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Geology and Geomorphology in Landscape Ecological Analysis for Forest Conservation and Hazard and Risk Assessment, Illustrated with Mexican Case Histories

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1. Introduction

The aim of landscape ecology is to understand both the effects of spatial patterns on ecological processes, and the development of those spatial patterns. It is considered holistic since it regards nature as a whole and it deals also with all human environment interactions. Application of landscape ecological principles for prioritizing rich species sites has the advantage of integrating spatial information, non-spatial information, and horizontal relationships in space and time.

Landscapes are complex systems constituted by a large number of heterogeneous components (with different geology, geomorphology, vegetation cover, ecological communities, land uses and so on) interacting in a non-linear way, that are hierarchically structured and scale-dependent (Wiens, 2009, Hall *et al.*, 2004). Landscape description and structure has traditionally been done on the basis of landscape metrics, that is, basic measures of the amount of habitat and core habitat, the number of discrete patches and the perimeter to area ratio. However many of these metrics are generally poorly tested and require of rigorous validation if they are to serve as reliable indicators of habitat loss and fragmentation (McAlpine and Eyrie, 2002). There are strategies which can help to improve the reliability of landscape pattern analysis (Shao and Gu, 2008). Since landscape pattern is spatially correlated and scale dependent, often multiscale information is required (Wu, 2004).

The study of causes, processes and consequences of land/cover change is one of the main research topics of landscape ecology. It is important to study processes and not merely spatial patterns considering cultures as a drivers of landscape change. Knowledge of temporal changes in landscape composition and structure, and their driving processes, can provide insight into regional landscape dynamics (Luke, 2000; Burgui *et al*, 2004).

Landscape information is of the out most importance to develop appropriate policies for environmental planning and nature conservation (Gulink *et al*., 2000). An example of recognition of landscape ecology as an essential field of science for territorial planning is the project of the metropolitan region of Barcelona (Forman, 2004), in which environmental principles based on landscape ecology and sustainable use of resources and basic spatial models are applied, even when lacking quantitative regional analysis.

2. Geology and geomorphology as fundamental elements in landscape analysis

Several terrain characteristics are important for soil scientists, geologists, and geographers, because of their strong influence in the capability of the land to support various plant or animal species, or for terrain evaluation. Geologic origin and structure can be estimated by air photo interpretation and satellite image analysis. Sedimentary (sandstone, shale, limestone) or igneous rocks can be differentiated using digital analysis (remote sensing and GIS). The recognition of strike and dip attitudes, land form types, drainage patterns and the orientation of highlights and shadows, as well as susceptibility to flooding, are based on geomorphology (Sabins, 1978, Lillesand and Keiffer, 1979, Verstappen, 1988). Geomorphological analysis is greatly improved by the use of aerial photographs and satellite images, since they provide a synoptic view of terrain and a relatively rapid description of geographic distribution of major landforms and dominant land cover. Terrain classification based on landforms, lithology and genesis (historical processes) can be further specified into biogeomorphic land units on the basis of geomorphologic processes, relative age, sediment, drainage, and land cover/use (García-Aguirre *et al*., 2010).

Ecological research provides ample evidence that topography can exert a significant influence on the processes shaping broad-scale landscape vegetation patterns. Unfortunately, the standard methods for landscape pattern analysis are not designed to include topography as a pattern shaping factor. Topography features may be derived from the digital elevation models (DEM) to obtain slope and aspect maps (Dorner *et al*., 2002, Peiffer *et al*. 2003). A DEM and Landsat images were used to assess topographical complexity and evaluate changes in landscape composition and structure after fire (Viedma, 2008). Simultaneous analysis of maps of non-biotic elements (such as geology, geomorphology and topography) and biotic elements (land use/cover) allow to generate synthetic and systematic information of landscape in the form of biogeomorphic land unit maps (Zonneved, 1995).

3. Remote sensing and GIS in landscape analysis

Remote sensing and GIS are essential tools for generation of landscape thematic information (Gulink *et al*., 2000) even when it is common to face problems during integration of different data sources in the GIS (Tinker *et al*., 1998). Advances in remote sensing technologies have provided practical means for land use/cover mapping, which is particularly important for landscape ecological studies. These tools can also efficiently identify and assess areas of landscape damage at different scales and help land managers to solve specific problems. However, it is a key consideration to evaluate the remote sensing data and methods used as well the scale and information needed, for instance, to correctly define the best resolution to use (Ludwing *et al*., 2007), as well as to find the best procedures to follow when linking data of different qualities (Falcucci, *et al*., 2007). Land cover change information through time, combined with thematic information can be stored and managed efficiently in a GIS since it relates different layers of spatial information. In addition, it is a powerful analysis tool that allows identification of spatial relationships among different maps, through connection of spatial data with its attributes (Belda and Melia, 2000, Baysnat *et al.,* 2000). Time series remote sensing provide researchers with a valuable tool for the dynamic analysis of landscape (Staus *et al*., 2002).

