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Morphological analysis of Nevado de Toluca volcano (Mexico): new insights into the structure and evolution of an andesitic to dacitic stratovolcano

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Abstract

We present a morphological analysis of Nevado de Toluca volcano located 80 km WSW of Mexico City based on digital elevation model study, where slope and aspect maps have been generated and analysed. Aerial photograph and satellite image observations improve the morphological analysis. The synoptic view which is offered by this analysis allowed for recognition and localization of the main volcanic and tectonic features of the area. On the basis of digital elevation model value distribution and surface textures, five morphological domains were defined. The most interesting domain, south of the crater, reflects the occurrence of an ancient complex volcano distinct from the adjacent areas. Interaction between the volcanic and volcano–tectonic evolution and the basement produced the other domains. Single volcanic edifices, like lava domes and scoria cones, and eruptive fractures were recognized. Finally, flank collapse scarps opened to the east and to the north were identified and four relevant morphostructural lineaments and their possible role in the Nevado de Toluca geological and structural evolution are discussed.

Keywords: Nevado de Toluca; Mexico; Volcanic geomorphology; DEM analysis; Fault systems

1. Introduction

Morphological analysis of volcanic areas is an important tool when used as an approach to the characterization of volcanic and tectonic structures (Favalli et al., 1999). This is particularly true in recently evolved volcanic regions, where exogenous processes have not had time to deeply dissect and modify the original landform. In this case, the morphologies and their spatial distribution represent the volcano–tectonics relationship, the nature of erupted products and the evolution of volcanic edifices (Aldighieri et al., 1998; Favalli et al., 1999). The information collected during a morphological analysis can be divided into linear data and areal data. The first allows identification of structural and volcano-structural features; the second permits recognition of morphological homogeneous zones,

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which can be directly related to different volcanic edifices, structural domains and evolutionary stages. Therefore, this information provides an opportunity to constrain the volcanological and structural development of recent volcanic areas.

In this paper, we present a morphological analysis of Nevado de Toluca volcano, the fourth highest peak in Mexico(4680 m a.s.l.) located 23 km SW of Toluca City and 80 km WSW of Mexico City; it is an andesitic to dacitic stratovolcano of late Pliocene–Holocene age (Cantagrel et al., 1981; García-Palomo et al., 2002). The analysis of topographic features enables Nevado de Toluca to be placed in its geological and structural setting. Moreover, the results of this work can be used for successive volcanological, stratigraphical and structural investigations of a volcanic area that poses potential hazards to more than 25 million inhabitants, including large cities such as Toluca and Mexico City.

2. Geological framework

Nevado de Toluca volcano is located at the boundary between the central and eastern sectors of the Trans-Mexican Volcanic Belt (TMVB; Fig. 1a) within the Guerrero Block, bounded by the Chapala–Tula fault system to the north and by the Oaxaca–Chapala fault system to the south (Pasquaré et al., 1987; Johnson and Harrison, 1990; García-Palomo et al., 2000, 2002).

Nevado de Toluca was built upon the intersection of three fault systems active at least since the late Miocene (García-Palomo et al., 1996, 2000). These fault systems are (Fig. 1b):

- Taxco–Querétaro fault system (TQFS), striking NNW–SSE, is a regional system reaching 250 km in length separating the central and eastern sectors of the TMVB. The TQFS consists of 10° and 340° of azimuth striking fault planes. Numerous volcanic structures are aligned along the TQFS, including San Antonio and Nevado de Toluca volcanoes. García-Palomo et al. (2000) documented normal and right-lateral episodes of activity of this fault system during the Cenozoic.
- San Antonio fault system (SAFS), striking NE–SW and reaching 60 km in length, is observed between the San Antonio and Nevado de Toluca volcanoes and is part of the Tenochtitlán Shear Zone (De Cserna et al., 1988). The SAFS consists of 30° of azimuth striking fault planes. This system has undergone a phase of movement with left lateral component and two successive extensional reactivations related to the youngest tectonic episode that affects the TMVB (García-Palomo et al., 2000).
- Tenango fault system (TFS), striking E–W, is part of the Chapala–Tula regional system, with a total length of 450 km from Chapala Lake to the northern part of Mexico City. The TFS consists mainly of 90° of azimuth striking fault planes; García-Palomo et al. (2000) suggest that some sets of faults striking from 320° to 60° of azimuth are associated with the TFS. This fault system has undergone two stages of movement. The first event was accommodated by strike–slip faults. An extensional phase, occurred during the Pleistocene–Holocene, follows the first event with the reactivation of older fractures as normal faults (García-Palomo et al., 2000).

The studied area has a complex volcanic history; from Miocene to present, numerous volcanic structures were built (Bloomfield and Valastro, 1974; Macías et al., 1997; García-Palomo et al., 2000, 2002). These are the San Antonio volcano (Miocene–Pliocene), a wide monogenetic dome field (Pliocene–Pleistocene), the Nevado de Toluca volcano (Pliocene–Holocene) and a recent monogenetic cones field named Chichinautzin (38,000–8000 years ago).

The geology of Nevado de Toluca is characterized predominantly by domes, short viscous lava flows and voluminous pyroclastic and epiclastic deposits, resting upon a complex volcano–sedimentary basement, of Jurassic to Late Miocene in age, affected by greenschist facies metamorphism (García-Palomo et al., 2000, 2002). The oldest Nevado de Toluca volcanic products were mainly derived by extrusions of viscous andesitic and, subordinately, dacitic lava (Bellotti et al., 2003). According to Cantagrel et al. (1981), this activity started 1.6–1.5 Ma ago and built the ancient sector of the volcano named "Paleonevado". Other authors suggest that the construction of the ancient part of Nevado de Toluca started earlier: a sample, recently collected on the southern flank of Nevado de Toluca, yielded a K/Ar age of 2.6 Ma and is the oldest dated product of the volcano (De Beni, 2001; Norini, 2001;

