Capítulo 22. Mass movement processes associated with volcanic structures in Mexico City

Víctor Carlos Valerio
Instituto de Geología, UNAM

Celia López Miguel
Centro Regional de Investigaciones Multidisciplinarias, UNAM

Irasema Alcántara Ayala
Instituto de Geografía, UNAM

Abstract

Mexico City, one of the most populated areas of the world, has been affected by various hazards of natural origin, such as subsidence and cracking of the soil, seismicity, floods and mass movement processes (MMPs). Owing to the lack of space on the plain, in recent years urban growth has been concentrated particularly on the slopes of the surrounding mountain ranges, and this has significantly modified the dynamics of the relief as well as the hydrogeological conditions. The specific character of natural susceptibility to mass movements is strongly dependent on the geological-structural and morphological characteristics of the volcanic bodies that form the mountainous relief. This natural susceptibility, combined with the characteristics of vulnerability of the society, creates risk conditions that can generate severe consequences for the population and the economy. Hence, based on an inventory of mass movement processes comprising 95 data points, the present study aimed to achieve a zoning of the areas susceptible to these processes, as well as to characterize the mechanisms of instability in the volcanic structures that form the relief of the area in question. The results of this work clearly show the role of the lithology, the mode of emplacement and the morpho-structural characteristics of the volcanic structures, in the types of mass movement processes. In addition, it identifies the diverse activities of anthropogenic origin that favour slope instability in the zone: deforestation and burning of rubbish, felling of timber on the slopes for building infrastructure and dwellings, leakages of water, vibrations of vehicles, rotating machinery and the use of explosives in mining works, overloading the heads of the slopes, disturbance of the geohydrological regime, generation of rubbish tips, terracing of the slopes for cultivation, inadequate building regulations, and the use of counterproductive or ineffectual stabilization measures.

Keywords: Mass movement processes, Mexico City, susceptibility, GIS.

Procesos de remoción en masa asociados a estructuras volcánicas en el Distrito Federal, México

Resumen

El Distrito Federal (D.F.), una de las áreas más pobladas del mundo, es afectado por diversas amenazas asociadas con el origen y la estructura geológica de la Cuenca de México, tales como el hundimiento y agrietamiento de suelo, sismicidad, inundaciones y los procesos de remoción en masa (PRM). Ante la falta de espacios en la parte plana del D. F., el crecimiento urbano se concentró en las laderas, lo cual ha modificado de manera importante el relieve y alterado las condiciones hidrogeológicas. Aunado a esto, en la zona montañosa son frecuentes los PRM, asociados a las características geológico-estructurales y morfológicas de los cuerpos volcánicos que la conforman. Esta susceptibilidad natural, combinada con las características de vulnerabilidad de la sociedad, crea condiciones de riesgo que pueden tener gran impacto en los ámbitos sociales y económicos. Por esta razón, este trabajo –basado en un inventario de PRM constituido por 95 puntos– tiene como objetivo identificar las zonas susceptibles a estos fenómenos gravitacionales, así como efectuar la caracterización tipológica de los procesos de remoción en masa asociados a las estructuras volcánicas. De manera adicional, también se identifica una serie de actividades antropogénicas que favorecen la inestabilidad de laderas en el área de interés: deforestación, quema de basura, cortes en las laderas ya sea para construcción de infraestructura y vivienda, fugas de agua, vibraciones de vehículos, maquinaria rotatoria y por el uso de explosivos en la explotación de minas, sobrecarga en la corona de los taludes, alteración del régimen geohidrológico, generación de tiraderos de escombros, terraceo de las laderas para el cultivo, diferentes criterios constructivos así como obras de estabilización contraproducentes o poco efectivas.

Palabras clave: Procesos de remoción en masa, Ciudad de México, susceptibilidad, SIG.

Introduction

Mexico City is affected by a range of natural hazards associated with the geological origin and structure of the Valley of Mexico, such as soil subsidence and cracking, seismicity, flooding, and mass movement processes (MMPs). In addition, the Federal District is one of the most populous cities in the world, with some nine million inhabitants (INEGI, 2005) and the prospect of further significant expansion in the future. In recent decades, urban growth has proceeded with neither planning nor control, and this has generated various problems such as over-exploitation of the aquifer layers, deforestation, pollution of soil, air and water, and the development of illegal settlements. In view of the lack of space on the plain of the D.F., urban growth has concentrated on the slopes, and this has significantly modified the relief and has altered the hydrological conditions. Combined with this, in the mountainous region there are frequent MMPs associated with the geological-structural and morphological characteristics of the volcanic bodies that shape it.

MMPs cause loss of human life and damage the civil infrastructure, and hence it is necessary to study them to identify the slope zones that are potentially unstable, as well as the typology of the movements and their geological control; this will serve as a base from which to generate more detailed maps in order to assist in emergency services, in land regulation and in risk management, and to guide mitigation and prevention measures. The aim of the present study is to analyse the spatial distribution and to describe the typology of the mass movement processes associated with volcanic structures, that have already occurred, on the basis of field work, of analysis of processes, and of the geological characteristics of the material viewed on a Geographic Information System platform.

Background

Various authors have studied the topic of MMPs in the D.F. and its environs. In the Sierra de Guadalupe, Lugo and Salinas (1996) studied the geomorphological character and produced a simplified map of the zones of flooding, rock falls and landslides; for this same area, the SEGEOMET (2005) produced a map of MMP records (García *et al*. 2006), and used superposition of thematic maps to produce a qualitative map of the risks of landslides. For the Sierra de Santa Catarina, Lugo *et al*. (1994) analysed the geomorphology and classified the different types of relief shown by the volcanic structures, and the SEGEOMET (2000) mapped the geological risk of landslides and rock falls in eight *colonias* [neighbourhoods] of the *delegación* [borough] of Iztapalapa. In a study of the borough of Álvaro Obregón, Lugo *et al*. (1995) identified the morphological, anthropogenic and lithological characteristics and the influence of these in the generation of hazards and risks, for example when there are tunnels or cavities, landslides, flows and erosion in the upper reaches of ravines and escarpments, rock falls and flooding. Recently, the Servicio Geológico Metropolitano mapped the distribution of MMPs in the D.F. on the basis of field work, lithology and slopes (SEGEOMET, 2005), and this has assisted in the work of emergency services; that map establishes in a general way the potential mechanisms of movement and their spatial localization, and this is an important advance in the study of these processes.

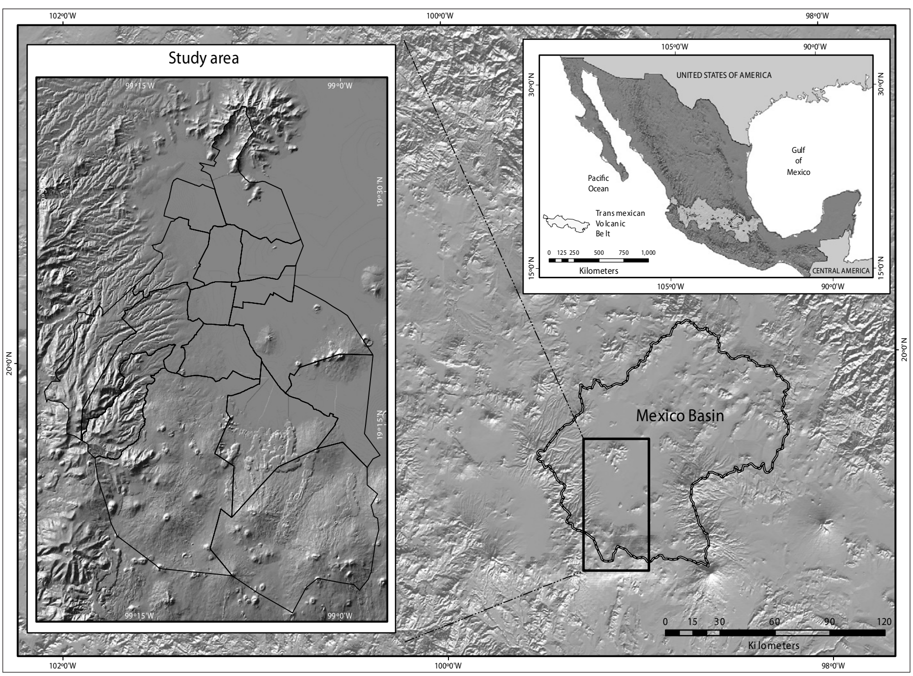


Figure 1. Study area within the Valley of Mexico.

Study Area

Location

The Valley of Mexico is in the eastern sector of the Trans-Mexican Volcanic Belt (TMVB), (Figure 1); it has been the subject of research during recent decades because in its south-western part lies Mexico City with its many problems resulting from the population explosion (Figure 2) and the geological complexity of the terrain. The present study area is in the south-west of the city and comprises all

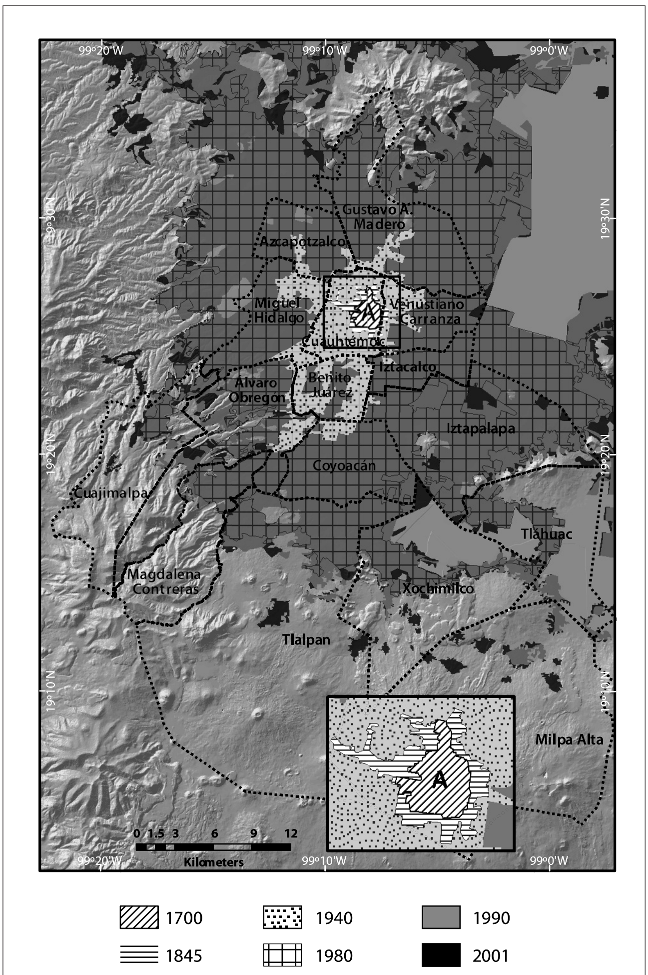


Figure 2. Map of urban growth in the Valley of Mexico (source: Gutiérrez, 1997).

the boroughs of the D.F. and part of the State of Mexico, in the municipalities of Tlalnepantla, Ecatepec, Coacalco, Tultitlán and Barrientos. It includes the whole of the Sierras Guadalupe, Barrientos and Santa Catarina, and part of the Sierras Las Cruces and Chichinautzin.