Environmental models implemented in computers have become important tools for designing management plans towards ecological and economic sustainability. Computers help to deal with the tremendous complexity reflected in the extensive temporal and spatial scales at which human and natural processes occur. Iverson and Prasad (2007) evaluated tsunami damage and built empirical vulnerability models of damage/no damage based on elevation, distance from shore, vegetation, and exposure**.**

4. An outline of the geology of Mexico

The geology of Mexico is the result of multiple tectonic processes that have taken place along its geologic history. Current geologic configuration of Mexico is the consequence of continental block interaction with surrounding oceanic provinces. As a result, young sedimentary and volcanic outcrops are dominant. 80% of exposed units are placed on Cenozoic and Mesozoic eras (less than 250 million years), 13% correspond to the Paleozoic and only 7 % belong to the Precambrian, belonging to the Proterozoic (up to 2500 million years ago (Ortega *et al*. 1992).

Precambrian

The oldest metamorphic Rocks in Mexico were found in Sonora State and belong to the Bamori Complex (Figure 1), it is conformed by muscovite schist, hornblende-amphibolites schist and quartzite, dated at 1755 ± 20 million years (myr) by Anderson and Silver (1981). In Chihuahua State a metamorphic complex outcrops (metagranite, metadiorite, amphibolite, gneiss, metalimestone and quartzite), these rocks have an age between 1025 ± 21 myr and 948 ± 14 myr (Blount 1983). In southeast Mexico one finds dispersed outcrops from the Proterozoic composed of metamorphic rocks (augengneiss, orthogneis, marble, amphibolite and migmatite) that belong to the Oaxaqueño Complex, with an age between 1300 to 700 myr (SGM, 2007). Along the southern coast from Zihuatanejo, Guerrero to Puerto Ángel, Oaxaca emerges a group of paragneiss, pelitic schist, boitite schist, quartzite, marble, orthogneiss, amphibolite and migmatites that has been grouped inside the Xolapa complex (between 980 and 1300 myr; SGM, 2007). Intrusive rocks of the Paleo and Mesoproterozoic, emerge in Sonora state, showing small outcrops of granite, granodiorite, and in less proportion, diorite. Their ages vary between 1440 and 1140 myr (Anderson and Silver, 1981).

Sedimentary rocks of the Proterozoic outcrop in Sonora state like small patches of dolomite, limestone and sandstone. These deposits were dated as Neoproterozoic owing to the presence of conic stromatolite fossils of the Conophyton genus (SGM, 2007).

Paleozoic

Metamorphic rocks from this period are schist, marble and quartzite. They are located in the states of Baja California, Sinaloa, Sonora and Chihuahua, their ages fluctuate between

Cambric and Carboniferous (Figure 1). Phyllites and schist with quartzite can be found at the southeast of the State of Chiapas (Late Mississippian). In Tamaulipas state metamorphic rocks appear in Huizachal-Peregrina Structure presenting mica-schist interstratified with green rocks, metaflints, serpentine, and metalimestones. In the Huizachal-Peregrina structure, near Ciudad Victoria, Tamaulipas, there are outcrops formed by mica-schist of low grade. The age for this unit was 330 myr (Stewart *et al.*, 1999). Low grade metavolcanic sedimentary rocks from the Permic (SGM, 2007) exist north of Durango city. Outcrop schists, phyllites, quartzite's and metalavas are found northeast of Puebla. These rocks are from Early Permic (280 myr; Iriondo *et al.*, 2003). There are outcrops of schists and quartzites in southeast Oaxaca. The age of these rocks ranges between 289±5 Ma and 219±6 Ma. (Grajales-Nishimura *et al.*, 1999). In Zacatecas outcrops are found of a metamorphosed sedimentary succession, from Late Paleozoic, 260.2 ± 3 Myr (Díaz-Salgado, 2004).

Fig. 1. Distribution of metamorphic rocks of Precambrian and Paleozoic

The metamorphic rocks from Mesozoic (Figure 2) in the northeast of the country are phyllites and chlorite and biotite schist, amphibolite gneiss, metatonalite and metadiorite (De Cserna *et al.*, 1962; 220 myr). A meta-volcanosedimentary succession was deposited from Late Jurassic to Early Cretaceous along the west of Mexico.

States of Michoacán, México and Guerrero present outcrops of metamorphic rocks of low grade, there are schist's, slates and quartzites. (Tejupilco Schist, Taxco Schist and Green Rock Taxco Viejo formations (De Cserna 1982) and probably belong to the Jurassic.