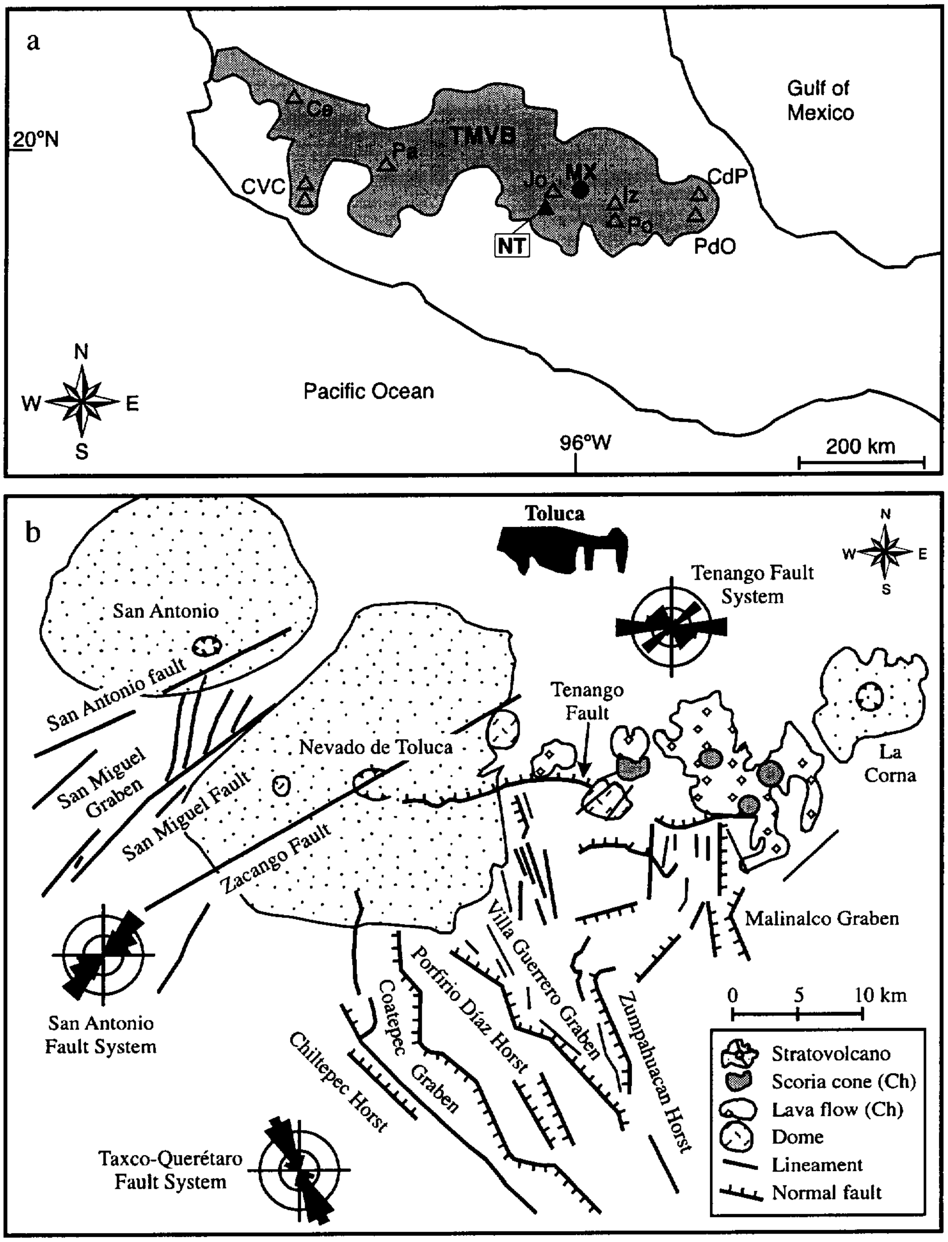

Fig. 1. (a) Sketch map of the studied area showing its location within the Trans-Mexican Volcanic Belt. CVC: Colima Volcanic Complex, Ce: Ceboruco, Pa: Patamban, NT: Nevado de Toluca, Jo: Joeotitlan, Iz: Izlaccihuatl, Po: Popoeatepetl, PdO: Rico de Orizaba, CdP: Cofre de Perote. (b) Schematic map of Nevado de Toluca area showing the principal volcanic and tectonic structures. Ch: Chichinautzin volcanic field (García-Palomo et al., 2000).

García-Palomo et al., 2002). The growth of "Paleonevado" (Cantagrel et al., 1981) ended 1.2 Ma ago and was followed by a long period of quiescence dominated by alteration and erosion. This exogenous activity, which included lateral collapse, was characterized by deep incisions of "Paleonevado" and extensive distri-