Geographic position of Mexico City

Although 28% of the area of Mexico City lies on level ground, 72% is on mountainous terrain, with 41% in the Chichinautzin ranges, 24% in Las Cruces, 5% in Santa Catarina, and 2% in the Guadalupe ranges. The boroughs with the largest area in the mountainous zone are as follows: Tlalpan (21%), Milpa Alta (16%) and Xochimilco (8%) within the Sierra de Chichinautzin; Iztapalapa (8%) in the Sierra de Santa Catarina; and Cuajimalpa (6%), Magdalena Contreras (6%) and Álvaro Obregón (6%) in the Sierra de Las Cruces. The boroughs of Gustavo A. Madero, Tláhuac, Miguel Hidalgo and Coyoacán have some 2-3% of their area in the mountainous zone. In the State of Mexico, the study area covers the whole of the municipality of Tlalnepantla and part of Atizapan, Ecatepec, Tultitlán and Coacalco, which are in the northern part of Mexico City, in the Barrientos and Guadalupe ranges.

Physiography and climate

Mexico City is in the physiographic province known as the Neovolcanic Axis. Its geographic and topographic position means that it is affected by systems of atmospheric circulation that clearly define two climatic periods: the humid season (June to October) and the dry season (November to March). The altitudes of more than 2 000 m asl, in a close relationship with temperature, define two major thermal zones in the study area: the temperate zone, with an annual mean temperature of 16.2° C and an annual average precipitation of 775 mm, and the semi-cold zone, characterized by an annual mean temperature of 10.8° C and an annual average precipitation of 1 276.3 mm. Moreover, a small dry area, located in the lowlands, presents an annual mean temperature of 16.6° C, and an average annual precipitation of 564.6 mm (INEGI, 2005).

The dominant soil types, according to the FAO-UNESCO (1974) classification, are Andosols, Cambisols, Phaeozems and Lithosols. The vegetation is influenced by the altitude: in lower areas there are halophilic rangelands, arboreal vegetation such as the pepper tree, eucalypts and casuarinas, and irrigated agriculture; in piedmont areas at medium altitudes, the vegetation is herbaceous with grasses, legumes and cacti, and arboreal with pepper trees, eucalypts, casuarinas and mimosas; in the high areas there are pine, sacred fir and oak forests as well as rain-fed agriculture (INEGI, 2005; Tapia and López, 2001).

Materials and methods

Starting from a digital topographic map, a digital model of the terrain (DMT) with a resolution of 25 m was produced in the geographic information system ILWIS version 3.0, and this served as a basis for producing the shaded model, and maps of the altitudes and gradients of the study area. Geological units consisting of stratovolcanoes, domes, cones, lava spills and volcaniclastic deposits were identified by analysis of aerial photographs, satellite images, digital models of the terrain with various angles of incident light, and topographic maps from the National Institute of Statistics and Geography (INEGI, in spanish) at 1:50 000 scale. Field work and bibliographic compilation verified the volcanic units and their contacts, lithology, directions of flow and ages. The cartography was produced on the topographic maps of the INEGI. Then areas or polygons were digitized to correspond to each geological unit, and these were labelled according to their lithology in order to generate a lithological map (SEGEOMET, 2005; Figure 3). Production and analysis of shaded models with differing angles of incident light was followed by identification and marking of erosion cirques and lines corresponding to faults, fractures and ravines, which in general were identified by zones of steep gradient, associated with slope processes. Finally, and with the aid of the MMP inventory of D.F., visits were paid to sites where there were already active slope processes, with the aim of describing their principal features, including the type of mechanism, lithology, form and geometry of the process.

An important input was the use of the MMP inventory of Mexico City. A database from 1999 onwards was compiled from a literature search (TGC, 1998; SEGEOMET, 2003; Concha, 2006), from field work and from an integration and analysis of reports and visits by personnel of the Civil Defence service of Mexico City for involvement and consultancy in cases of emergency in zones affected by MMPs (Dirección General de Protección Civil, 2004); this database presents information concerning the location and type of process observed, lithology, general observations, damages and a qualitative hazard assessment. The database comprises an inventory of 95 points or zones where MMPs have occurred, the majority of them affecting the population and the civil infrastructure. Note that this database has lacunae in some fields, owing to deficiencies in the information

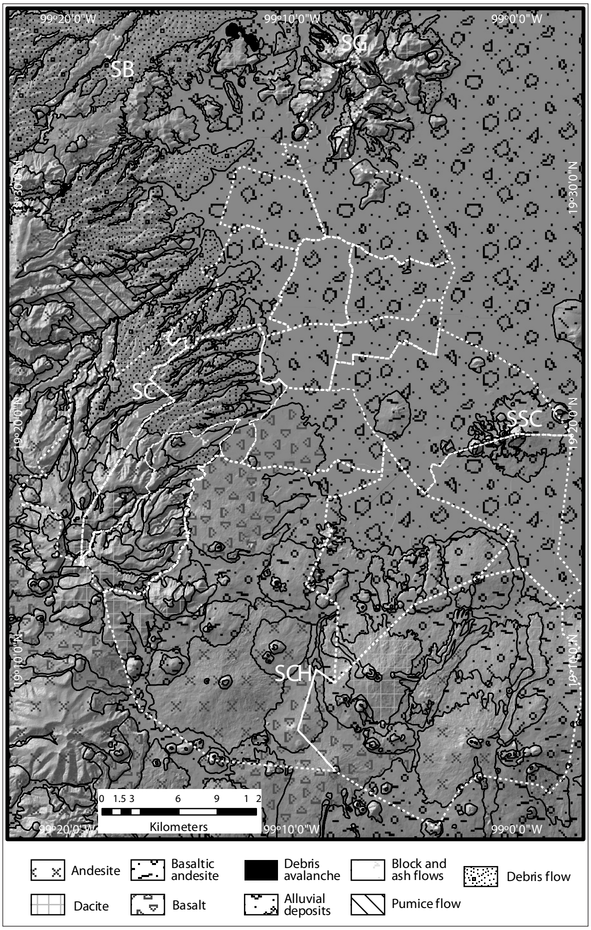


Figure 3. Lithologic map of the study area. SG, Sierra de Guadalupe; SB, Sierra de Barrientos; SC, Sierra de las Cruces; SCH, Sierra de Chichinautzin; SSC, Sierra de Santa Catarina (source: Servicio Geológico Metropolitano, 2005).

received. When the MMPs had not been georeferenced by GPS, they were located with the aid of maps, with subsequent field visits, and with the help of the Internet through Google Earth and local maps.

Considering the scale of work used and the geological characteristics of the material forming the mountainsides, the existing lithological map (SEGEOMET, 2005) was reclassified in order to obtain a simplified integrated version for four types of material (Figure 4): *a)* acid and intermediate lavas (andesites and dacites), *b)* basic lavas (basaltic and basaltic-andesite lava spills), *c)* scoria cones and *d)* granular and blocky materials (volcaniclastic deposits).

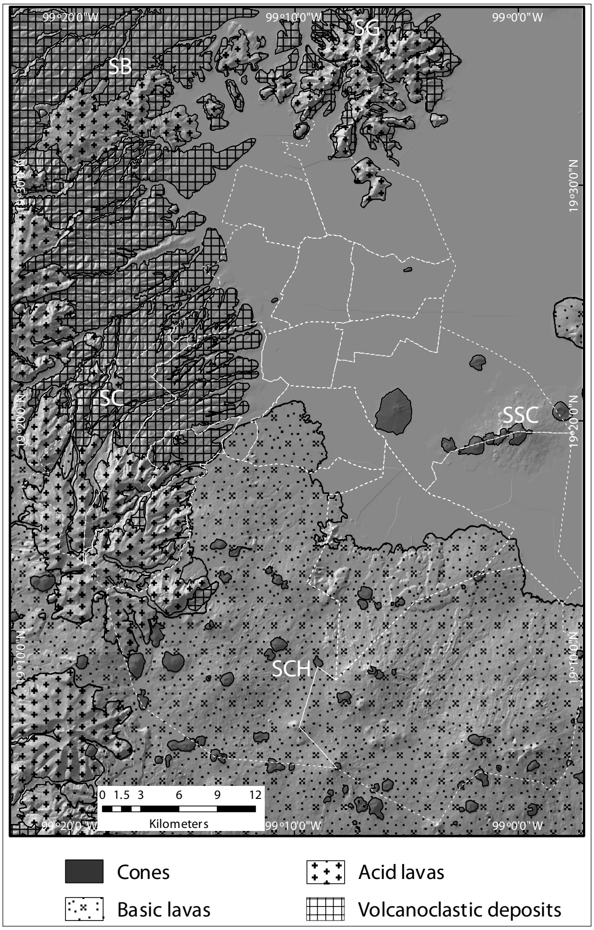


Figure 4. Reclassified lithological map.

Finally, a susceptibility map was generated using thematic maps like slopes, lithology, altitude, erosion cirques, lineaments, drainage and urban area, and statements based on the set theory of Boolean algebra. For this, the levels of susceptibility HIGH, MEDIUM and LOW were determined from the combination of the three principle variables: the gradient, the lithology and the altitude. Subsequently, the other variables represented in thematic maps served as input for delineating critical zones, and the level of susceptibility grew to VERY HIGH.

Geological Framework

Regional Geology

The Trans-Mexican Volcanic Belt (TMVB) is a continental volcanic arc of a predominantly calco-alkaline composition, tectonically active and extending from the Pacific coasts to the areas near the Gulf of Mexico. At the regional level, the TMVB is divided into three main sectors: the western sector formed by the tectonic trenches of Tepic, Colima and Chapala; the central sector, formed principally by monogenetic volcanism of the Michoacán-Guanajuato region; and, lastly, the eastern sector, including the Valley of Mexico, characterized by the presence of large stratovolcanoes (Pasquaré *et al*., 1987).

The Valley of Mexico is an endorheic lacustrine basin of volcano-tectonic origin, lying at a mean altitude of 2240 m asl. It is elongate, with its long axis in a NW-SE direction. It is bordered by volcanic chains of various ages, whose rocks are affected by fault systems, principally with N-S, NE-SW and E-W orientation (De Cserna *et al*., 1988; SEGEOMET, 2003). These three fault systems were formed at different times, with the N-S being the oldest and forming part of the Basin and Range system (Alaniz *et al*., 1998). Next to be formed was the NE-SW system, belonging to the Tenochtitlan shear system (De Cserna *et al*., 1988; García *et al*., 2002), which is considered to be an intracontinental fault zone. The most recent, the E-W system is formed by the intra-arc deformation within the central part of the TMVB (Suter *et al*., 2001).

The Valley of Mexico is bordered on the west by the Sierra de Las Cruces, formed by overlapping stratovolcanoes, with an overall N-S orientation and surrounded by extensive fans formed by pyroclastic flows, rockfall deposits; to the east it is bounded by the Sierra Nevada, consisting of the Tláloc, Telapón, Iztaccíhuatl and Popocatépetl volcanoes; the northern part is bounded by the volcanic zone of Pachuca and the southern part by the Chichinautzin Volcanic Field, which is formed from cineritic cones and lava flows. Within the basin there are some volcanic prominences such as El Pino hill, and the Sierra de Santa Catarina, Sierra de Barrientos and Sierra de Guadalupe.