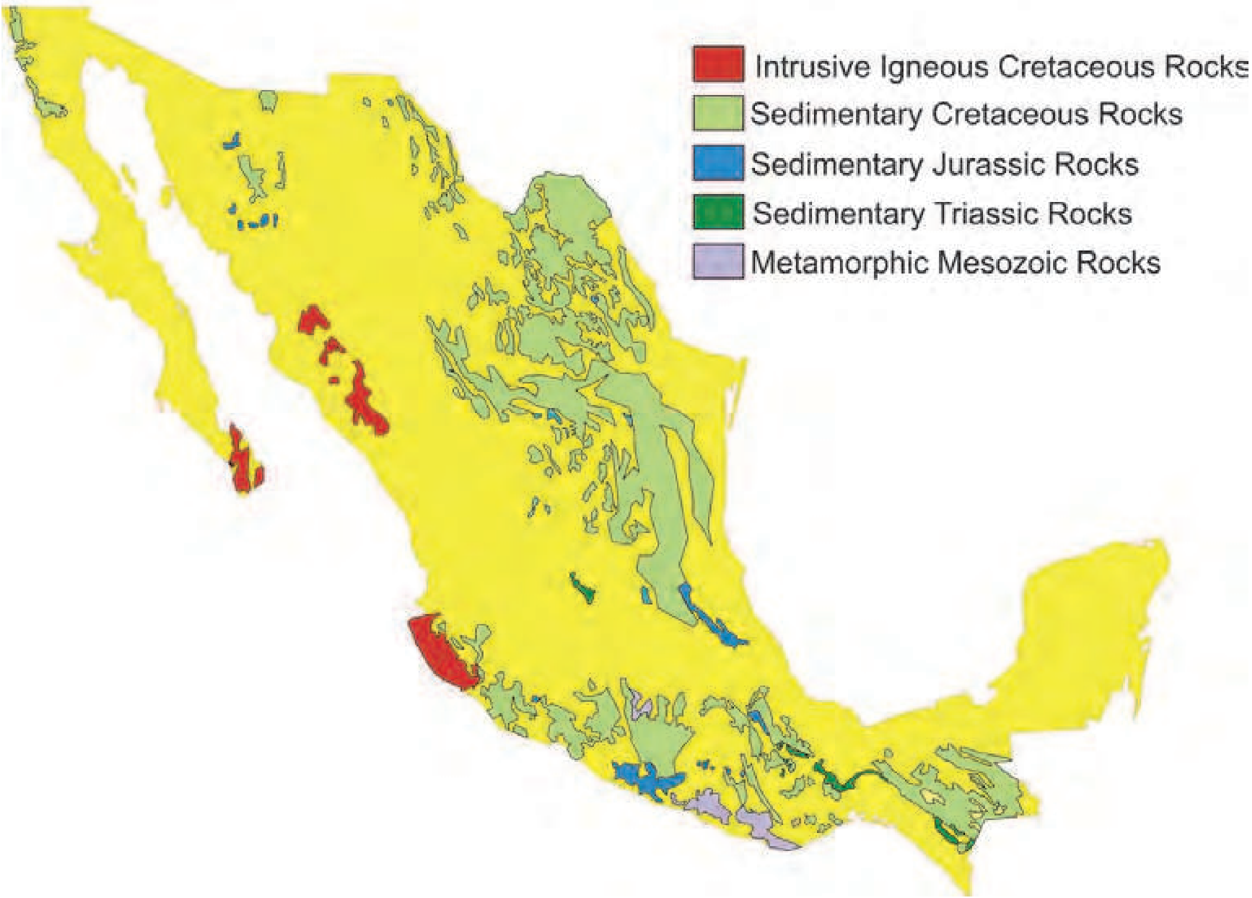

Fig. 2. Mesozoic Lithologic Units

Outcrops from Triassic are scarce. In southwest Sonora there is calcareous sandstone, alternated with limonite. This rock contains fossils of gastropods, coral, bryozoans, sponges and ammonites from this period (González-León, 1980), and the same in northeast Mexico were deposited at the Huizachal Formation conglomerate (SGM, 2007).

Along the Lower Jurassic an alternate succession of shales and limestones are deposited in the states of San Luis Potosí, Querétaro and Hidalgo. Jurassic sediments in southern Mexico (Oaxaca and Guerrero states) is composed of a conglomerate and sandstone succession with quartz clasts (Cualac Formation). The Upper Cretaceous was identified with ammonites and radiolarian fossils. In south Baja California the lower Cretaceous is represented by sandstones, limonites, shales and conglomerate successions.

To the east, in Chihuahua and Nuevo León states the great sea transgression deposited thick beds of calcareous and siliceous rocks (Formations Taraises, Cupido, La Peña, La Virgen.). At the same time calcareous anhydrite and clayish successions were deposited in Tamaulipas, San Luis Potosí, Hidalgo, Queretaro, Puebla and Veracruz states. The most important formations are Lower and Upper Tamaulipas, Otates, El Abra, Tamabra, Tamasopo and Cuesta del Cura. The last Formation is composed of limestone and chert. In south and central Mexico sedimentary rocks appear in the states of Jalisco, Michoacán, Guerrero, México, Morelos and Oaxaca, where calcareous successions settled, and clayish components are constituted by conglomerates, sandstones and limonites, with interstratified limestone, marls, and gypsum in different facies. The most important formations are Zicapa, Tepexi de Rodríguez, Xochicalco, Morelos, Cuautla y Mexcala. These formations contain a wide variety of mollusca, gasteropods, ammonites, and milliolids.

A change in sedimentation takes place in the Upper Cretaceous marked by the suffocation of the platforms with a series of terrigenous successions that show the evolution of deltas and basins. These successions form big bundles of sandstone, conglomerate, limonite, marl, and shales.