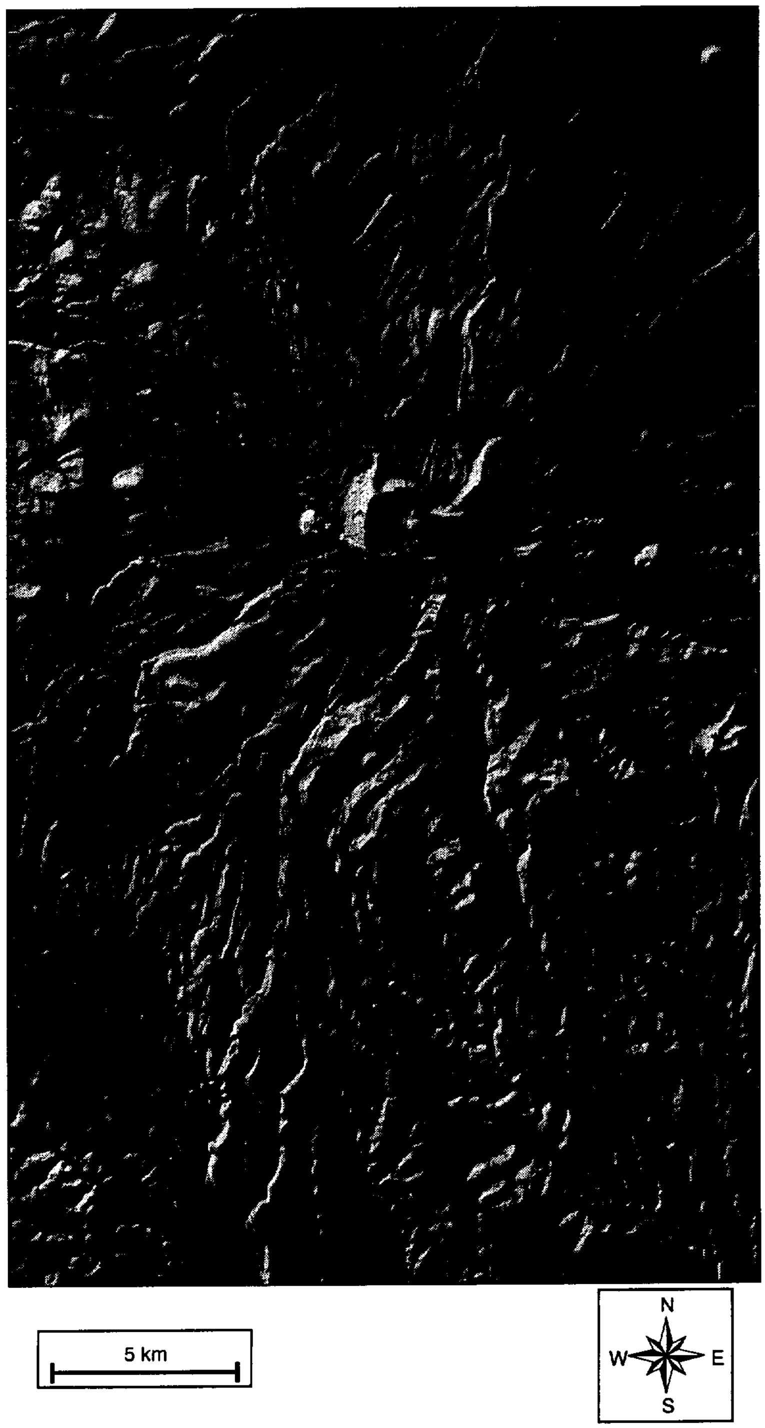

Fig. 2. Shaded image of the Nevado de Toluca digital elevation model. The artificial illumination is from the northwest and has an elevation of 45°.

bution, predominantly to the south, of epiclastic deposits (Cantagrel et al., 1981; García-Palomo et al., 2002; Capra et al., 2002). The quiescence of volcanic activity ended 0.1 Ma ago with the growth of the modern Nevado de Toluca cone, made of dacitic domes and mantled by complex sequences of pyroclastic deposits. These sequences are composed of pyroclastic flows, surge and fall deposits and, subordinately, debris avalanches and debri-flow deposits (Bloomfield and Valastro, 1974, 1977; Bloomfield, 1975; Cantagrel et al., 1981; Macías et al., 1997; Capra and Macías, 2000).

3. Morphological analysis of Nevado de Toluca volcano

3.1. Methodology

The Nevado de Toluca morphology has been studied by analysing black and white aerial photographs (1:75,000 scale), a Landsat satellite image (band 7) and a digital elevation model (DEM). The DEM of Nevado de Toluca volcano, a continuous raster layer in which data values represent elevation, has been obtained with GIS software by interpolating a set of contour lines that describe topography of the studied area. This set has been derived by digitising contour lines, every 20 m, of the 1:50,000 topographic map produced by Instituto Nacional de Estadística Geográfica y Informática (INEGI). The DEM has been obtained with a pixel size of 20 m and has an area of 20 × 35 km. A surface shadowing provides digital perspective views, where relief is more or less outlined depending on the sunlight and observer positions (Figs. 2–4). Furthermore, the DEM has been used to calculate slope and aspect maps (Fig. 5).

The aerial photographs, satellite image and DEM analysis permit the recognition of areal and linear morphology resulting from the complex interplay

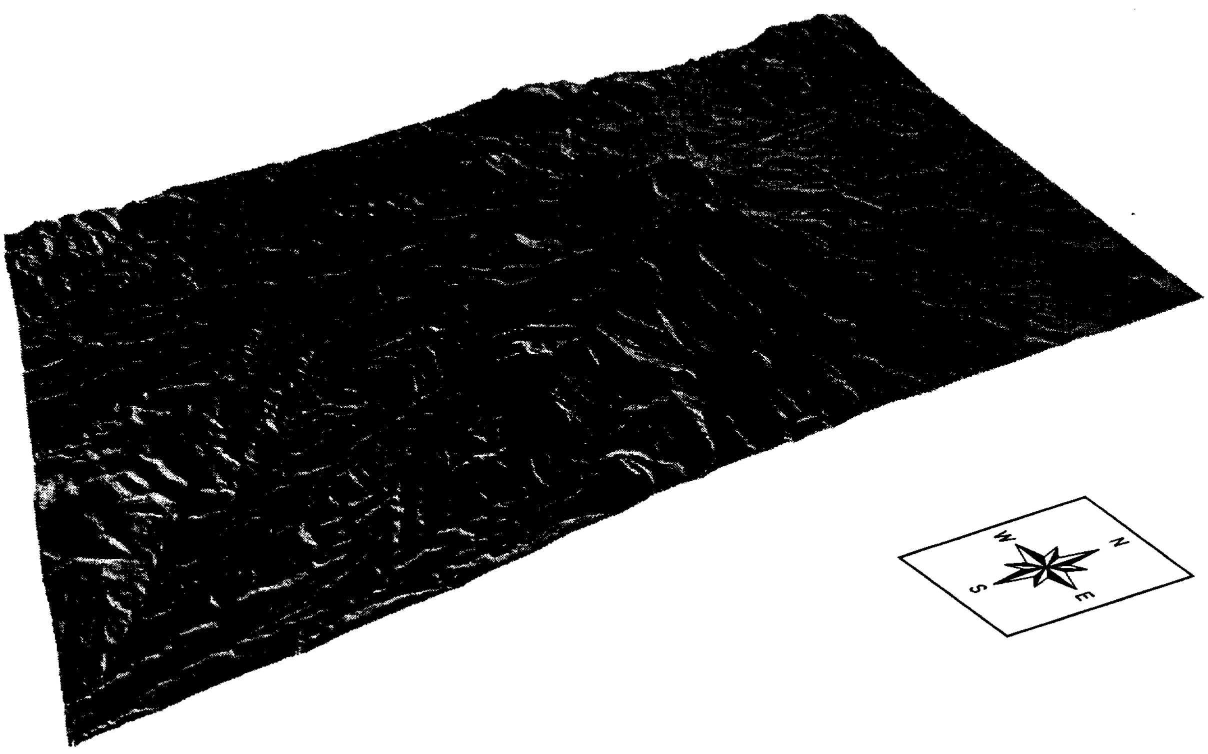

Fig. 3. Perspective view of Nevado de Toluca from ESE. Sunlight from northwest.

Fig. 4. Perspective view of Nevado de Toluca from south. Sunlight from northwest.

between regional and volcano–tectonic regimes, the rheology of erupted materials and the effect of exogenous processes.

Particularly, linear features were identified from aerial photographs, satellite images and DEM-derived shaded images. Furthermore, slope and aspect maps reveal sharp slope and aspect changes that in most cases are related with geological lineaments (Fig. 5).

Areal morphologies were delimited principally observing the slope-value distributions and the different textures shown on the slope and aspect maps. An accurate classification of these maps has been obtained analysing frequency and cumulative value distribution (Fig. 5). Moreover, aerial photographs allow domain characterization and the individuation of volcanic and volcano–tectonic structures as explained in the next section.