Geological and structural characteristics of the mountain ranges that form the study area

The mountain chains within the study area are as follows: to the north, the Sierra de Guadalupe and Sierra de Barrientos; to the west, the Sierra de Las Cruces; to the south, the Chichinautzin Volcanic Field; and to the east the Sierra de Santa Catarina. The type of relief is volcanic, formed by large stratovolcanoes, domes, scoria cones, shield volcanoes, lava flows and extensive sequences of volcaniclastic deposits; this obviously determines the types of MMPs that occur and their potential impact. The most notable characteristics of these ranges are described below.

a) Sierra de Guadalupe

The Sierra de Guadalupe (SG) is the result of intense tectonic activity which produced faults and volcanism (Lugo and Salinas, 1996). It consists of at least 14 volcanic units, comprising domes and volcanoes of various sizes; some of these structures show collapses (SEGEOMET, 2003). These volcanic edifices originated pyrocolastic flow, debris avalanche and debris flow deposits. The rocks of the SG are predominantly of acid composition, such as dacites and rhyolites, and a smaller proportion of intermediate rocks such as andesites (*Ibid.*). The age has been estimated by various radiometric datings at between 14 and 16 Ma (Jacobo, 1985), which places the SG within the middle Miocene.

The relief of the SG varies between 2 240 and 3 010 m asl and seen from above is circular with a diameter of 17 km. The relief is dissected by ravines, erosion cirques and valleys, some of which are horse-shoe shaped. The central part of the sierra has strong vertical and horizontal dissection, fractures, and hydrothermal disturbance (Lugo and Salinas, 1996). The drainage is essentially radial and dendritic and is controlled by the extensive fracturing and faulting of the rock, as well as by the morphology.

With regard to the structural geology of the SG, Lozano (1968) considers the presence of two systems of fractures: WNW-ESE and N30°-45°E. The Metropolitan Geological Service has recognized three principal fault systems. The oldest is oriented N-S, over which there is a series of trenches and tectonic pillars, and locally it is characterized by small zones of shear that indicate a normal movement. The second system of faults is oriented NE-SW (De Cserna *et al.*, 1988; Mooser *et al.*, 1992) and the most important faults belonging to this system are the Tenayuca and Chiquihuite faults (Mooser *et al.*, 1992), which define one of the most prominent structures of this system, the Cuautepec Trench (Mooser, 1975). In the fault planes are features such as striations with at least two generations of movement, tectonic brecciation, fault flour and sigmoidal structures (SEGEOMET, 2003). The third system of faults is oriented E-W and affects the youngest rocks, and hence is considered to be the most recent. It is characterized by the presence of fault flour, breccia, and sigmoidal structures.

b) Sierra de Barrientos

The Sierra de Barrientos (SB) is formed by domes oriented ENE, which extend to the W; it cuts the Caldera de Atizapán and to the E it extends below the Sierra de Guadalupe (Mooser *et al.*, 1992). In it there are rocks of acid type such as dacites and, to a lesser extent, intermediate and basic rocks such as andesites and basalts.

In the Sierra de Barrientos there is evidence of the existence of a volcanic structure during the Miocene that later collapsed towards the N. The volcanic structure has a series of faults in an E-W direction which form the so-called Fosa de Barrientos. The Fosa de Barrientos, first identified by Mooser *et al.* (1992), is 21 km long, with an irregular width that varies from 100 m to 2 km, an altitude of 2 260 to 2 300 m asl, and an overall orientation that is mainly E-W K-Ar dating has indicated ages of 14-15 Ma for rocks of the Cerro de Barrientos and the Fosa de Cuautepec (Lozano, 1968).

The SB reaches heights of up to 2 500 m asl and the gradient of the slopes is 18º-30º or even more. Drainage is determined by fracturing and faulting of the rock, and also by the morphology of the mountainsides, many of which have collapsed areas. The drainage type is essentially radial and dendritic. The structural geometry of the Fosa de Barrientos is characterized by the presence of trenches and pillars (Flores, 2006).

c) Sierra de Las Cruces

The Sierra de Las Cruces (SC) forms the eastern limit of the Valley of Mexico and separates it from the Toluca basin. It has a generally N-S orientation and its length from Cerro la Bufa in the north to the volcano Zempoala at the southern end is ~110 km.

The stratovolcanoes of the SC show extrusive and explosive activity, characterized by the formation of domes, lava flows, pyroclastic flows and falls, debris, avalanches and debris flow deposits. The SC consists of andesites, dacites and rhyodacites (Gunn and Mooser, 1971). Radiometric dating and paleomagnetic studies have placed it in the Late Miocene (3.71 ± 0.40 Ma) to Pliocene (1.79 ± 0.1 Ma), with a migration of its volcanic activity from north to south (Mooser, 1974; Mora *et al.* 1991; Osete *et al.*, 2000).

The SC has an altitude of 3 800 m asl and in it can be identified structures such as craters, erosion cirques associated to collapses or ancient landslides, domes, lava flows, scoria cones and fault scarps. The distribution of the lithological units, in addition to the tectonic influence, determines the diverse patterns of the drainage network that occur along the entire length of the mountain range and that are characterized by parallel channels and by gullies with angular or rectangular arrangements. The gradient ranges from 0º to 40º, exceeding 60º only in restricted areas that correspond with structural limits (García *et al.,* 2008).

The SC is affected by three systems of faults and fractures (De Cserna *et al*., 1998; García *et al*., 2008): the N-S system, the N-E system and the E-W system. The N-S system is the oldest, with a direction that varies between N15º W and N20º E; it predominates mainly in the northern zone and part of the southern zone, has a stepped echelon arrangement, lightly anastomosed and with the planes inclined predominantly towards the east. The direction of the second system of faults and fractures is between N45º E and N65º E and it occurs in the central part of the SC, where it is characterized by a parallel arrangement. Lastly, the E-W fault system cuts longitudinally down the entire mountain range and is characterized by short lengths, arranged in parallel.

d) Sierra de Chichinautzin

The Sierra de Chichinautzin (SCH) covers an area of ~2 500 km^2 and the thickness is estimated to be 800 m (Bloomfield, 1975). It consists of some 220 volcanic systems and there are three types of volcanic structures (Martín del Pozzo, 1982; Marquez *et al*., 1999): lava flows or lava domes, scoria cones with gradients of 30° and associated flows, and shield-shaped lava cones. The lava flows are generally of basaltic or andesitic composition with an arrangement in blocks. The Sierra de Chichinaut-zin is the youngest volcanic chain in the Valley of Mexico. Siebe *et al*. (2004, 2005) determined ages for Tláloc volcano (6 200 years), Cuauhtzin (8225 ± 130 to 7 360 ± 120 years), Pelado (10 000years), Guespalapa (2 800 to 4 700 years) and Chichinautzin (1 835 years). The most recent activity is given by the eruption of Xitle, makes1 665 ± 35 years (Siebe *et al*., 2005).

The volcanic forms of this monogenetic field originated mainly in activity of Strombolian freato magmatic and with Hawaiian type activity originating fissural lava flows.

The SCH rests on a substratum of tertiary rocks, having as its initial volcanic base the Xochitepec Formation (Martín del Pozo *et al*., 1997; Siebe *et al*., 2005).

The majority of the volcanoes of the SCH occur in small groups aligned in the main direction of fracture of the E-W region (Bloomfield, 1975), although some follow NE and NW directions of fracture (Martín del Pozzo, 1980). The height of the cones ranges from 10 to 315 m and the diameters range from 50 to 750 m.

e) Sierra de Santa Catarina

The Sierra de Santa Catarina (SSC) is to the east of Mexico City and covers an area of 75 km^2. It is a monogenetic volcanic complex that gave rise to a series of small volcanoes during the Late Pleistocene, arranged in an E-NE direction.

The Sierra de Santa Catarina includes extrusive and explosive volcanism which is characterized principally by the formation of scoria cones accompanied by lava flows, scoria and ash (Lugo *et al.*, 1994). The lavas that form the Sierra de Santa Catarina are andesitic and andesitic-basaltic with variations in the content of silica and hydrated minerals such as hornblende and biotite. The alignment of the volcanoes in the Sierra de Santa Catarina defines a fault zone with a preferential E-W direction, via which magma rises. With the morphological analysis of the south of the Valley of Mexico, the information from the Tulyehualco-1 shaft and gravimetric sections, it has been concluded that this zone has a structure of semi-graben type called Tláhuac-Tulyehualco, with an E-W orientation and a stepped arrangement of blocks towards the north, which is bounded by a series of vertical and subvertical faults that do not reach the surface (Colín, 2006). De Cserna *et al*. (1988) recognises a fault oriented N 75-80° E, which dominates the Sierra de Santa Catarina.

Mass Movement Processes Associated with Volcanic Structures

Slope instability

In recent decades, many illegal human settlements have grown up on the slopes that surround Mexico City, as shown in the map of urban development (Figure 2). In these zones of potential instability, the movement processes can be triggered by natural factors such as high rainfall, faulting or earth tremors, or can be anthropogenic in origin. In Mexico City the MMPs associated with rainfall are frequent and are generally concentrated in the June-November period. The anthropogenic factor that favours these processes is usually important and occurs particularly through deforestation, felling on the mountainsides, vibrations caused by the passage of heavy vehicles, the use of explosives in quarries, dumping of rubble, and the presence of water owing to leaks or domestic waste. There are various examples of the effects that these phenomena have on the population, such as the rock falls and landslides on the slopes of the Sierra de Guadalupe and Sierra de Santa Catarina, as well as flows of mud and detritus in the western ravines, for example in the boroughs of Álvaro Obregón, Cuajimalpa and Magdalena Contreras.

Relationship of lithology and volcanic structure with type of process

Geology is the principal factor that determines the presence of MMPs. Lithology is fundamental, above all in the type of process or of the potential mechanism of the slope movement. Among the characteristics that can be associated with the lithology are the following: resistance to compression, tension and cutting force, degree of disturbance, porosity, permeability, and the presence of discontinuities associated with the formation of the material. Materials of volcanic origin have characteristics inherent to the processes that produced them. In the case of rocks formed by sequences of lava flows, we have the presence of discontinuities such as planes of flow and of cooling (Fink and Anderson, 2000), cavities (vesicles) and planes of contact between different flows. Also, there are generally tectonic processes in the volcanic structures, which generate fracturing and brecciation of the rocks; this contributes to the formation of blocks or breccias that can introduce slope movements. The type of movement that is kinematically possible is determined by the form and size of the blocks, their position within the rock mass, and the relative orientation of the discontinuities with respect to the slopes. Volcaniclastic deposits have a wide range not only in their granulometry and degree of consolidation, but also in their geomechanical characteristics, which determine different types of processes, which can include falls of rock or granular material, landslides and flows.

Herein follows a description of the rock lithology and volcanic features associated with types of MMPs. This is an adaptation of the terminology proposed by Hutchinson (1988) and Suárez (1998), which focuses on the following types of movement: tumbling of blocks, planar and wedge landslides, superficial sliding of detritus, falling by detachment (primary process), falling by rolling (secondary process), and flow of mud or detritus.