The outcrops of intrusive rocks are scarce and dispersed along the territory. The most important deposits are found in southern Baja California (granites, Peridotite, utramafic sequence, and an ophiolite sequence (Kimbrough and Moore, 2003). A sequence of granite and diorite from Middle Jurassic is located in Puebla (Macizo de Teziutlán), dated between 163 ± 13 and 134 ± 11 Myr (Manjarrez and Hernández, 1989). In Guanajuato state outcrops a sequence of granite, diorite and tonalite from the Upper Jurassic outcrops, these deposits are related to the evolution of Mesozoic insular arcs from this period (SGM, 2007). Plutonic magmatism appears in southern Mexico, probably from Late Jurassic to Early Cretaceous, with a variable composition: granite, granodiorite and diorite. Some localities in which this plutonic intrusive appears are Tumbiscatio, near Zitácuaro city.

Cenozoic

A continental sedimentation of the Early Cenozoic marks the change of sedimentary rocks to volcanic sequences (Figure 3). The Red Conglomerates with intercalation of sandstones and limonites represent them in the Balsas, Red Conglomerate of Guanajuato, and Tehuacán formations. Transgressive events are reflected by the horizons of sandstone, lutite and conglomerates. In the Eocene-Oligocene, deposits of conglomerate and sandstone, limonite,

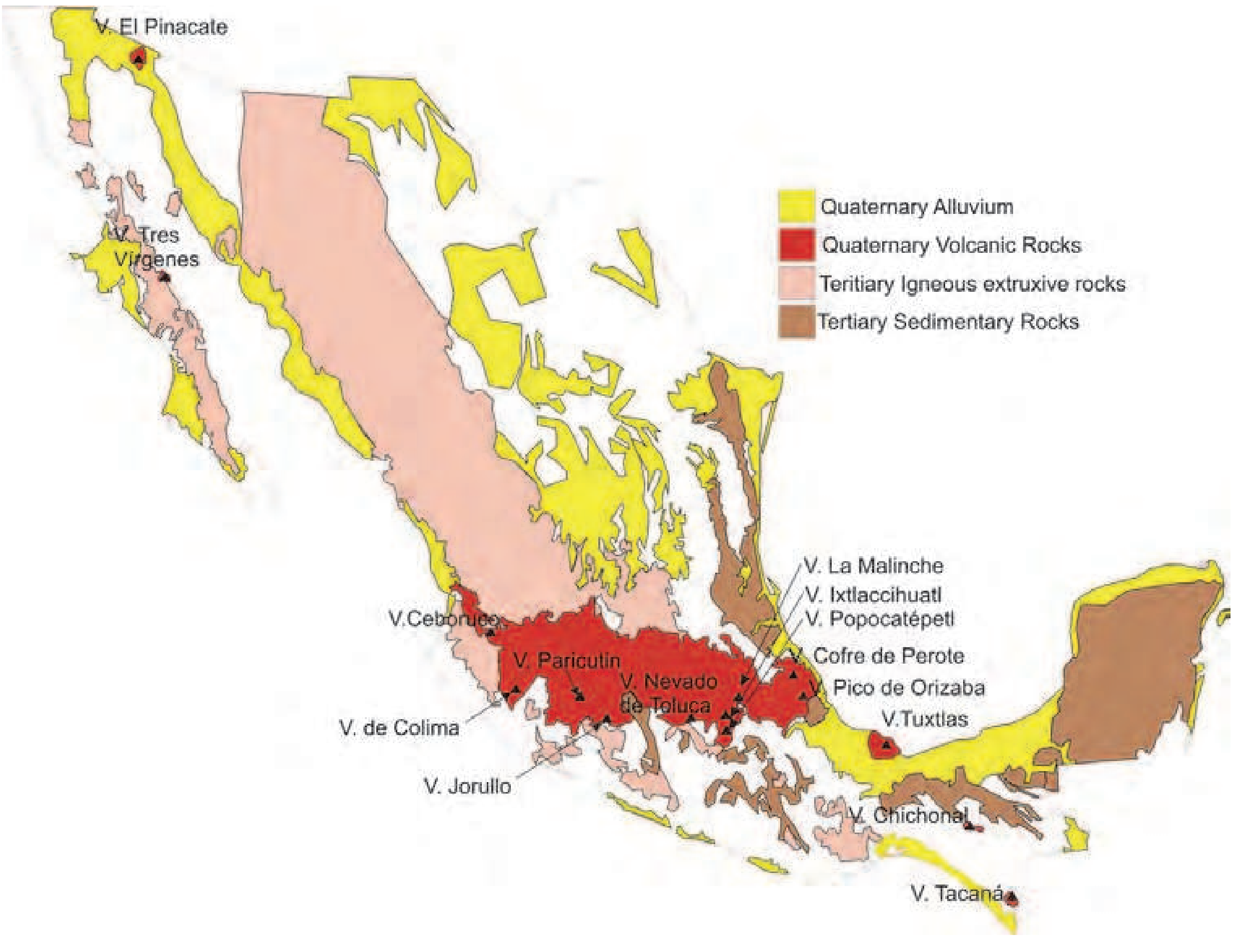

Fig. 3. Cenozoic Lithologic Units

and sandstone and limestone are distributed in grabens and synclinal valleys in the Sierra Madre Oriental and Sierra Madre Occidental. In the Sierra de Chiapas, the Miocene differed in the deposition of the clay-calcareous successions, as well as in the thin horizons of the conglomerates.