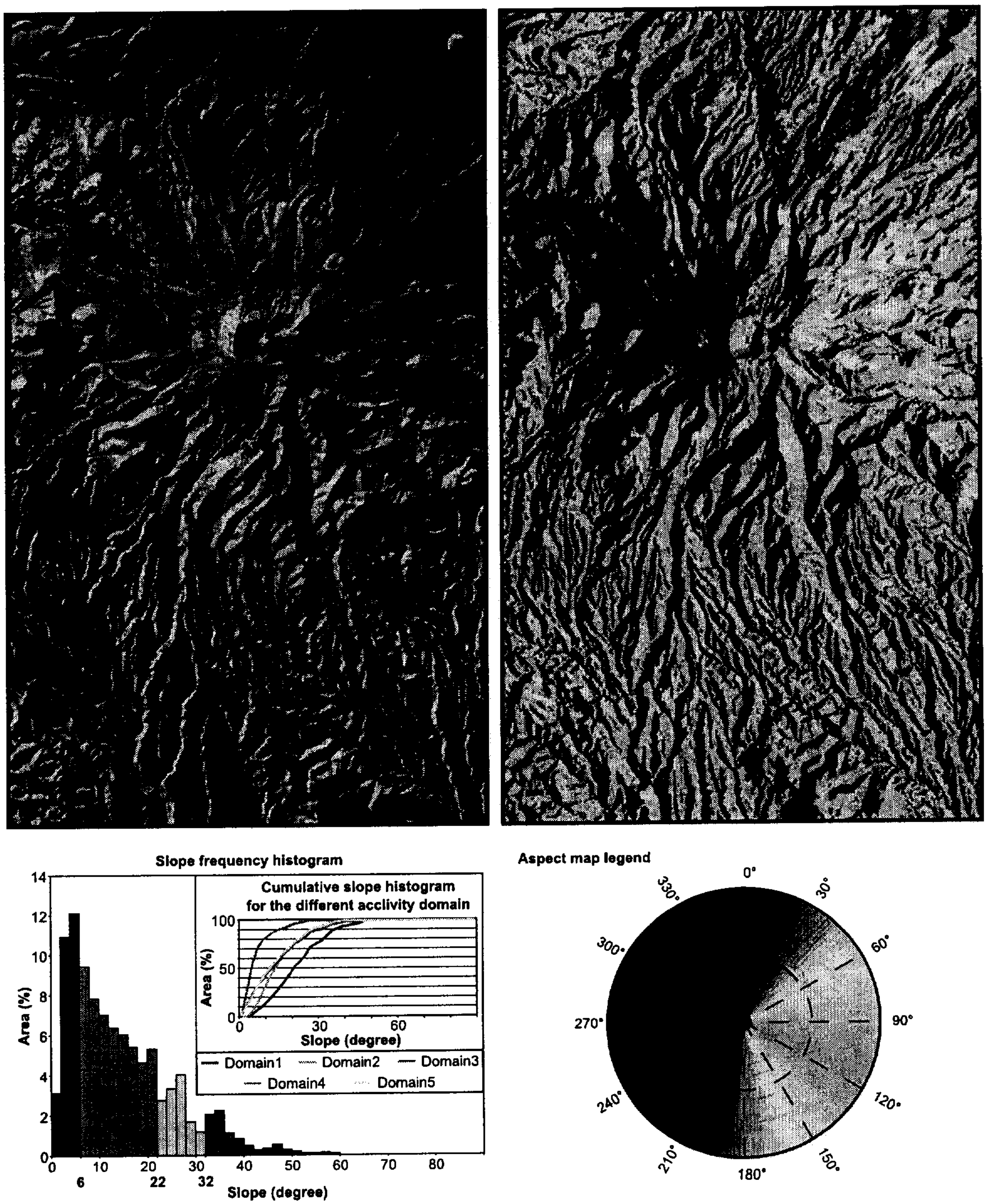

Fig. 5. Slope (left) and aspect (right) maps of Nevado de Toluca volcano. Different colours identify slope and aspect classes, respectively. Slope map is superimposed on a shaded image (illumination from northwest). Slope map is accompanied by a value distribution graph. Scale bar and north arrow are the same as in Fig. 6.

3.2. Morphological features

Relevant morphological units and lineaments are displayed in the shaded images and the slope and aspect distribution maps, giving important insights into the volcanic system. We describe below the main results emerging from the analysis of the slope and aspect distribution maps and the more evident topographic features identified by the shaded images and perspective views.

3.2.1. Areal morphology

On the basis of slope and aspect distribution maps, shaded image and perspective views (Figs. 2–5), Nevado de Toluca volcano can be subdivided into five domains (Fig. 6a). Every domain is characterized by different slope and aspect distribution, aside from the surface texture.

- Domain 1 is localized south and southeast from the Nevado de Toluca crater with an area of 75 km^2, limited to the west and north by curvilinear deeply incised valleys and to the south by a sharp change in slope. It is characterized by high slope value; more than 50% of the area of this sector has slopes greater than 20°. This domain presents an irregular morphology with numerous flank ruptures but its texture is relatively smooth. This is clearly visible