Intermediate and acid lavas

Rock type

Andesites: dark grey, fine porphyritic rocks, with crystals of quartz and plagioclase. At the level of the rocky mass it occurs as parcels of very fractured rock alternating with massive blocks of irregular form. On occasions, systematic fracturing forms slabs or blocks of rock.

Dacites: grey to light pink rocks of porphydic texture, with crystals of plagioclase and quartz, with a flow structure. At the level of the rocky mass, systematic arrangements of discontinuities occur, such as planes of flow or of cooling and fractures. The fractures generally intersect, whether this is orthogonally or obliquely, thereby creating tabular, columnar, cubic or irregular blocks.

Type of volcanic structure
Volcano: given the conical shape, the processes are generally radially distributed. In the case of volcanoes that have a collapse of part or all of the structure, this gives rise to the formation of erosion cirques, which are horse-shoe shaped structures with scarps and associated processes of fluvial erosion. The erosion cirques influence the generation of movement processes: at the head of the cirque, blocks detach and are overturned; towards the intermediate and lower parts of the cirque, blocks that roll are common.

In the zones of fault scarps, toppling is common (Figure 5, left photograph). Landslides can occur both in densely fractured rocky zones and in clayey materials (Figure 5, right photograph). Planar and wedge landslides can occur when discontinuities erupt on the face of a slope. Volcanoes occur principally in the nucleus of the Sierra de Guadalupe and in the Sierra de Las Cruces (Table 1).

Dome: the discontinuities that affect the domes are planes of flow or of cooling and generally also fractures of tectonic origin. On the flanks of the domes the

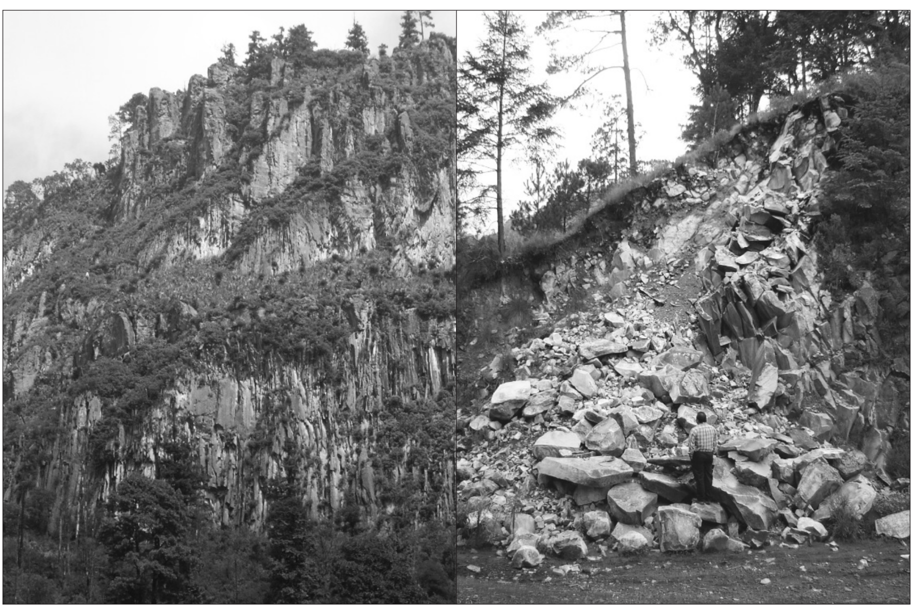


Figure 5. Toppling on fault scarps (left photograph) and landslides on slopes formed by fractured andesitic rocks (right photograph).

development of normal faults is common, so that this tectonic process induces fracturing in the rocks. These characteristics of the domes cause the structure of their surface to consist of blocks, whose geometry and arrangement reflect the dynamic of the placement. The form of the blocks is varied, with rectangular, irregular and rounded geometries predominating. The rolling of rocks is frequent, since there are blocks that are loose and resting freely on the surface (Figure 6, upper photograph). In addition, the overturning of rocks is common on the flanks of the domes and on the fronts of spills. Planar or wedge landslides occur mainly on cuts or cliffs, where discontinuities arise on the face of the slopes, and blocks or wedges of rock can move (Figure 6, lower photograph) (Table 1).

Figure 6. Rock falls (upper photograph) and fall of blocks and wedges in zones containing past mine workings (lower photograph).

Table 1. General summary of the types of processes associated with the volcanic structures, and their principal characteristics

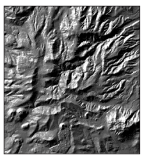
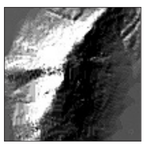
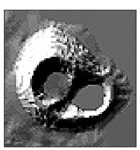
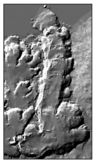
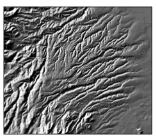
Shaded model relief	Volcanic structure and type of volcanism	Lava type and lithology	Structural features	Morphological features	Characteristics of rock masses	Potential mass movement
	- Volcanoes. - Stratovolcanoes. Effusive and explosive. Vulcanian and plinian eruptions.	Aa and blocky lavas. Andesite, dacite and rhyolite.	Generally affected by normal and lateral faults. Presence of fractures usually forming arrangements, fault breccia and scarps.	Presence of cirques, development of parallel and radial drainage. They have conic shape and present strongly dissection in faulting directions.	They are heterogeneous and anisotropic. Have discontinuities (flow bands, cooling surfaces and fractures). Their surface consists on an array of blocks of varied size and geometry.	Slide (plane, wedge, rotational, composite). Fall (block rolling or detachment of blocks in steep zones). Toppling (columnar blocks in steep areas).
	-Domes. Extrusive (mainly) and explosive.	Blocky lavas. Dacite and rhyolite.	They are affected by normal faults on its flanks When they presents elliptic form, reflects a structural control.	They have ellipsoidal shapes and present cirques associated with old collapses or landslides. Drainage is radial.	They are affected by discontinuities (planes of flow, cooling joints and tectonic fractures). The surface presents systematic arrangement of blocks with different size and geometry.	Slide (plane, wedge, rotational, composite). Fall (block rolling or detachment of blocks in steep zones). Toppling (columnar blocks in steep areas).
	- Scoria cones. - Tuff rings. - Tuff cones Explosive (mainly) and effusive. Strombolian and hydromagmatic activity.	Aa and pahoehoe lavas associated with flows. Basalt, basaltic andesite.	They are affected by normal faults. Elongation in one direction and the alignment of cones reflects a structural control.	They have conic shape and slopes ranging from 20 to 33 °. Their morphology is basically defined by the height, diameter of the crater and the outer diameter.	They form accumulations of granular material dispose in their friction angle. When exist lava flows, they consist in an arrangement of blocks.	Debris slide. Debris flows. Rock fall, by rolling when exists loose blocks on the terrain and by detachment in vertical slopes.

Table 1. Continue.

	- Lava flows. Effusive. Hawaiian activity.	Pahoehoe and aa lavas. Basalt, basaltic andesite.	Lava flows are controlled by crust fissures, and are associated with extensional environments.	They are extended and have low height. They emplace following the paleotopography. In front of lava flows The greater slopes generally are in the front of lava flows.	They present cooling surfaces and fractures generated during the emplacement. The discontinuities present columnar or aleatory arrangement.	Slide (rotational or composite). Rockfall (by rolling or detachment). Occasionally toppling.
	- Volcanoclastic deposits (block and ash, debris avalanches, mudflows). Explosive. Plinian and vulcanian activity	Heterogeneous lithology.	They can be removed after their emplacement. Can be affected by normal faulting and show cinematic indicator s like sigmoidal fractures or displacement of horizon guides.	They form the foothills of the stratovolcanoes. The drainage is parallel and reflects a structural control.	They are heterogeneous due to the presence of many types of deposits. The occurrence of differential erosion, rock falls,	Rockfall (detachment of blocks by erosion of the surrounding matrix). Unchannelized flows in the face of slopes. Channeled flows in rivers and ravines.

Basic lavas flows

Type of rock
Basalt: dark grey or black rocks with an aphanitic texture; quartz or olivine crystals can occasionally be seen, generally disturbed. At the fronts of the lava spills the presence of breccias is common. In general, the rocky masses formed by this type of rock have a chaotic or aleatoric fracturing. In some cases the fracturing is columnar, and structures typical of these flows can also be distinguished such as vesicles, corded lavas, tubes of lava and the presence of scorias.

Type of volcanic structure
Lava spills. These are widespread and of variable height. The steepest gradients occur at the edges of the spill, where there are lag breccias formed since the cooling of the frontal part of the flow; this is broken up by the advance of the flow, creating blocks. Blocks also form owing to cuts on the slopes, since there are discontinuities such as planes of cooling, contacts and cavities. In this type of volcanic structure the detachment of blocks is frequent and very characteristic. On very high slopes, with intense fracturing and disturbance, there can be landslides (Figure 7, left photograph). Rocks can roll when blocks of diverse sizes and shapes separate themselves from the rocky mass and remain freely scattered on the mountainsides (Figure 7, right photograph). Lava spills are characteristic of the volcanism of the Sierra de Chichinautzin, and are present in the boroughs in the south of Mexico City (Table 1).

Scoria cones
The cones are generally formed of dark to reddish rocks, vesicular, with granulometry that varies from sand to gravel with blocks intercalated in the sandy matrix. They are formed of granular material, occasionally with intercalations of lava. The movement processes are distributed radially, given their morphology. Depending on the predominance of blocks or detritus, the processes can be as follows: fall of rocks by rolling (loose blocks, bombs), superficial sliding of detritus (Figure 8, left photograph) and flows in cases where rainfall or anthropogenic changes mobilize the loose materials (Figure 8, right photograph) (Table 1).

These structures are typical of the volcanism that occurred in the southern part of the basin and they are found in the Sierra de Santa Catarina, Sierra de Chichinautzin, and towards the southern part of the Sierra de Las Cruces, in its intersection with Chichinautzin.

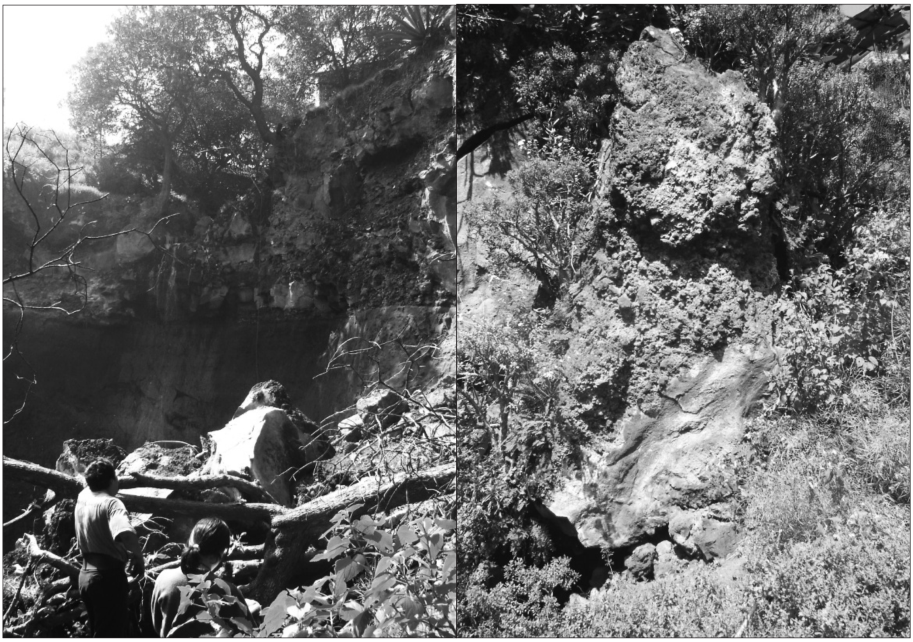


Figure 7. Landslides on basaltic fronts affected by infiltration of water (left photograph) and unstable scattered blocks (right photograph).