On the other hand, in the regions of the rim of the Yucatan Platform the bar reefs and lagoons keep on developing carbonate sediments of limestone and dolomites. The Holocene deposits of coastal environments of the coast of the Gulf of Mexico in the states of Tamaulipas, Veracruz, Tabasco, Campeche, Yucatan, and Quintana Roo, are still in the process of sedimentation of silts, clays and marshy sand, flat dunes of coastal sand, and continental shelf carbonate sediments.

The volcanic units of the Cenozoic are widely distributed in the Mexican territory, including the ignimbrites of the Sierra Madre Occidental and the Pliocenic-Quaternary sequences of the Transmexican Volcanic Belt (TMVB). The Sierra Madre Occidental is formed by an extensive volcanic plateau affected by grabens and normal faults. It spreads from Sonora to Guerrero states, although in the states of Jalisco, Michoacán and Guerrero it is fragmented and mixed with the Transmexican Volcanic Belt and the rocks of the Sierra Madre del Sur. The TransMexican Volcanic Belt (TMVB) extends from the Pacific Ocean up to the coast of the Gulf of Mexico along 920 km between parallels 19 and 20. It is formed by a large variety of volcanic rocks produced by a number of volcanic buildings, some of which constitute the main elevations in the country. Likewise, this activity has caused a big number of endorreic basins with the consistent development of lacustrine landscapes. The principal volcanoes of the TMVB are stratovolcanoes of variable dimensions, such as Pico de Orizaba, Popocatépetl, Iztaccíhuatl, La Malinche, Nevado de Toluca and Nevado de Colima.

5. Case studies

Landscape studies in Mexico are numerous: Ochoa (2001) undertook the integration of geologic and geomorphic units, incorporating afterwards variables of climate, hydrology, vegetation and soil in the Tehuacán-Cuicatlán, Puebla, area. Casals-Carrasco *et al.,* (2000) performed a geomorphologic analysis in order to establish relationships among land cover, landforms and soils using interpretation of a stereoscopic pair of SPOT-PAN, and a TM false color composite image. Martínez (2002) elaborated environmental land unit maps of a sub watershed in Morelos State. García (1991) studied the influence of relief dynamics in landscape structure on the vegetation in Zapotitlán, Puebla watershed. García (1998) analized the east slope of Sierra de la Cruces, Monte Alto and Monte Bajo while, Garcia-Aguirre *et al.* (2007) related geology, landform and vegetation in the Ajusco volcano area in central Mexico. Aguilar (2007) performed an environmental diagnostic of the Parque Nacional Nevado de Toluca from the biogeomorphic land units of the region.

Two case studies will be described in detail. The first is related to the use of biogeomorphic land units of a region located nearby Mexico City as a basis for hydrology and vegetation analysis. The second case refers to the evaluation of risks and hazards of the fourth highest summit in México, the Nevado de Toluca.

5.1 Sierra de las Cruces

The objectives of the first study are two-fold: to identify the most degraded areas of the region through the land unit analysis, and to study the relationship between forest loss and runoff in the region (scale 1:250,000) through a conceptual and cartographic model.

Landscape analysis was performed to describe regional characteristics in an integral form; land cover features were overlaid with other landscape elements (geology, geomorphology, soils and climate) to obtain a land unit map (García-Aguirre, 2008).

Mountainous relief and flat plain may be appreciated in the shadow relief model derived from a DEM (figure 4). Chichinautzin region, towards the south of the zone, being an infiltration zone is very important from the hydrological view point. Refief of the east slope of the Sierra de las Cruces, Monte Alto and Monte Bajo is constituted by four geomorphic units: mountain, upper and lower piedmont, and hills. Notice the N-S orientation of this mountain range.