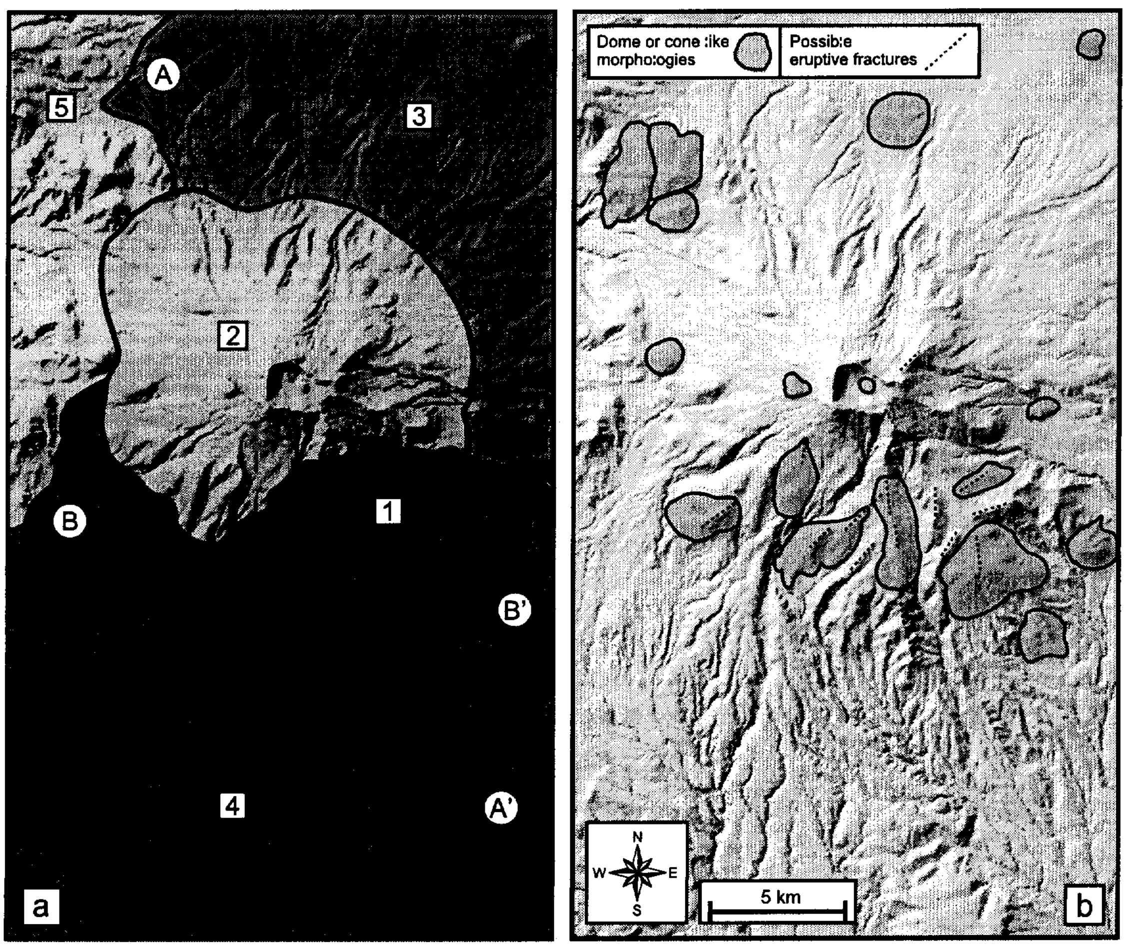

Fig. 6. (a) Morphological domains extension and profile traces (Fig. 9). (b) Dome- or cone-like morphologies and possible eruptive fractures map. Each map is superimposed on a shaded image (illumination from northwest).

on the aspect map (Fig. 5): the domain is represented by numerous different aspect classes, although the area that is occupied without interruption by a single aspect class is relatively wide. Furthermore, domain 1 is readily observable on the shaded image and perspective views where it appears as an elevated area with a relatively flat top dissected by a very deep incised valley oriented NNW–SSE (Figs. 2–4). The flanks of this valley reach an elevation of 450 m from bottom to top.

- Domain 2 comprises the Nevado de Toluca cone and is limited from west to north to east by breaks in flank slope, as shown by slope map (Fig. 5). Two curvilinear deeply incised valleys separate domain 2 from domain 1. Domain 2 covers an area of 120 km^2 and is characterized by relatively high slope value; more than 60% of the domain area has slope greater than 10° (Fig. 5). The high slope of domain 2 is due principally to the Nevado de Toluca wide amphitheatre crater open to the east. This domain is characterized by regular morphology and moderately smooth texture. On shaded images, perspective views and slope and aspect maps, a regular cone is visible incised by numerous, but not very deep, valleys (Figs. 2–5).
- Domain 3 represents the northeastern lower flank of the volcanic edifice, wide and relatively flat, with 50% of the area lower than 5° slope. Its limits are marked by slope breaks as shown by the slope map (Fig. 5). This domain has a very regular morphology with some shallow valleys predominantly oriented in accord with the topographic gradient of domain 2; the aspect map reveals a moderately rough texture (Fig. 5). This domain is clearly visible on the shaded image and perspective views as a wide and plane area (Figs. 2–4).
- Domain 4 includes the southern DEM portion, limited by a more or less sharp slope break. The slope is relatively high with more than 60% of the area having slopes greater than 10° (Fig. 5). The aspect map shows a very fragmented morphology, detectable also on shadow and perspective views (Figs. 2 and 3), in particular, numerous deeply incised valleys cut this area with variable direction resulting in a rough texture. The southern part is dominated by a horst and graben structural arrangement formed, from west to east, by Chiltepec horst, Coatepec graben, Porfirio Díaz horst and Villa Guerrero graben (García-Palomo et al., 2000; Fig. 1b). Coatepec graben is easily observable on the slope map as a flat area (represented in blue on Fig. 5). A similar appearance characterizes the Porfirio Díaz horst top. Furthermore, the horsts are evident on aspect map due to their north-oriented surface (represented in red on Fig. 5) and relatively smooth texture.
- Domain 5 consists of the north-westernmost DEM portion. Its limits are characterized by a morphological break visible on slope and aspect maps (Fig. 5). The slope is relatively high; more than 50% of the area of this sector has slopes greater than 10° (Fig. 5). A flat area, connected directly with domain 2, separates domain 5 in a northern and a southern portion. A rather irregular morphology and a moderately smooth texture characterize this domain, as shown by the slope and aspect maps (Fig. 5).

A more detailed observation of the DEM and aerial photographs reveals some characteristic morphological features that probably document volcanic and volcano–tectonic structures. Above all, as expected in an andesitic to dacitic volcanic area, these morphologies have a dome (or cone) appearance and can be limited as single edifices (Fig. 6b). Some of these edifices are known to be monogenetic domes, e.g., C. Calotepec dome and El Ombligo dome (Figs. 6b and 8; García-Palomo et al., 2000; Bellotti et al., 2003). These features are easily recognizable on the shadow image, perspective views, slope and aspect maps, satellite image and topographic profiles (Figs. 2–5, 7, 8). Their dimensions range from 500 to 3500 m and the morphology is in some cases regular and in other ones very fragmented. These characteristic topographic features are concentrated only in some portions of the studied area, principally in and near domain 1 (Fig. 6b).