Granular volcaniclastic materials

These are formed from products derived from volcanic edifices and there are various types of deposits as follows. *a)* Flows of blocks and ash. This type of material consists of a heterogeneous mixture of irregular blocks of various sizes, embedded in a finer matrix, generally silty-sandy. *b)* Debris flows. These deposits are formed from granular material (gravels and sands) and form the ravines sides in the western and northern part of Mexico City. *c)* Debris avalanches (Table 1). These materials are the product of the collapse of volcanic structures and the materials are deposited lower down the mountainside. They consist of accumulations of blocks embedded within a finer matrix. Typical of these deposits are jig-saw fit structures. They are predominant in the Sierra de Las Cruces and are present to a lesser degree in the sierras of Barrientos and Guadalupe.

Type of structure

Volcanic deposits: these are heterogeneous, and most are a mixture, cemented or not, of particles that vary from sands and gravels to blocks. Because of the

Figure 8. Falls of detritus on scoria cones (left photograph) and flows of granular material in mining zones and affecting dwellings (right photograph).

alternation of blocks within the matrices of fine material (sand, silts), erosion and falls of detached rocks and detritus are frequent in this type of deposit, owing to the erosion of the matrix that surrounds the blocks. In addition, this alternation of materials with different resistances leads in some parts of these slopes to layers or strata that are cantilevered, *i.e.* without support below.

Channels and ravines have developed on these deposits, and these generally follow a structural control; they are prone to erosion of the walls, and to extensive inundations and flows of mud and/or detritus originating in the higher parts.

Unchannelled removal of material can occur when highly disturbed and weathered portions of the slopes lose cohesion or are affected by triggering agents such as rain, vibrations or excavations at the base (Table 1).

Susceptibility to Mass Movement Processes

The map of susceptibility (scale 1:75 000) of the SW portion of the Valley of Mexico, which includes Mexico City and part of the State of Mexico, was generated from the superposition of the thematic maps described above, in the Geographic Information System ILWIS, version 3.1.

The size of the cell considered was 25 m, which generated a mesh of 3 250 lines and 2 300 columns. The method used was based on assessment of the susceptibility in a heuristic manner, i.e. taking into account the criterion and the knowledge *a priori* of the study zone. The nature of this method is subjective, since evaluation of the maps and their rankings can vary as a function of the criterion of each specialist. However, this subjective assessment took into account the characteristics of the zone, and also incorporated the observations obtained during the field surveys, the information of the MMPs inventory (Figure 9), and the various experiments cited in the

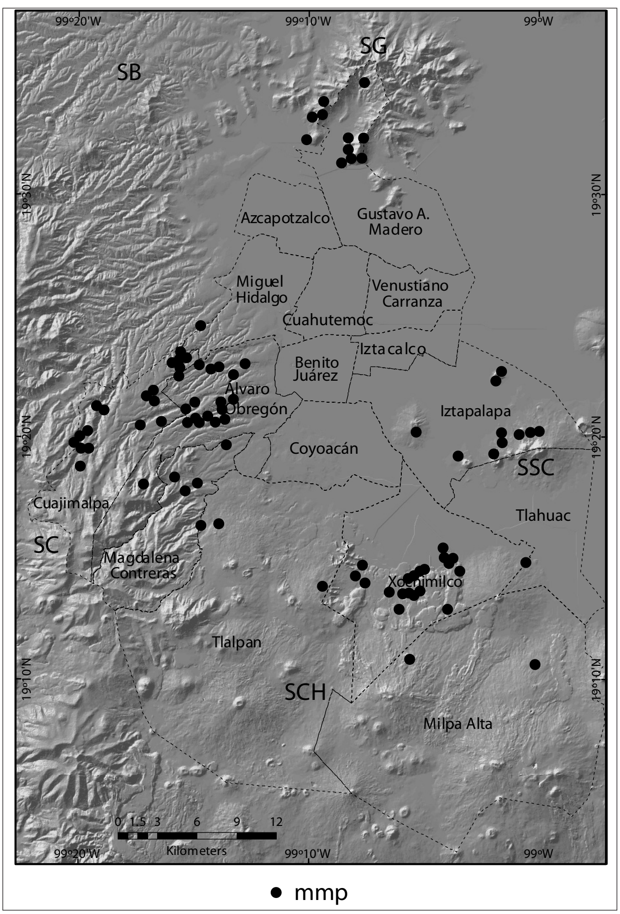


Figure 9. Mass movement processes inventory map.

literature with regard to the influence of each variable in the generation of these processes (Dai and Lee, 2002; Menéndez and Marquínez, 2002; Lee *et al*., 2002; Foumelis *et al*., 2004; Gómez and Kavzoglu, 2005; Moreiras, 2005; Van Westen *et al.,* 2006; Margielewski, 2006; Komac, 2006).

Thematic maps of the factors used for the cualitative estimation of susceptibility

The occurrence of mass movement processes is related to diverse factors, such as the lithology, geological structure, hydrogeology, topography, climate, seismicity and anthropogenic influence. Taking into account all the factors is a complex and laborious task. The elevation, the gradient and lithology are considered to be fundamental factors in the occurrence of MMPs (Brabb *et al*., 1972; Menéndez and Marquínez, 2002) and are considered to be the principal inputs in the production of maps of susceptibility that consider more variables (Figures 10 and 11).

Elevation

Altitude has an influence on the generation of MMPs. A correlation has been observed between rockfall and toppling processes and climatic factors associated to high elevation areas (*Ibid*.). Freeze-thawing processes are common in highlands; they induce stresses in rocks and discontinuities, and moisture due to rain and snow promote the disintegration and detachment of blocks and detritus in these areas. In order to produce the final susceptibility map, the altimetry was reclassified into three ranges (Figure 10A):

a) <2 700, covering the flat areas, foothills and the lower parts of the slopes;
b) 2700 - 3 100, including the middle sectors of the slopes;
c) > 3 100, defining the higher areas and the main bodies of the volcanic structures on the S and SO sectors.

Gradient

The gradient is one of the most influential factors in the occurrence of mass movement processes, and in ma-ny regional analyses it is used as one of the most important independent variables (Moreiras, 2005).

The following rankings were defined for the map of gradients: 0-3º constitutes the lacustrine plain in the central part of the study area, as well as relatively flat areas embedded within the mountainous zone that correspond with changes

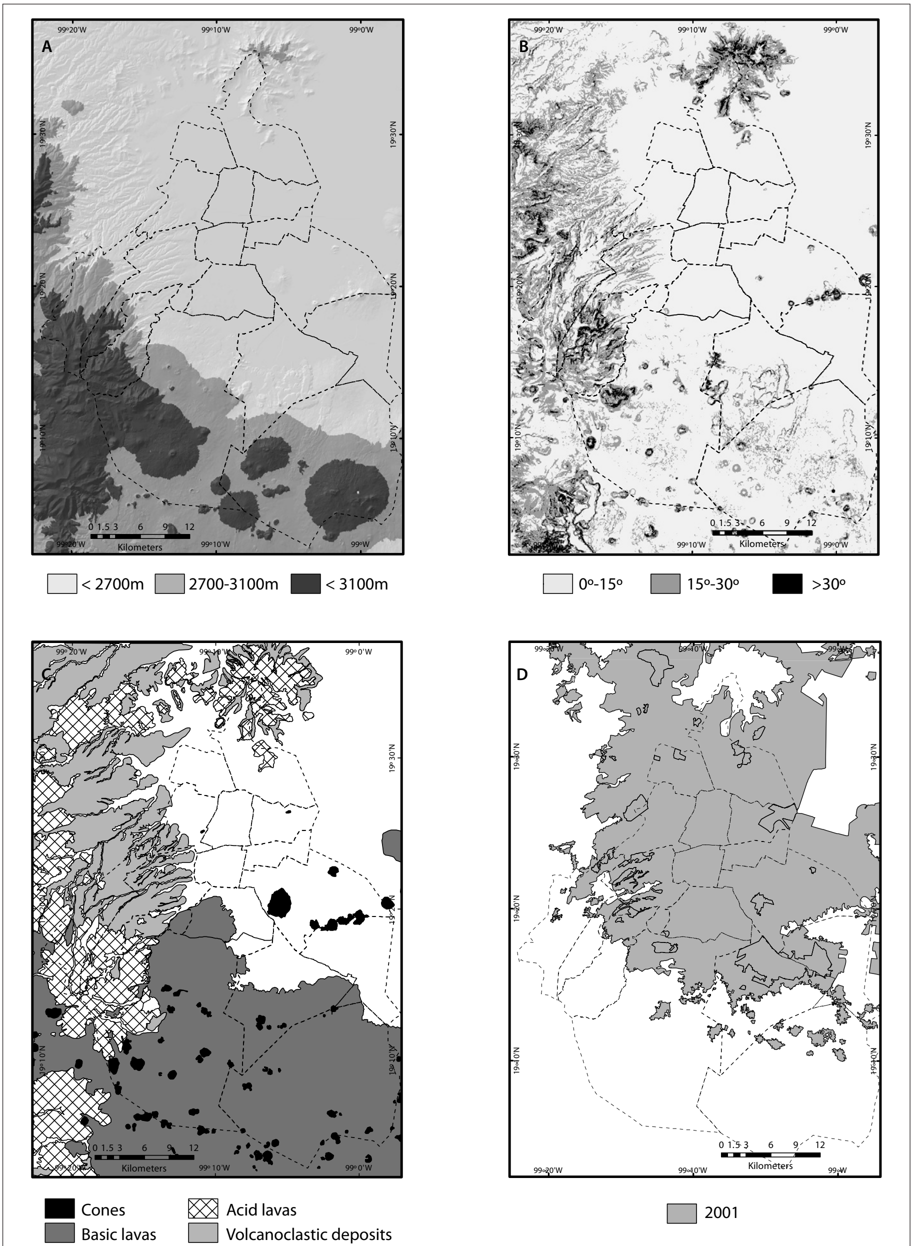


Figure 10. Thematic maps of the factors used for the estimation of MMP's susceptibility in the study area (1/2). A. Hypsometry; B. Slope; C. Reclassified lithology; D. Urban growth.

in the curvature of the slopes and with the higher parts and planes of lava spills or sequences of volcaniclastic flows; 3-6º includes the alluvial plain and slight inclinations of the piedmont; 6-12º defines the piedmont of the slopes, formed essentially from deposits of scree and transported material; 12-18º defines zones of curvature of the slopes and represents the lower zones of the mountains; 18-30º defines the high mountain zones and is very frequent mainly because of the influence of the denuding processes, and it also occurs at the fronts of lava flow and on the flanks of ravines and erosion cirques; and finally >30º defines the high mountain zones, the acute peaks and the slopes with a steep gradient related to scarps or signs of faults, fronts of lava flows, the heads of erosion cirques and the heads and flanks of ravines. This last range of gradients, in general, represents rocky and/or granular outcrops with active gravitational processes.