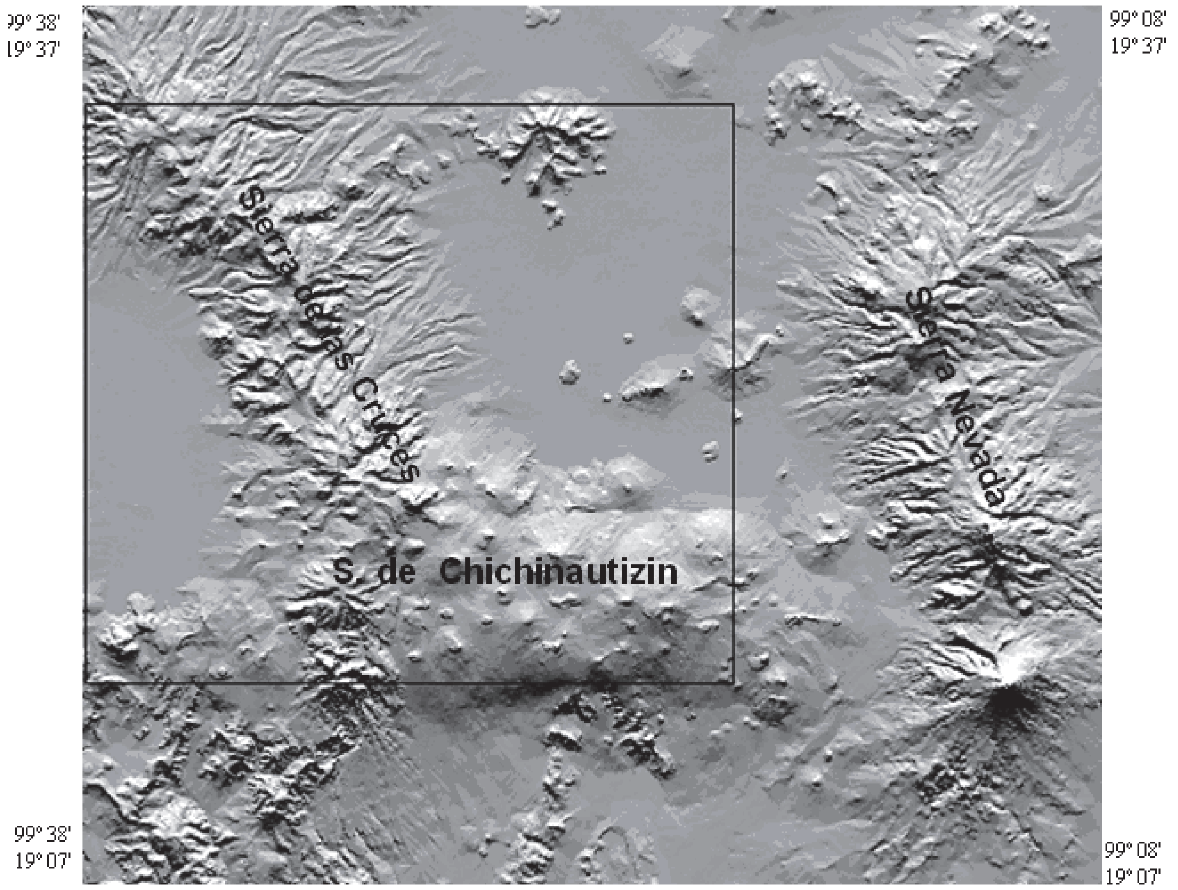

Fig. 4. Shadow relief model derived from the DEM. Study area is located inside the square. Sierra de Chichinautzin is located to the south, and Sierra Nevada toward the east

Land unit map

Remote sensing and GIS were linked to integrate geomorphological and geological information to find mayor associations among variables. Then, biogeomorphic land units were delineated on the basis of homogeneity of a dominant factor.

Figures 5 and 6 show the geology and geomorphology maps of the region. These maps were obtained by digitizing hardcopy maps of INEGI (1993) and reclassified using IDRISI (Eastman, 1997). Andesite and basalt are dominant in the area and in turn, andosols and lithosols (Figure 5). Lugo (1984) points the south of Cuenca de México as one of the zones of the country with higher concentration of young volcanoes, from the late Pleistocene and Holocene (Figure 6).