3.2.2. Linear features

Morphological analysis reveals on Nevado de Toluca and surrounding areas a large number of linear features detectable as rectilinear or curvilinear valleys and, subordinately, as long linear ridges (Fig. 9a). The lineament density reaches a maximum in the southern portion of Nevado de Toluca DEM, probably due to

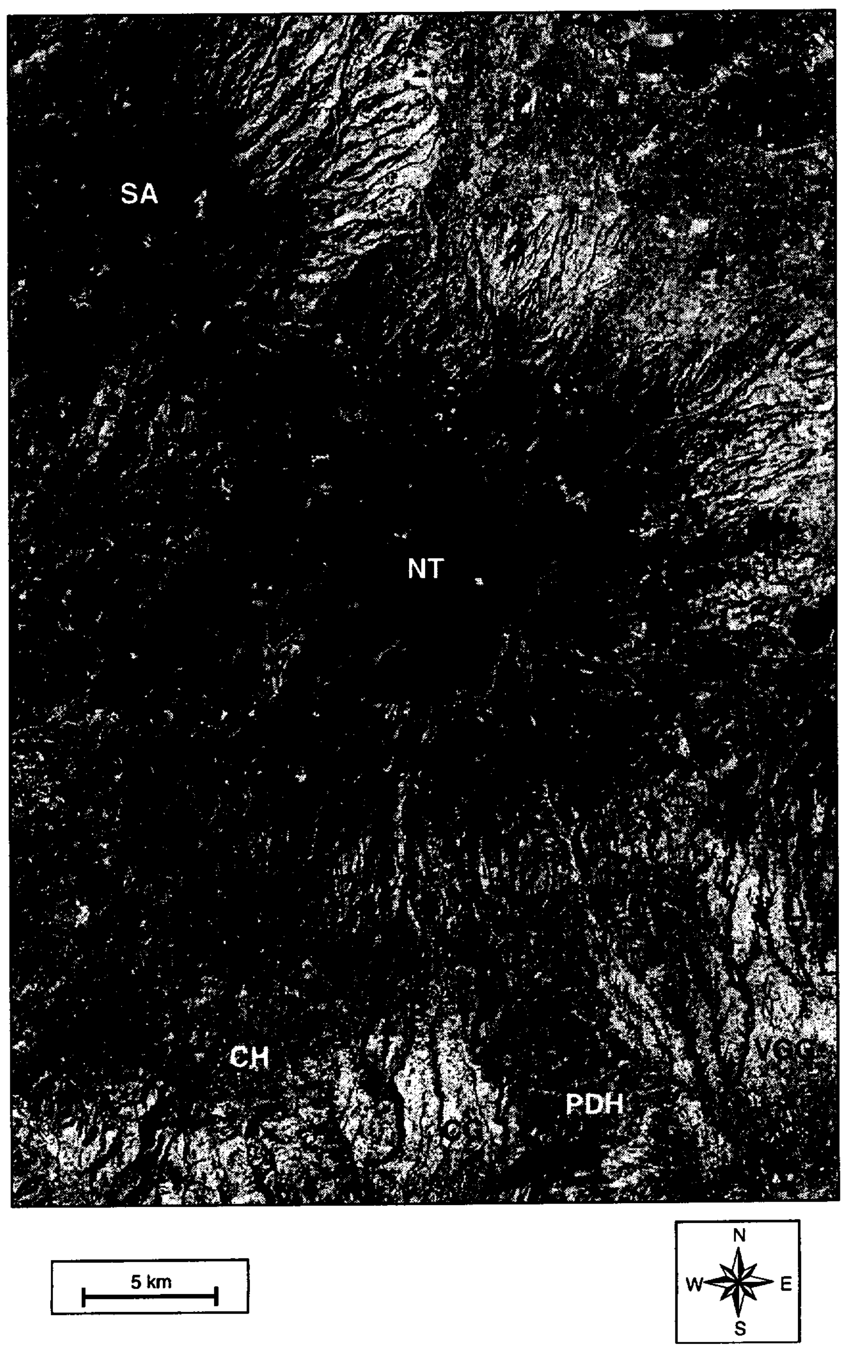

Fig. 7. Black and white Landsat imagery (band 7) of the Nevado de Toluca area. NT: Nevado de Toluca; SA: San Antonio volcano; CH: Chiltepec Horst; CG: Coatepec Graben; PDH: Porfirio Díaz Horst; VGG: Villa Guerrero Graben.

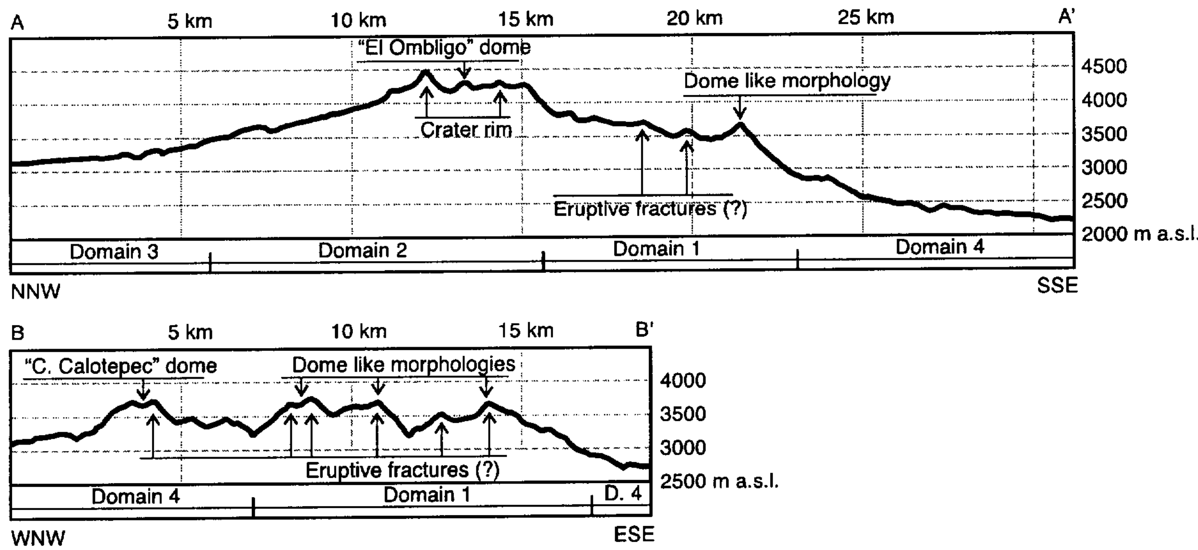

Fig. 8. NNW–SSE (A–A′) and E–W (B–B′) topographic profiles across the studied area. Dome- or cone-like morphologies and eruptive fractures are outlined.

age and rheology of the geological units cropping out in this area that correspond with volcaniclastic sequences (Capra and Macías, 2000). Although there are some single main lineaments, extensive lineament networks and groups characterize the morphology; these groups are defined only using lineament orientation. The absence of clear lineament intersections makes impossible to establish the relative age and kinematics of the structures.

We define four different groups of lineaments based on orientation and spatial distribution. These four groups are labelled a, b, c and d and are described below.