Taking into account the relationship that exists between the gradient and the mechanical properties of the materials, whether they be massive, fractured or granular, a gradient of 30º is considered as a threshold above which the MMPs increase in importance, since generally the majority of the rocks and discontinuities have an angle of friction that varies between 25º and 50º (Hoek and Bray, 1996) and the angle of friction of the loose to compact granular materials (sands and gravels) varies from 20º to 45º (González *et al*., 2002).

In order to produce the final susceptibility map, the gradient was reclassified into three ranges (Figure 10B):

a) 0-15°
b) 15-30°
c) >30°

Lithology

It is important to know the type of rock and the geological structure of the slopes of the study area, since, depending on their origin and formation, the rocky slopes inherit structural and lithological features that will influence their behaviour (Hutchinson, 1988). The geological map was reclassified into four lithologies with the aim of simplifying it and grouping the lithologies that present similar mechanisms of movement, given their geologic characteristics (Figure 10C).

Urban area

Mountain terrains subjected to urbanization may have stability problems associated with anthropogenic influence, the overload of constructions, cuts in the slopes either for road construction or housing, leakage of water for domestic use, and presence of debris or loose material on the slope, have a significant influence on stability. Such influence is aggravated by the use of inappropriate construction methods that do not take into account the characteristics and behavior of materials, in addition to the lack of mitigation works. A map of urban growth was used as an input to increase the weight of susceptibility (Figure 10D). The later as a result of field work observations which suggest the negative impact of human settlements in terms of activities such as cutting of slopes, the consequent generation of loose material, domestic water infiltration, generation of vibrations due to heavy vehicles and construction overburden.

Faults and tectonic lineaments

Some studies have shown that the probability of occurrence of MMPs increases significantly in zones near tectonic lines (Lee *et al*., 2002; Gómez and Kavzoglu, 2005). Landslide susceptibility is increased in these areas due to presence of fracturing and breccias associated with faults.

Faults form a line or zone of weakness characterized by heavily fractured rocks, which generates blocks with the possibility of sliding, toppling or detachment.

From the analysis of shaded relief models, considering inclinations of the angle of light to every 45°, the tectonic lineaments of the area of interest were marked and a buffer or zone of influence of 25 m on both sides was later applied (Figure 11A).

Erosion cirques

Erosion cirques are a concave shape of mountainous relief. They resemble an amphitheater with steep slopes, which is originated in the headwaters of some streams, by sliding, volcanic collapse and erosive action of small river runoff affecting a main channel (Lugo, 1989). Moreover, in the case of structures such as volcanoes, erosion cirques are scars originated by partial collapse and generally are erosive forms that control runoff from the highlands.

The orientation of discontinuities in the heads and flanks of the erosion cirques determine the types of MMPs, which may be sliding if the discontinuities are inclined and exposed in the front, or toppling if they are subvertical. In lower parts of the head of erosion cirques, it is common to find loose blocks on the surface, that can slide or roll, depending on their shape and topography. From the analysis of shaded relief models, with inclinations of the angle of light to every 45°, the erosion cirques were marked. Given the work scale, a buffer of 25 m on

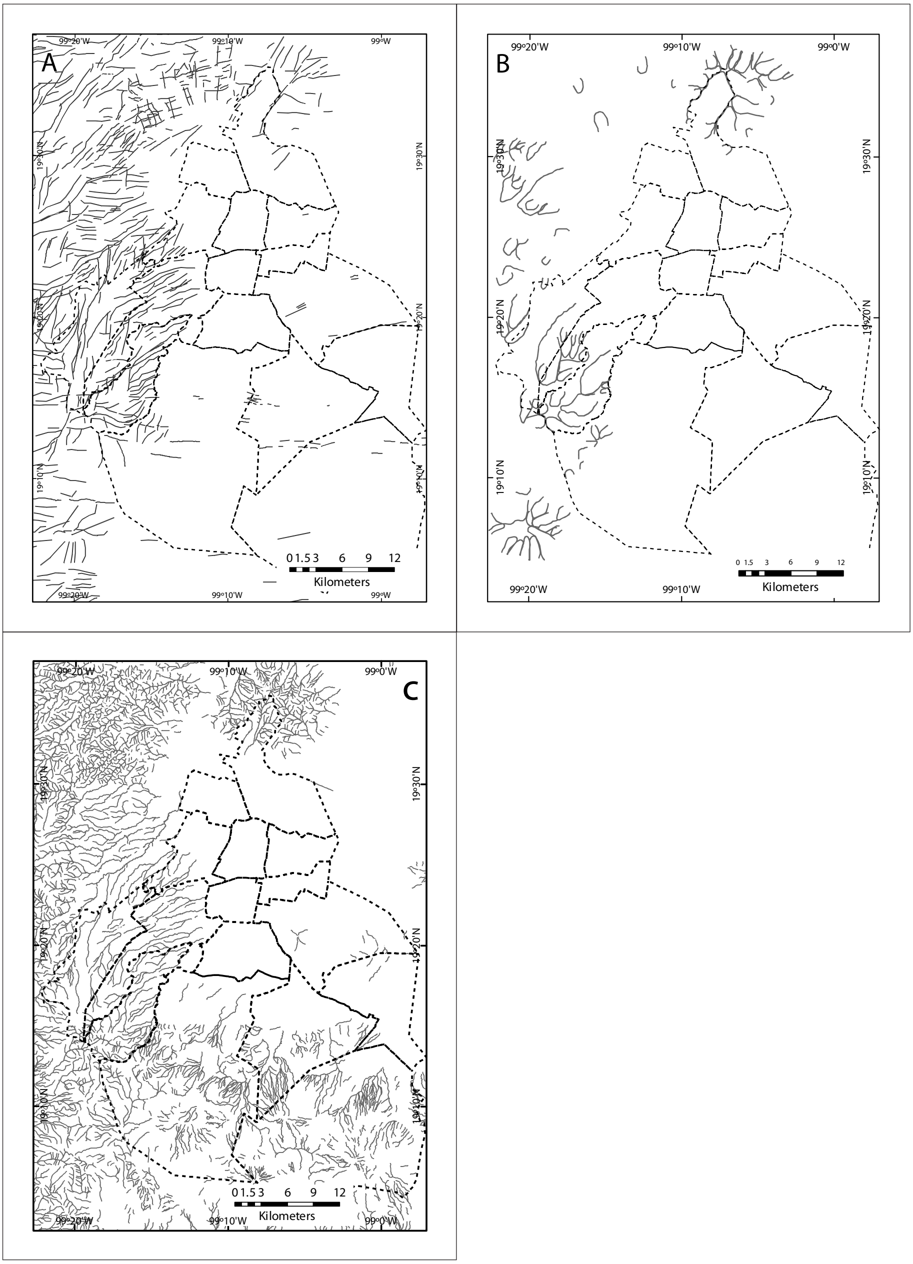


Figure 11. Thematic maps of the factors used for the estimation of MMP's susceptibility in the study area (2/2). A. Lineaments; B. Erosion cirques; C. Stream networks.

both sides of these features was considered in order to extend the affected area (Figure 11B).

Drainage

Several studies have shown the correlation between the generation of MMPs and the proximity to drainage lines (Dai, 2002; Foumelis *et al*., 2004). Erosion in streams and ground saturation control the occurrence of landslides and flows.

The drainage is expressed by the generation of gullies, which are negative forms of relief, with steep slopes, often branching towards the head, with the banks without vegetation. A gully is prone to present erosion processes and MMPs depending on the type of material, degree of fluvial erosion, and interaction of internal and external forces. MMPs that occur in these areas are mainly landslides, rock falls, mud and debris flows.

In this investigation, the drainage network instead of the density value of dissection (stream length/area) has been taken into account. Moreover, it has been assumed that the influence of drainage occurs precisely where these features are located. A buffer or zone of influence of 25 m, according the scale of work (Figure 11C), was considered, in addition to the assumption that drainage lines themselves define zones likely to be susceptible to present slides and debris flows.

The variables and their rankings, together with the maps of lineal and areal features, were combined by use of the principles of Boolean algebra, which assigned levels of susceptibility in a qualitative and subjective manner. Obviously, this can lead to generalizations owing to the subjective basis of the method, and because of the scale and the parameters involved; however, it also represents an advance in the study and analysis of MMPs, in the sense of determining the critical areas, taking as a base the most important characteristics of the relief, as well as the occurrence of mass movements within the region

The resultant map (Figure 12) is of great importance, since as well as being the first of its type, it is useful in establishing the areas that are likely to have some type of instability; this is an input necessary for taking corrective and preventative measures, and also for establishing the points or zones that are critical where special attention should be paid in risk management.

Statements based on the set theory of Boolean algebra were used in order to obtain the ranking HIGH, MEDIUM and LOW. For this, the levels of susceptibility were determined from the combination of the three principle variables: the gradient, the lithology and the altitude. Subsequently, the other variables represented in thematic maps of lineaments, erosion cirques, drainage and urban

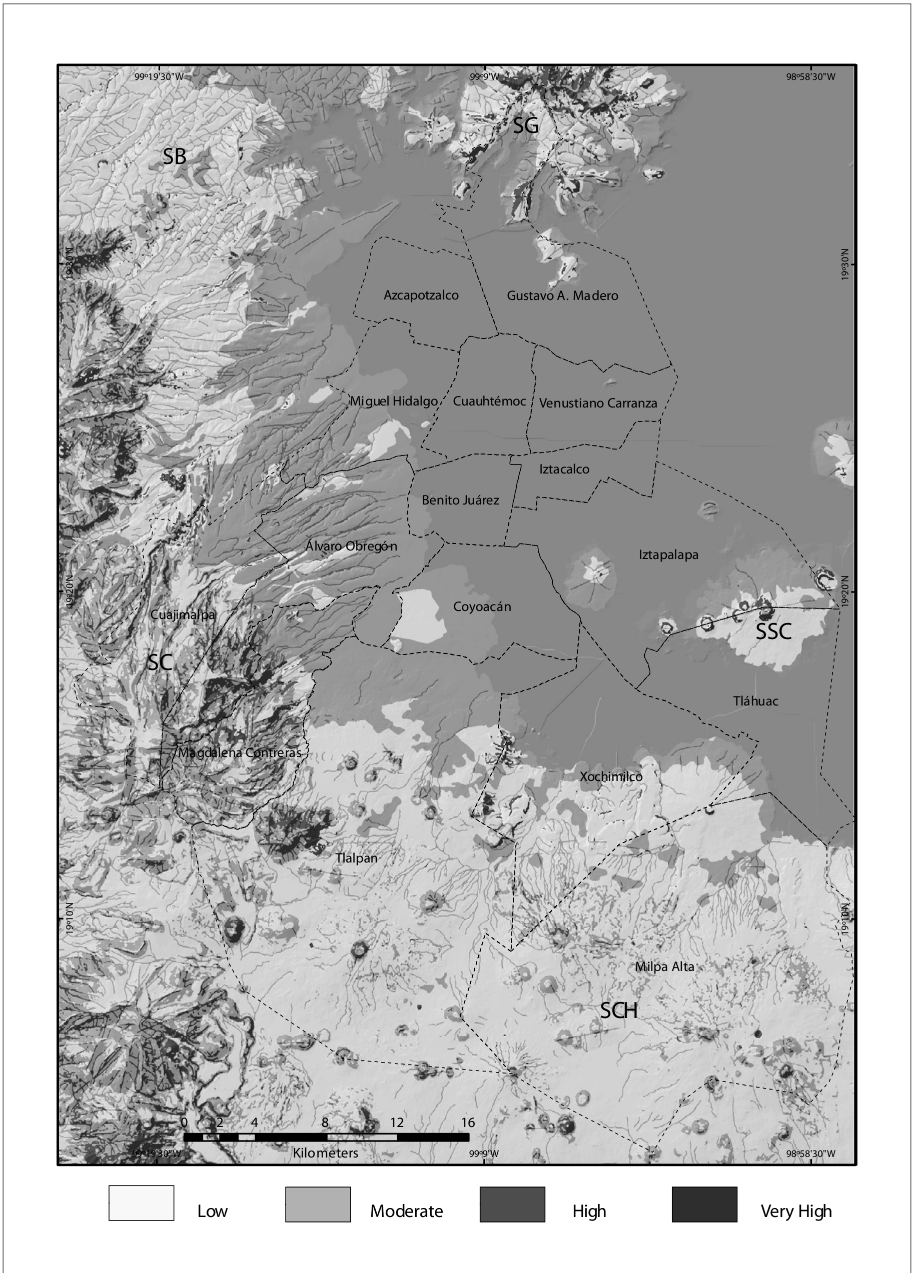


Figure 12. Mass movement processes susceptibility map.