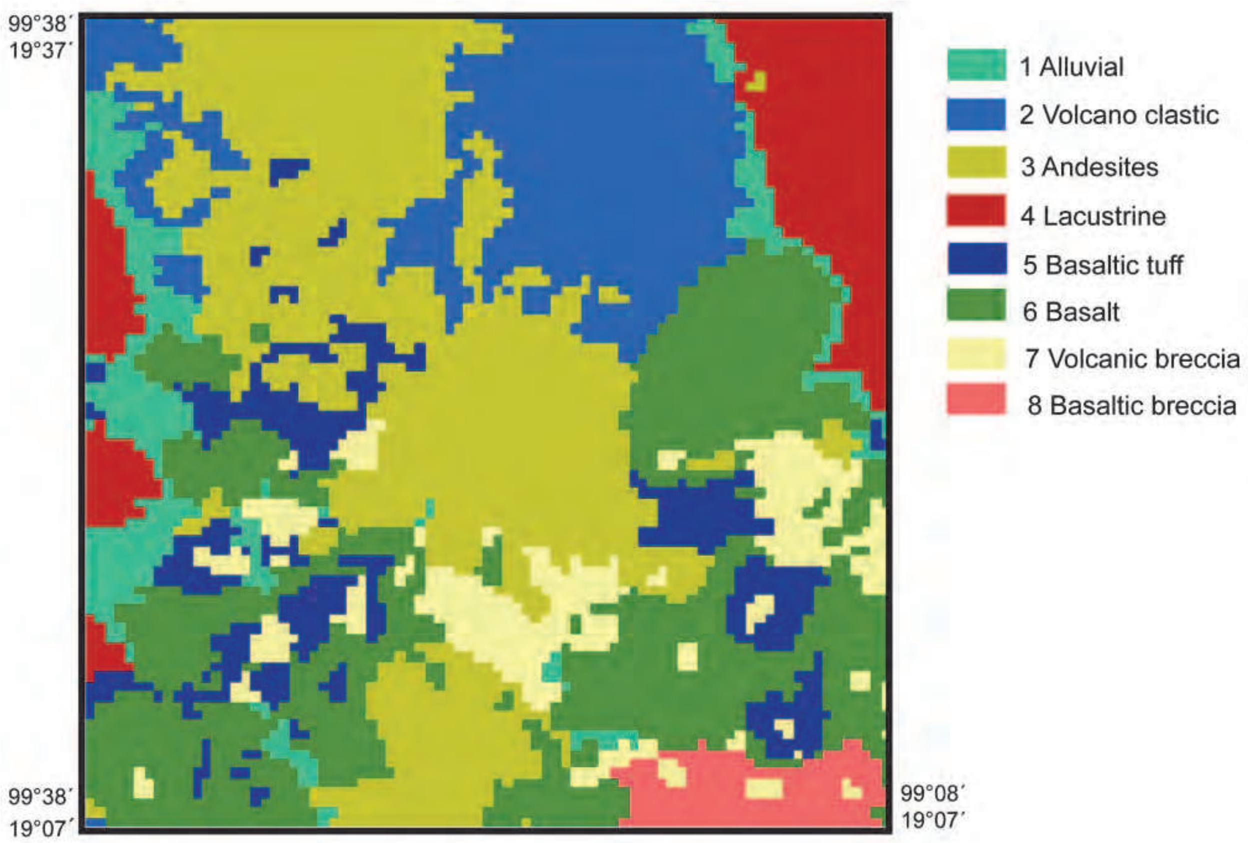

Fig. 5. Geologic map. Andesites and Basalt are dominant in this region

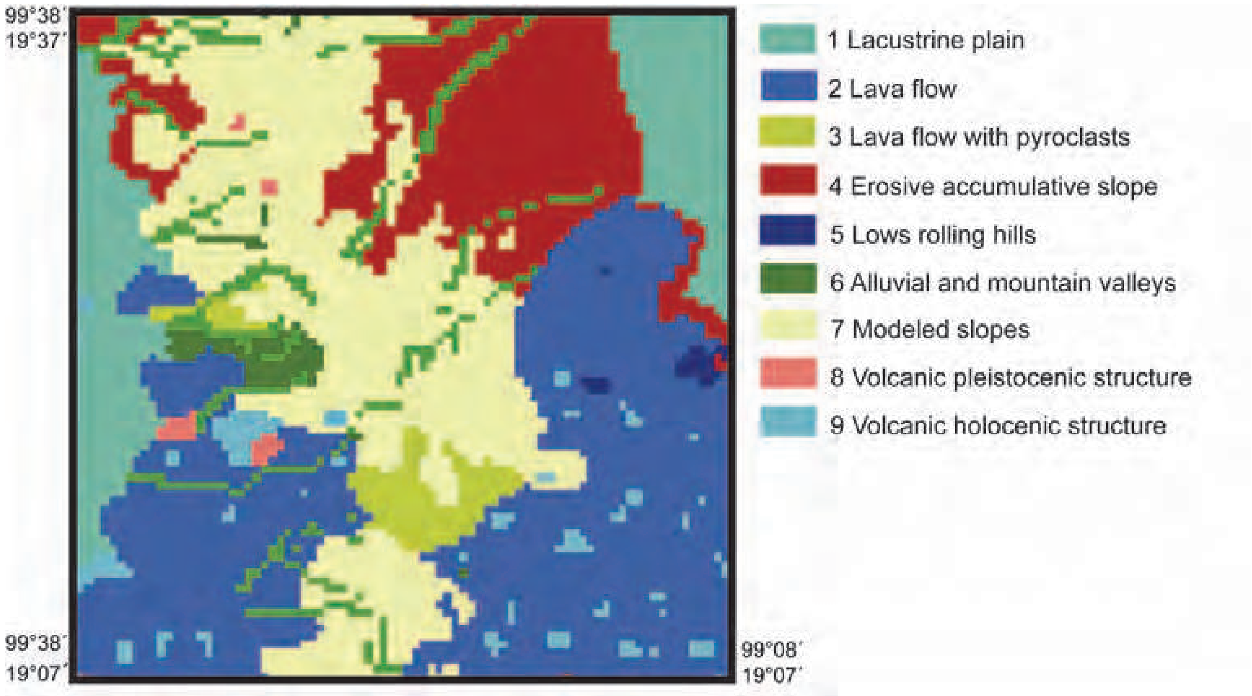

Fig. 6. Geomorphologic map. Dominant geoforms are modeled slopes and lava flows

Geomorphologic map (Figure 6) shows modeled slopes and lava flows as dominant geoforms. The region has an extense footslope, in which half the area slopes down to the piedemont and the other half is mountainous terrain. Also extensive lava flows show the active quaternary volcanism in this zone.

Combination of biotic and non biotic features generated more than 100 units, that were reclassified into 48 units on the basis of its surface (only units with more than 500 ha), for map legibility (Figure 7). Alluvial and lacustrine units are mainly covered with pheozem and hystosol, agriculture and grasslands. The modeled slopes of andesites with andosol are subdivided into those with Abies and those with Pine forest. Towards the east (BGU39, BGU40, and BGU2), there are abundant lacustrine forms with agriculture, grasslands and human settlements. Basalt is abundant to the south with forest cover, agriculture and grassland (BGU29, BGU33). In the footslopes, mainly towards the north, there are units constituted by andesites, modeled slopes and cambisols, that are covered by oak forests, crops and grasslands. There are many holocenic volcanic structures over the mountainous area, with andosol and litosol, covered mainly by forests.

