcanoes; 2: folded sedimentary structures with gulches; 7: dissected volcanic relief; 9: eroded explosive volcanoes with gulches; 10: alluvial plain valleys; and 11: gullies.

which will be evident in the proportions of the resultant morphometric classes on the DTD.

Besides allowing us to locate any landform in DTD, the areal and pointed percentages give us a better idea of relief composition; this may be additionally used in designing a numerical index of areal versus pointed properties, which should be useful for characterizing and classifying landforms.

6. Conclusions

Generation of relief models from simple elements, such as the morphometric classes here proposed, can lead to the description of continuous surfaces making up landforms as composed of ridges, channels, planes, peaks, pits, and passes. These morphometric terms coincide with actual geomorphologic entities, and DTD is useful for studying geomorphological processes wherein areal and point values and properties have expressions which are topographically quantifiable. Automation of the characterization processes and classification of relief attributes has considerable potential use within geomorphology.

7. Future work

The parametrization of relief in the manner here described has the advantage of being naturally conducive to the relief's vectorial expression (i.e., magnitude and direction). It is possible to classify large surfaces using this method; the magnitude and orientation of mountain chains can be calculated from vectorization of the ridge and channel morphometric classes, and thus the geometry of the mountain parameters may be figured.

Our aim is to obtain textures and fabrics of the earth's surface based on vectorial analysis of the morphometric classes derived from a DEM. It is also possible to envision the conversion of morphometric classes into vectors and image objects, something which may have applicability to other classification methods, such as fuzzy logic (Blaschke and Dragut, 2003). One interesting aspect of fuzzy logic classification is that it allows integration of a wide spectrum of different characteristics, such as spectral values, form, and texture. In this context, it is worth mentioning that multiresolution segmentation and fuzzy knowledge-based classification methods are today on research (Argialas and Tzotsos, 2003).

Acknowledgements

We would like to express our gratitude to the National Investigation and Development Academy (ANIDE) for its technical and financial support, as well as the Interdisciplinary Laboratory of Geographic Information Systems, Sierra de Huautla Environmental Education and Research Center (CEAMISH) at the Autonomous University of Morelos State (UAEM) for the data set of Morelos State Landuse Planning. We are also very grateful to Dr. Néstor Mariano for the consultancy in the statistical analysis and also thank the Biological Sciences Faculty of the UAEM for the grant awarded for doctorate studies. Last, but not least, we express our gratitude to the SEMARNAT-2002-C01-0794 project for their financial support.

References

Adediran, A.O., Parcharidis, I., Poscolieri, M., Pavlopoulos, K., 2004. Computer-assisted discrimination of morphological units on north-central Crete (Greece) by applying multivariate statistics to local relief gradients. Geomorphology 58, 357–370.

Aguilar, S., 1989. Ecology del Estado de Morelos. Un enfoque geográfico, 2nd ed. Praxis, México, DF. 469 pp.

Argialas, D., Tzotsos, A., 2003. Geomorphological feature extraction from a digital elevation model through fuzzy knowledge-based classification. In: Buchman (Ed.), Proc SPIE 4886, Remote Sensing for Environmental Monitoring, GIS Applications, and Geology, vol. II, pp. 516–527.

Blaschke, T., Dragut, L., 2003. Integration of GIS and object-based image analysis to model and visualize landscapes. ISPRS Commission IV Joint Workshop Challenges in Geospatial Analysis, Integration and Visualization, vol. II, Stuttgart, pp. 18–23.

Blaschke, T., Strobl, J., 2003. Defining landscape units through integrated morphometric characteristics. In: Buhmann, E., Ervin, S. (Eds.), Landscape Modeling: Digital Techniques for Landscape Architecture. Wichmann-Verlag, Heidelberg, pp. 104–113.

Clarke, K.R., 1993. Non-parametric multivariate analysis of changes in community structure. Aust. J. Ecol. 18, 117–143.