(a) In the southern DEM portion (domains 1 and 4), a series of long deeply incised valleys and some linear narrow ridges striking NNW–SSE are clearly visible (Fig. 9a). The most noticeable lineament of this group is a very deeply incised valley that cuts domain 1 and continues to the south through domain 4 (Figs. 2 and 4); in this last domain, group "a" reaches maximum density. To the north, some lineaments with the same orientation start at the Nevado de Toluca cone base and incise domain 3; these lineaments are represented by rectilinear segments of some, not very deep, valleys.

(b) Numerous NW–SE striking lineaments pass through the studied area (Fig. 9a). Long rectilinear valleys with vertical flanks represent these lineaments in domain 4 (Figs. 2 and 3). A series of group "b" lineaments affects a narrow zone passing through the Nevado de Toluca horseshoe shape crater, as illustrated by shadow image and aspect map (Figs. 2 and 5). Particularly, the aspect map shows an area, starting from Nevado de Toluca crater and extending to the NW, characterized by a distinctive texture, different from that of contiguous areas.

(c) Domains 1, 2 and 3 are affected by some lineaments striking NE–SW (Fig. 9a). Rectilinear valleys and ridges represent network of lineaments; the former are distributed principally in domains 2 and 3, the last in domain 1 (Figs. 2–4). Other short group "c" lineaments seem to affect the Porfirio Díaz horst in domain 4 (Fig. 2).

(d) Concentrated in a relatively narrow band, intersecting the Nevado de Toluca crater, there are a lot of NNE–SSW rectilinear valleys (Fig. 9a). The portions of the studied area affected by these group "d" lineaments are domains 2, 3 and 4. The most noticeable lineament of this group is a rectilinear valley that starts at Nevado de Toluca

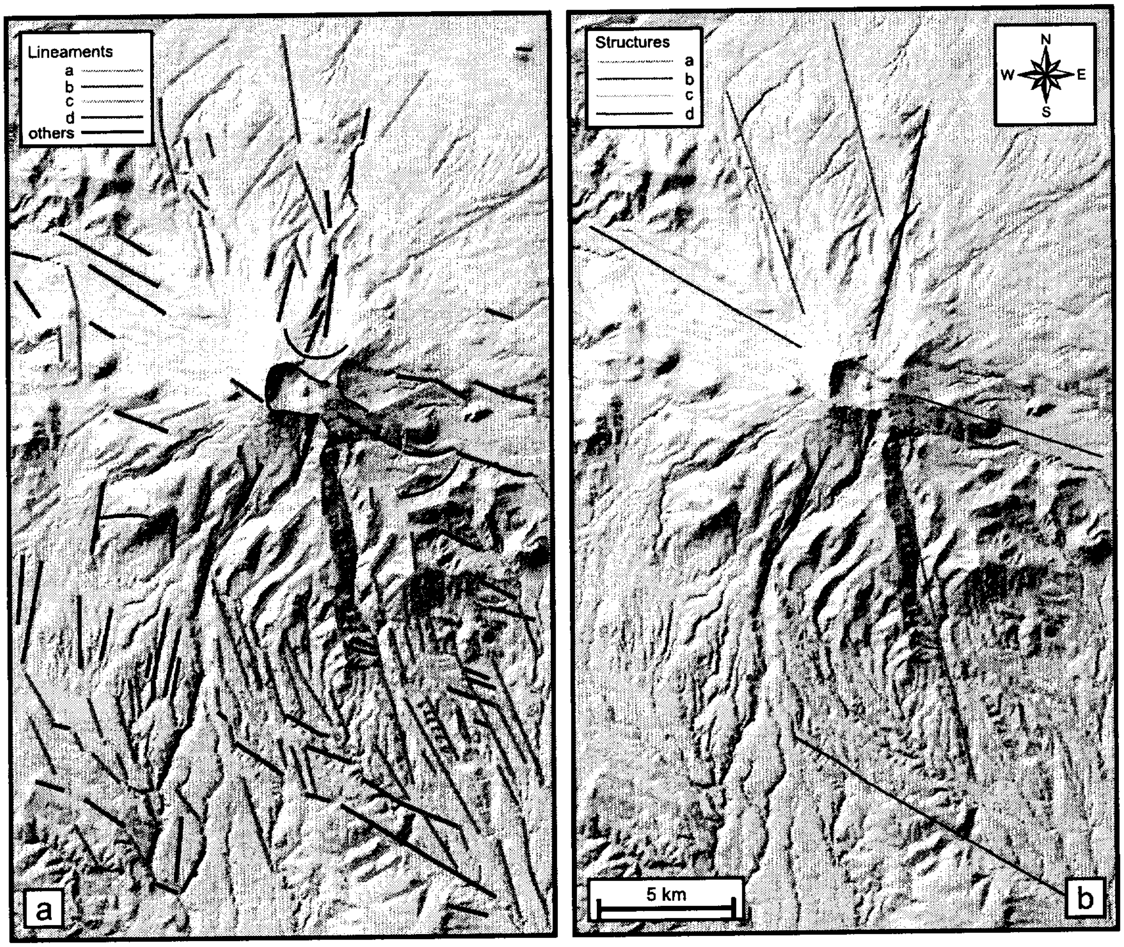

Fig. 9. (a) Lineament network map. (b) Map of the main structures identified. Each map is superimposed on a shaded image (illumination from northwest).

crater and affects its northern flank cutting domain 3; this lineament is clearly visible on a perspective view (Fig. 4). Furthermore, an analogous lineament, generating a nearly identical, but more incised, feature, is visible 20 km northwest from the Nevado de Toluca crater, on the deeply eroded San Antonio volcano (Fig. 7).

General observations of the DEM and satellite image reveal that some of the lineaments recognized and described above are part of major and continuous structures (Fig. 9b). Two of these correspond to faults already described in the bibliography; the other ones are reported here for the first time. One of the structures already known is the Zacango fault, which strikes NE–SW and passes through the Nevado de Toluca crater (Fig. 1b; García-Palomo et al., 2000; Fig. 9b, c group, in light blue). An evident structure cuts the studied area from NNW to SSE; domain 2 is not deeply affected, and in domain 3, the structure is wide (Fig. 9b, a group, in green). This structure can be linked to the Taxco–Querétaro fault system (García-Palomo et al., 2000; Fig. 1b). Another main structure that crosses the summit region of Nevado de Toluca strikes from NNE to SSW (Fig. 9b, d group, in red). A long structure striking NW–SE, the already known Tenango fault, cuts across the studied area passing through the Nevado de Toluca crater (Fig. 1b; García-Palomo et al., 2000; Fig. 9b, b group, in blue). Finally, structures striking NW–SE affect domain 4 and limit the northern extent of the Porfirio Díaz horst; these structures are probably part of the Tenango fault system (Fig. 9b, b group, in blue).