Table 2. Mass movement processes susceptibility levels

Susceptibility level	Description
LOW	Slope range smaller than 30°, lack of urbanization. The presence of lineaments or erosion cirques is not significant. Elevations greater than 2 700 m.a.s.l. in all lithological groups.
MODERATE	Moderate slopes, ranging from 15 to 30°, with existence of urban areas and drainage networks. Areas with slopes greater than 30°, and presence of lineaments, erosion cirques and elevations above 2 700 m.a.s.l., but lacking of urbanization. It stands out, a wide area located in the western sector of the area of interest, where lithology is comprised by granular deposits, an urban area, drainage networks and less than 2700 m.a.s.l. elevations.
HIGH	Incidence of granular materials, drainage networks, and urbanization in areas of elevations minor than 2 700 m.a.s.l. and slopes lower than 30°. Such areas are stream or gullies subjected to anthropic influences located in the lower zones, where drainage networks initiated in the erosion cirques merge.
VERY HIGH	Areas with slopes greater than 30° with presence of lineaments or erosion cirques. In higher ground they comprise all lithological types. Occasional drainage networks.

zones served as input for delineating critical zones, and the level of susceptibility grew to VERY HIGH (Table 2).

This can be useful for mitigation measures, since the appropriate stabilization measures are a function of the specific mechanism of the slope movement.

Results and Conclusions

Volcaniclastic deposits have a wide range of granulometry, form of emplacement or deposition on the terrain, and geomechanical characteristics; this determines different types of processes that can involve falls of rock and granular material, landslides, and flows along channels and ravines. In particular, the characteristics of the volcanic rocks that influence the generation of MMPs in the area of interest are (1) the presence of anisotropic sequences (lavas and pyroclasts), (2) fissures associated with cooling, (3) planes of flow, (4) fractures, (5) vesicles and cavities, (6) the presence of loose blocks, and (7) accumulations of granular material.

The presence of sequences of lava intercalated with pyroclastic deposits gives the rocky masses a heterogeneous and anisotropic character. The heterogeneity implies the existence of zones with different mechanical and hydraulic properties, degree of alteration, and water content, among other characteristics. The anisotropy implies the presence of surfaces of contact across which the properties of resistance and of permeability are different from those obtained in other directions.

Falls by detachment are associated with zones of gradient, such as scarps and cliffs of anthropogenic origin (such as quarries), which have cubic or irregular blocks in a cantilever position and demarcated by planes of weakness. The original movement is in free fall, and rebounds and rolling can occur. Fall by rolling is related to blocks with a rounded, sub-rounded or irregular form, which become separated from rocky masses simply scattered on the slopes.

Turning over of blocks is characteristic where there is associated vertical fracturing and tabular blocks or columns formed by the orthogonality of the discontinuities. This mechanism is associated with zones of steep gradient such as fault scarps, heads of landslide cirques and fronts of lava flows.

Rotational slides occur at lava fronts characterized by the presence of chaotically fractured breccias and with fractures filled with material that varies from sands to clays, in zones of listric faults, on slopes formed by a superficial clay layer. The superficial sliding of detritus is frequent on slopes or taluds formed from loose material and blocks arranged at an angle greater than the angle of friction of the materials.

Sliding of blocks is associated with blocks or wedges whose planes or lines of intersection rise to the surface of the slope, their movement being kinematically admissible. It also arises in tabular blocks that are scattered on the soil cover in zones with steep gradients.

Flows of detritus can form during intense precipitation in zones with a steep gradient and where intense fracturing exists, which gives rise to detrital material and blocks.

The triggering agents that are of anthropogenic origin merit particular attention, since their influence can be avoided or reduced, unlike those of natural origin (intense rainfall, seisms, biological agents, progressive loss of resistance to undercutting, weathering and erosion). Among the actions of anthropogenic origin observed with the greatest frequency are the following: deforestation and burning of rubbish, felling on the slopes for building infrastructure and dwellings, leaks of water, vibrations from vehicles, rotating machinery and the use of explosives in mine works, overloading at the top of the slopes, alteration of the geohydrological regime, dumping of rubble, terracing the slopes for cultivation, inadequate building regulations, and counterproductive or ineffectual stabilization works (as in the occasional use of sprayed concrete).

The map of susceptibility indicates that the critical zones or those with the greatest tendency to experience MMPs are distributed as follows.

a) To the north, in the Sierra de Guadalupe, they occur principally in its central and highest part, affecting andesitic volcanoes, and they also occur in very localized areas of the periphery, near dacitic domes. In this mountain range the abundant erosion cirques and lineaments are conspicuous; these define scarps and zones of steep gradient. The urban growth in this region extends in many cases towards the high parts of the slopes, near the outcrops affected by intense fracturing and brecciation and with an abundance of blocks loose on the slope. The points where MMPs have been registered are found on Tenayo Hill, in the zone known as Cabeza de Águila and on Chiquihuite Hill, where there is a major recurrence.

b) To the east, in the Sierra de Santa Catarina, the zones of very high susceptibility are on the periphery of the scoria cones. The MMPs in this region occur principally on the lava spills that surround the range, mainly in the northern zone, which includes the Iztapalapa borough; even though this zone is not classed as having very high susceptibility, the anthropogenic factor added to local conditions favours the occurrence of movements. In addition, two events have been recorded on Peñón del Marqués Hill, and these virtually coincide with zones of high or very high susceptibility.

c) A notable feature in the Sierra de Santa Catarina is that in the southern part, corresponding to the Tláhuac borough, where there is no urban zone because this area has been reserved for conservation, the susceptibility has a low level; this contrasts with the northern part where the Iztapalapa borough is found, which is subject to considerable urban growth.

d) To the south, the zones of very high susceptibility occur on the periphery of the scoria cones as well as on some portions on the fronts of lava spills of the Sierra de Chichinautzin. The boroughs affected are Xochimilco, Tlalpan and Milpa Alta.

e) The incidence of MMPs on the lava fronts is clearly illustrated in the Xochimilco borough, where 19 events have been recorded. The zone most affected coincides with the lava spill in the central part of this borough, bordering on the Teuhtli volcano.

f) To the west, there are large concentrations of areas classified as having a high or very high level of susceptibility. In general, in the Sierra de Las Cruces there is the greatest number of erosion cirques, lineaments and also considerable drainage lines with radial, dendritic or parallel patterns. This zone includes the highest altitudes in the study area (3 870 m asl on the San Miguel volcano). In addition, in many zones the gradient exceeds 30° and in some cases, such as in the zone of los Dinamos, the scarp of the Magdalena Contreras fault forms a virtually vertical wall. However, the MMPs recorded are found principally in the volcaniclastic deposits that form the relief of the Miguel Hidalgo, Álvaro Obregón, Cuajimalpa and Magdalena Contreras boroughs, principally on the lateral walls of the ravines as well as in the zones on the channels. It is noticeable that according to the criterion established by the superposition of the thematic maps, many drainage lines change their level of susceptibility from medium to high when they join the urban zone, and this is due to the qualitative weight established for this variable. This is because in the urban zones there are cases in which the channel bed is blocked or even built on, which obstructs the flow of water when it rains, and there is felling and undermining. Also, it is common practice to throw waste, rubbish and rubble into the ravines.

Indisputably, the process of urbanization experienced by Mexico City has been accompanied by increased risk for its inhabitants, given its topographical, geological, and structural conditions and the mechanical behaviour of the volcanic materials that form the slopes that surround it, as well as the vulnerability of the population (Alcántara, 2002; Alcántara, 2010a, b).

MMPs harm the population and the civic infrastructure, and for this reason it is imperative that more detailed and larger-scale studies be undertaken in order to characterize these processes with greater precision. The generation of maps of susceptibility, danger, vulnerability and risk with regard to MMPs and also other processes, is fundamental for Mexico City, given its importance and the great nucleus of population that forms it. The result of the present work allows a regionalization of the slope processes that affect Mexico City, but these should be studied in more detail, in order to arrive at specific mitigation measures that are adapted to the conditions determined for each slope, in an attempt to avoid the use of geotechnical treatments that are very extensive but of little efficacy when used indiscriminately.

References

Alaniz Álvarez, S. A., A. F. Nieto Samaniego and L. Ferrari (1998), "Effect of the strain rate on the distribution of monogenetic and polygenetic volcanism in the Transmexican Volcanic Belt", *Geology*, vol. 26, pp. 591-594.

Alcántara Ayala, I. (2002), "Geomorpholgy, natural hazards, vulnerability and prevention of natu-
ral disasters in developing countries", *Geomorphology*, no. 47, pp. 107-124.

Alcántara Ayala, I. (2010a), "Disasters in Mexico and Central America: a little bit more than a century of natural hazards", in Latrubesse, E. (ed.), *Natural Hazards and Human Exacerbated Disasters in Latin America*, Elsevier, The Netherlands, pp. 75-98.

Alcántara Ayala, I. (2010b), "Geomorphology and disaster prevention", in Alcántara Ayala, I. and A. Goudie (eds.), *Geomorphological Hazards and Disaster Prevention*, Cambridge University Press, Great Britain, pp. 269-278.

Bloomfield, K. (1975), "A late-Quaternary monogenetic volcanic field in Central Mexico", *Geology Research*, vol. 64, pp. 476-479.

Brabb, E. E., E. H. Pampeyan and M. G. Bonilla (1972), "Landslide susceptibility in San Mateo County, California", *U. S. Geological survey Miscellaneous field Studies* Map, scala 1: 62 500.

Colín, A. (2006), *Neotectónica del graben de Tláhuac-Tulyehualco*, Escuela Superior de Ingeniería y Arquitectura, Instituto Politécnico Nacional, tesis profesional (inédita).