Dehn, M., Gärtner, H., Dikau, R., 2001. Principles of semantic modeling of landform structures. Comput. Geosci. 27 (8), 1005–1010.

Dikau, R., 1989. The application of a digital relief model to landform analysis in geomorphology. In: Raper, J. (Ed.), Three Dimensional Applications in Geographical Information Systems. Taylor and Francis, London, pp. 51–77.

Dikau, R., Brabb, E.E., Mark, R.K., Pike, R.J., 1995. Morphometric landform analysis of New Mexico. Z. Geomorphol., Suppl. Bd. 101, 109–126.

Etzelmüller, B., Sulebak, J.R., 2000. Developments in the use of digital elevation models in periglacial geomorphology and glaciology. Physische Geographie, vol. 41. Geographisches Institute der Universität Zürich, pp. 35–58.

Evans, I.S., 1972. General geomorphology, derivatives of altitude and descriptive statistics. In: Chorley, R.J. (Ed.), Spatial Analysis in Geomorphology. Harper and Row, NY, pp. 17–90.

Felicísimo, A.M., 1999. Modelos Digitales del Terreno. Curso Introductorio. http://www.etsimo.uniovi.es/~feli/.

INEGI (National Institute of Statistics, Geography and informatics)., 1996. Geoforms of Altimetry (GEMA) of the National Territory. México.

Moore, I.D., Nieber, J.L., 1989. Landscape assessment of soil erosion and non-point source pollution. J. Minn. Acad. Sci. 55, 18–24.

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A., 1993a. Soil attribute prediction using terrain analysis. Soil Sci. Soc. Am. 57, 443–452.

Moore, I.D., Turner, A.K., Wilson, J.P., Jenson, S.K., Band, L.E., 1993b. GIS and land–surface–subsurface process modeling. In: Goodchild, M.F., Parks, B.O., Steyaert, L.T. (Eds.), Environmental Modeling with GIS. Oxford University Press, New York, pp. 196–230.

Morán-Zenteno, D., 1990. Geology of the Mexican Republic. National Institute of Statistics, Geography and Computing, Mexico, DF, pp. 88.

Morán-Zenteno, D., Alba-Aldave, L., Solé-Viñas, J., Gonzáles Torres, E., 2002. The Tilzapotla-Buenavista Caldera: a tectonic-magmatic feature associated with Eocene–Oligocene Strike–slip tectonics in Southern México. Cordilleran Section, 98th Annual Meeting. The Geological Society of America, Boulder, CO.

Pike, R.J., 1988. The geometric signature: quantifying landslide-terrain types from digital elevation models. Math. Geol. 20 (5), 491–512.

Pike, R.J., 2000. Geomorphometry: diversity in quantitative surface analysis. Prog. Phys. Geogr. 24 (1), 1–20.

Pike, R.J., 2002. A Bibliography of Terrain Modeling (Geomorphometry), the Quantitative Representation of Topography-Supplement 4.0. Open-File Report 02-465, U.S. Geological Survey.

Pike, R.J., Dikau, R., 1995. Advances in geomorphometry. Z. Geomorphol., N.F. Suppl. Bd. 101, 238.

Pike, R.J., Acevedo, W., Card, D.H., 1989. Topographic grain automated from digital elevation models. Proceedings 9th International Symposium on Computer Assisted Cartography, Baltimore, April 2–7, 1989. ASPRS/ACSM, pp. 128–137.

SEDESOL (Social Development Ministry), 2000. Land Arrangement Program of the Morelos State, Phase I. Secretaria de Desarrollo Urbano y Vivienda del Gobierno del Estado de Morelos, Vol. II. (Característica diagnóstica) subsistema natural, México, pp. 1–40.

Sulebak, J.R., Etzelmüller, B., Sollid, J.L., 1997. Landscape regionalization by automatic classification of landform elements. Nor. Geogr. Tidsskr. 51 (1), 35–45.

Wood, J.D., 1996. The geomorphologic characterization of digital elevation models. PhD Dissertation, University of Leicester, UK.