Detailed aerial photograph observation shows that extensive and continuous summit outcrops are nearly all associated with linear ridges. Moreover, these morphologies have a relatively high altitude and are frequently associated with dome-like morphologies (Fig. 6b). For these reasons, we consider that these linear ridges may represent eruptive fractures that have built domain 1 and a limited portion of domain 2 (Fig. 6).

4. Other relevant morphological features

Nevado de Toluca crater has a clearly detectable horseshoe shape open towards east whose morphology is very similar to that of the depression formed by the 1980 flank collapse of Mount St. Helens volcano, U.S.A. (Lipman and Mullineaux, 1981). The crater rim is roughly elliptical (1.5–2 km in diameter), with its major axis trending E–W, and is characterized by straight walls intercepting at high angles. At least two debris avalanche deposits were identified on the eastern flank of the volcano (Bellotti et al., 2003); these findings allow interpretation of the crater morphology as a consequence of one or more wide sector collapses. Furthermore, the more recent volcanic eruptions of the Nevado de Toluca (at least 4 Merapi-type dome collapse and four plinian eruptions) and glacier activity could have affected the crater morphology (Heine, 1986, 1994; Macías et al., 1997).

The northern and eastern flanks of the Nevado de Toluca volcano, just below the crater region, have other wide amphitheatre shapes (1.5–2 km in diameter; Fig. 9a). Finally, two curved scarps affect domain 1 (Fig. 9a). These features may be associated with lateral collapses, although it should be noted that glacial activity may have occurred around 60,000 years ago (Heine, 1986, 1994).

5. Results

The morphological analysis of Nevado de Toluca volcano, based on aerial photographs, a digital elevation model and a satellite image, provides a comprehensive view of this volcanic area. Above all, the DEM and its derived slope and aspect maps give evidence of relevant spatial relationships between the main morphological elements affecting the area. On the whole, the area analysed consists of distinct domains, each characterized by different morphological features such as slope and texture. Furthermore, important structures and related linear networks, affecting the entire region or only some domains, are clearly outlined. Their analysis contributes to a better understanding of the volcanological and structural development of the Nevado de Toluca volcano.

The most relevant areal morphological feature is the southern flank of the Nevado de Toluca volcano, which corresponds to domain 1 (Fig. 6). Particularly, we note a significant difference between this domain and the adjacent domain 2 (Figs. 6 and 8). Domain 1 has an irregular morphology, a relatively flat top dissected by a very deep incised and rectilinear valley, striking NNW–SSE (group "a" lineament), and comprises some distinct edifices (dome-like morphologies). Moreover, domain 1 has a relatively high altitude and is limited by sharp scarps; for these reasons, this domain appears as a unique complex construction distinct from the adjacent areas, including the actual cone of the Nevado de Toluca volcano. In fact, domain 2 is a regular cone without a trace of deep erosion, as shown by comparison with the older San Antonio volcano, and is not affected by the NNW–SSE structure that cuts domain 1 (Fig. 7; García-Palomo et al., 2002). Thus, we forward the hypothesis that domain 1 represents a volcanic unit that is both morphologically and temporally distinct from the recent central volcano (domain 2). Based on previous works, this volcanic complex probably formed between 2.6 and 1.2 Ma ago, and it is mainly constituted by andesitic lava flows (García-Palomo et al., 2002; Bellotti et al., 2003). The presence of a linear structure striking NNW–SSE that cuts domains 1 and 3, but fades out into domain 2, suggests that this structure is younger than domain 1 but older than domain 2 (Fig. 9b, a group).

Another morphological evidence is the complex topography of the southern part of the studied area (domain 4), outlined by a very articulated drainage network, which is clearly structurally controlled. Domain 4 is characterized by a horst and graben arrangement and appears as a natural accumulation area of the domains 1 and 2 volcaniclastic deposits. In fact, at least two debris-flow deposits have been reported; these deposits are younger than the tectonic activity responsible for the horst and graben opening, and they drape these structures (Capra and Macías, 2000).

Domain 3 probably has a same role for domain 2, but its less-developed drainage system may be due to a low topographic gradient, a minor accentuated structural control and different lithology. Domain 3 comprises pyroclastic deposits younger than 40,000 years (Macías et al., 1997).

Finally, the complex morphology of domain 5 is due to the interaction between peripheral areas of San Antonio and Nevado de Toluca volcanoes.

Other morphological features that were revealed by the study carried out are the so-called "dome- or cone-like morphologies" and the "possible eruptive fractures". The spatial distribution of these elements reflects the relationship between the feeder systems and the topography (Fig. 6b). Those relationships are particularly well displayed in domain 1 and the surrounding areas.

Furthermore, our analysis allows to define networks of lineaments and single important lineaments, characterized by orientation and spatial distribution, which are considered to correspond to major faults or fractures systems (Fig. 9). This structural arrangement has influenced the evolution of Nevado de Toluca. The possible eruptive fractures are systematically oriented aligned with the "a" and "c" lineaments groups. It suggests that the faults or fracture systems striking NNW–SSE and NE–SW were exploited by ascending magma, during the volcanic activity in domain 1 and surrounding areas (Figs. 6 and 9). Additionally, the main structures that cross the horseshoe shape Nevado de Toluca crater probably played an important role in its formation. As shown in Fig. 9, the main structures "b" and "d" are parallel and perpendicular, respectively, to the sector collapse direction, and thus may have controlled the slope failure.

6. Concluding remarks

The synoptic view offered by an accurate morphological analysis demonstrates the contribution of this approach to the characterization of volcanic and tectonic structures. Particularly, the digital nature of DEM, and thus the opportunity to generate perspective views and slope and aspect maps constitutes a valuable tool in defining the occurrence and spatial distribution of relevant topographic features. In particular, the aspect map can reveal valuable information about areal morphologies and linear features.

For the studied area, the morphological analysis reveals the existence of a complex volcanic edifice, older than the central Nevado de Toluca cone, formed by numerous partially superimposed lava flows and domes fed by eruptive fractures oriented N–S and NE–SW. The presence of this older edifice influences the distribution of pyroclastic and epiclastic deposits and represents a topographic barrier that can provoke the deflection of future flows. In addition, we determined that the morpho–tectonic lineaments described for the Nevado de Toluca area controlled the volcanological and structural evolution of the volcano: they could influence the distribution of new eruptive centres as well as the directions of massive failures, events already described for the southern and eastern flank of the volcano (Capra and Macías, 2000; Bellotti et al., 2003).

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