Concha, A. (2006), *Caracterización geomecánica y modelación numérica de los deslizamientos críticos de la Sierra de Guadalupe, Edo. de México*, Instituto de Geología, UNAM, México.

Dai, F. C. and C. F. Lee (2002), "Landslide characteristics and slope instability modeling ising GIS, Lantau Island, Hong Kong", *Geomorphology*, no. 42, pp. 213-228.

De Cserna, Z., M. De la Fuente, M. Palacios, L. Triay, L. Mitre and R. Mota (1988), *Estructura geológica, gravimetría, sismicidad y relaciones neotectónicas regionales de la Cuenca de México*, Instituto de Geología, Boletín 104, UNAM, México.

Dirección General de Protección Civil (2004), Internal Reports.

FAO-UNESCO (1974), *Soil Map of the World*, 1:5 000 000, vol. 1, Legend, Unesco, Paris.

Fink, J. H. and S. W. Anderson (2000), "Lava domes and coulees", in Sigurdsson, H. (ed.), *Encyclopedia of volcanoes: Estados Unidos de América*, Academia Press, pp. 307-319.

Flores Moro, V. (2006), *Geometría estructural y cinemática de la Fosa de Barrientos, zona centro-poniente de la Cuenca de México*, tesis profesional, Instituto Politécnico Nacional, México.

Foumelis, M., E. Lekkas and I. Parcharidis (2004), "Landslide susceptibility mapping by GIS-based qualitative weighting procedura in Corinth area", *Bulletin of the Geological Society of Greece*, vol. XXXVI, pp. 904-912.

García Palomo, A., J. L. Macías, J. Tolson, G. Valdez and J. C. Mora (2002), "Volcanic stratigraphy and geological evolution of the Apan Region, East-Central Sector of the Trans-Mexican Volcanic Belt", *Geofísica Internacional*, vol. 41, no. 2, pp. 133-150.

García Palomo, A., V. Carlos Valerio, C. López Miguel and A. Galván García (2006b), "Landslide inventory map of Guadalupe Range, north of the Mexico Basin", *Boletín de la Sociedad Geológica Mexicana*, número especial de Geología Urbana, tomo LVIII, núm. 2, pp. 195-204.

García Palomo, A., J. J. Zamorano, C. López Miguel, A. Galván García, V. Carlos Valerio, R. Ortega and J. L. Macías (2008), "El arreglo morfoestructural de la sierra de Las Cruces, México Central", *Revista Mexicana de Ciencias Geológicas*, vol. 25, núm. 1, pp. 158-178.

Gómez, H. and T. Kavzoglu (2005), "Assessment of shallow landslide susceptibility using artificial neural networks in Jabonosa River Basin, Venezuela", *Engineering Geology*, no. 78, pp. 11-27.

González, L., M. Ferrer, L. Ortuño and C. Oteo (2002), *Ingeniería Geológica*, Prentice Hall, Pearson Education, Madrid.

Gunn, B. M. and F. Mooser (1971), "Geochemistry of volcanics of central Mexico", *Bull. Volcanol*, vol. 34, pp. 577-616.

Gutiérrez de MacGregor, M. T. (1997), "Crecimiento espacial de las principales ciudades", *Atlas Nacional de México*, sec. III, tomo I, Instituto de Geografía, UNAM, México.

Hoek, E. and J. W. Bray (1996), *Rock Slope Engineering*, 3a. ed., Institution of Mining and Metallurgy.

Hutchinson, J. N. (1988), "General Report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology", *Proceedings of the Fifth International Symposium on Landslides*, vol. I, editado por Christophe Bonnard.

INEGI (2005), *Estadísticas del medio ambiente del Distrito Federal y Zona Metropolitana 2002*, Instituto Nacional de Estadística, Geografía e Informática.

Jacobo Albarrán, J. J. (1985), "Estudio petrogenético de las rocas ígneas de la porción Central del Eje Neovolcánico", *Revista del Instituto Mexicano del Petróleo*.

Komac, M. (2006), "A landslide susceptibility model using the Analytical Hierarchy Process method and multivariate statistics in perialpine Slovenia", *Geomorphology*, no.74, pp. 17-28.

Lee, S., U. Chwae and K. Min (2002), "Landslide susceptibility by correlation between topography and geological structure: the Janghung area, Korea", *Geomorphology*, no. 46, pp. 149-162.

Lozano Barraza, L. (1968), *Geología de la Sierra de Guadalupe, México, D.F.*, tesis profesional, Instituto Politécnico Nacional, Escuela Superior de Ingeniería y Arquitectura, México.

Lugo Hubp, J. (1989), *Diccionario geomorfológico*, Instituto de Geografía, UNAM, México.

Lugo Hubp, J., F. Mooser, A. Pérez Vega and J. J. Zamorano Orozco (1994), "Geomorfología de la Sierra de Santa Catarina", *Revista Mexicana de Ciencias Geológicas*, vol. 11, no. 1, Instituto de Geología, UNAM, pp. 43-52.

Lugo Hubp, J., M. Cordero Estrada and J. J. Zamorano Orozco (1995), "Relieve, litología y riesgos en la zona urbana de la delegación Álvaro Obregón, Distrito Federal, México", *Revista Mexicana de Ciencias Geológicas*, Instituto de Geología, UNAM, vol. 12, no. 1, pp. 52-67.

Lugo Hubp, J. and A. Salinas Montes (1996), "Geomorfología de la Sierra de Guadalupe (al norte de la Ciudad de México) y su relación con peligros naturales", *Revista Mexicana de Ciencias Geológicas*, vol. 13, no. 2, Instituto de Geología, UNAM, México, pp. 240-251.

Margielewsky, W. (2006), "Structural control and types of movements of rock mass in anisotropic rocks, Case studies in the Polish Flysch Carpathians", *Geomorphology*, no. 77, pp. 47-68.

Márquez, A., S. Verma, F. Anguita, R. Oyarzun and J. Brandle (1999), "Tectonics and volcanism of Sierra Chichinautzin: extension at the front of the Central Trans-Mexican Volcanic belt", *Journal of Volcanology and Goethermal Research*, vol. 93, pp. 125-150.

Martín del Pozzo, A. L. (1980), *Volcanología de la Sierra Chichinautzin*, tesis de Maestría, UNAM, México.

Martín del Pozzo, A. L., C. Córdova and J. López (1997), "Volcanic impact on the Southern Basin of Mexico during the Holocene", *Quaternary International*, vol. 43/44, pp. 181-190.

Martín del Pozzo, A. L. (1982), "Monogenetic vulcanism in sierra Chichinautzin, Mexico", *Bull. Volcanol.*, vol 45-1, pp. 9-24.

Menéndez, D. R. and J. Marquínez (2002), "The influence of environmental and lithologic factors on rockfall at a regional scale: an evaluation using GIS", *Geomorphology*, no. 43, pp. 117-136.

Mooser, F. (1974), *Paleomagnetic investigations of Tetiary and Quaternary igneos rocks, VII, a paleomagnetic and Petrologic study of volcanics of the Valle de Mexico*, pp. 451-483 y mapa geológico.

Mooser, F. (1975), *Historia geológica de la Cuenca de México, Memoria de las Obras de Drenaje Profundo del Distrito Federal, México, D.F.*, Departamento del Distrito Federal, tomo1, p. 7-38, mapa geológico.

Mooser, F., A. Montiel and A. Zuñiga (1992), "Nuevo mapa geológico del sur-poniente del Valle de México", *Simposio "Experiencias geotécnicas en la zona Poniente del Valle de México"*, Sociedad de Mecánica de Suelos de México, pp.3-32.

Mora Álvarez, G., C. Caballero, J. Urrutia Fucugauchi and S. Uchiumi (1991), "Southward migration of volcanic activity in the Sierra de Las Cruces, basin of Mexico? A preliminary K-Ar dating and paleomagnetic study", Geofísica Internacional, vol. 30, no. 2, pp. 61-70.

Moreiras, S. M. (2005), "Landslide susceptibility zonation in the Rio Mendoza Valley, Argentina", *Geomorphology*, no. 66, pp. 345-357.

Osete, M. L., V. C. Ruíz Martínez, C. Caballero, C. Galindo, J. Urrutia and D. Tarling (2000), "Southward migration of continental volcanic activity in the Sierra de Las Cruces, Mexico: paleomagnetic and radiometric evidence", *Tectonophysics*, vol. 318, pp. 201-215.

Pasquaré, G., L. Vezzoli and A. Zanzhi (1987), "Morphological and structural model of Mexican Volcanic Belt", *Geofísica Internacional*, no. 26, pp. 159-176.

Romero Terán, E. (2001), *Geología del Complejo Volcánico San Miguel, al sur poniente de la Cuenca de México*, tesis de Licenciatura, UNAM, México.

SEGEOMET (2000), Mapa de riesgos geológicos del flanco norte de la Sierra de Santa Catarina, delegación Iztapalapa, D. F., Programa parcial de desarrollo urbano de la Sierra de Santa Catarina, Servicio Geológico Metropolitano, México.

SEGEOMET (2003), Proyecto "Evaluación y zonificación de los peligros geológicos por deslizamiento en las laderas de la Sierra de Guadalupe, Estado de México", Servicio Geológico Metropolitano, México.

SEGEOMET (2005), Proyecto "Mapas de peligro sísmico y de susceptibilidad por procesos de remoción en masa", Servicio Geológico Metropolitano, México.

Siebe, C., V. Rodríguez Lara, P. Schaaf and M. Abrams (2004), "Radiocarbon ages of Holocene Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico City: implications for archaeology and future hazards", *Bulletin of Volcanology*, vol. 66, no. 3, pp. 203-225.

Siebe, C., L. Arana Salinas and A. Michael (2005), "Geology and radiocarbon ages of Tláloc, Tlaco-
tenco, Cuauhtzin, Hijo del Cuautzin, Teuhtli, and Ocusacayo monogenetic volcanoes in the central part of the Sierra Chichinautzin, Mexico", *J. Volcanol. Gheotherm. Res*, vol. XX, pp. 1-19.

Suárez, J. (1998), *Deslizamientos y estabilidad de taludes en zonas tropicales*, Instituto de Investigaciones sobre Erosión y Deslizamientos, Colombia.

Suter, M., M. López Martínez, O. Quintero Legorreta and M. Carrillo Martínez (2001), "Quaternary intra-arc extension in the central Trans-Mexican volcanic belt", *GSA Bull.*, vol. 113, no. 6, pp. 693-703.

Tapia Varela G. and J. López Blanco (2001), "Mapeo geomorfológico analítico de la porción central de la Cuenca de México: unidades morfogenéticas a escala 1:100 000", *Revista Mexicana de Ciencias Geológicas*, vol. 19, no. 1, pp. 50-65.

TGC Geotecnia (1998), "Análisis de la estabilidad de los taludes de la zona norte del conjunto habitacional "Peñón Viejo"", localizado en Congreso de Apatzingán No. 266, Iztapalapa, México.

Van Westen, C. J., T. W. Van Asch and R. Soeters (2006), "Landslide hazard and risk zonation-why is it still so difficult?", *Bull Eng Geol Env.*, no. 65, pp. 167-184.