The regional vision provided by this study allowed to have a rapid overview of sites that should be preserved, such as basalt zones, that are nevertheless continuously invaded by human settlements. Results indicate that Sierra de Chichinautzin is the main recharging area, but the foot slopes of the Sierra de Las Cruces are also important infiltration and recharging zones as a result of the abundance of clastic volcanic forms therein.

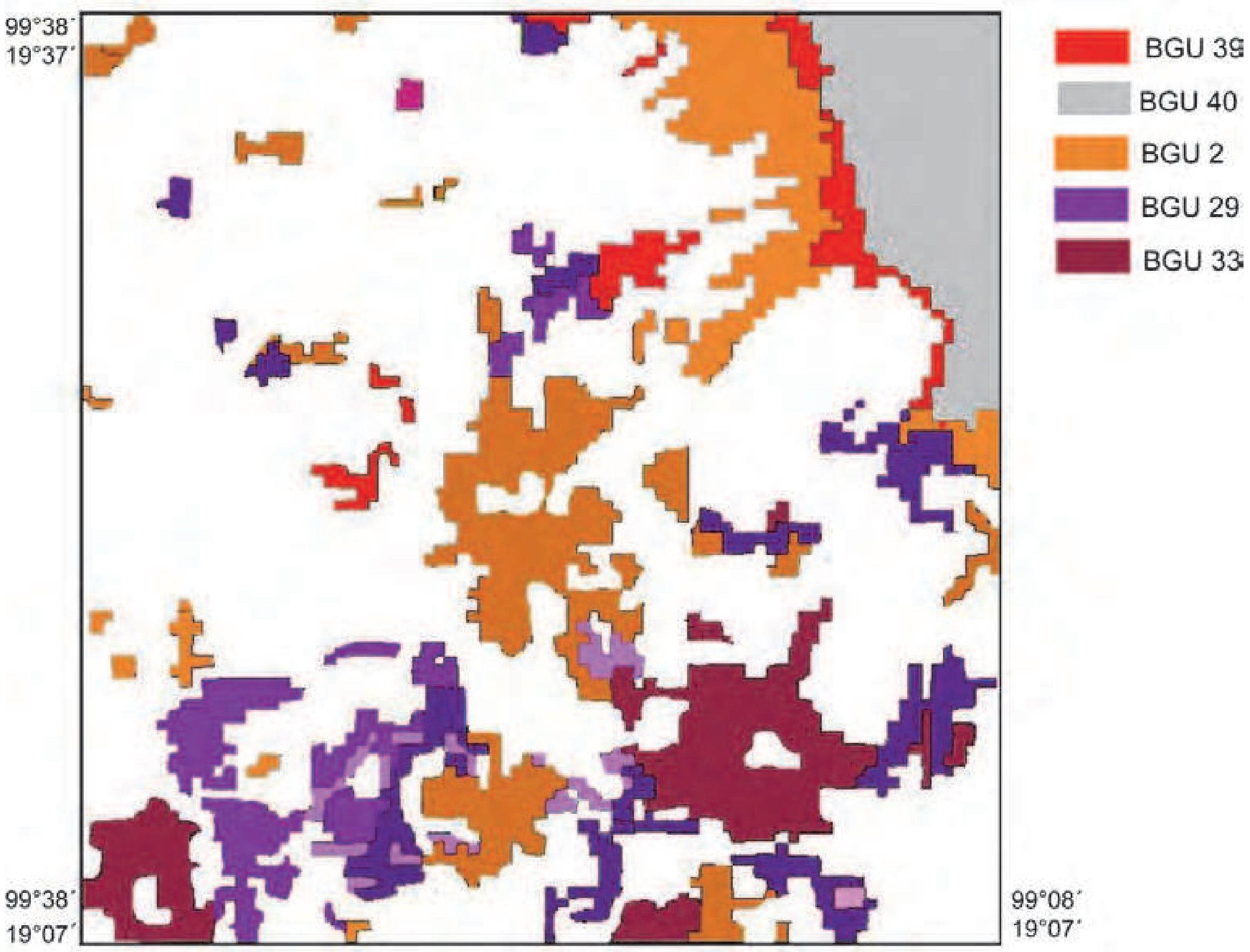

Fig. 7. Land unit map (BGU=biogeomorphic land units)

5.2 Nevado de Toluca geologic history and hazards

Nevado de Toluca Volcano (NTV), located in central Mexico, is a large stratovolcano, with an explosive history. The area is one of the most important human developing centers (>2 million people) in Mexico and in the last 30 years large population growth and urban expansion have increased the potential risk in case of a reactivation of the volcano. NTV is the fourth highest summit in Mexico (4,665 masl) and it is a potentially dangerous large stratovolcano, that lies in the southeastern part of the Toluca Basin, some 70 km east of Mexico City (Figure 8). The NTV has been characterized by very explosive eruptions with long periods of dormancy; the periods between eruptions are discussed below.

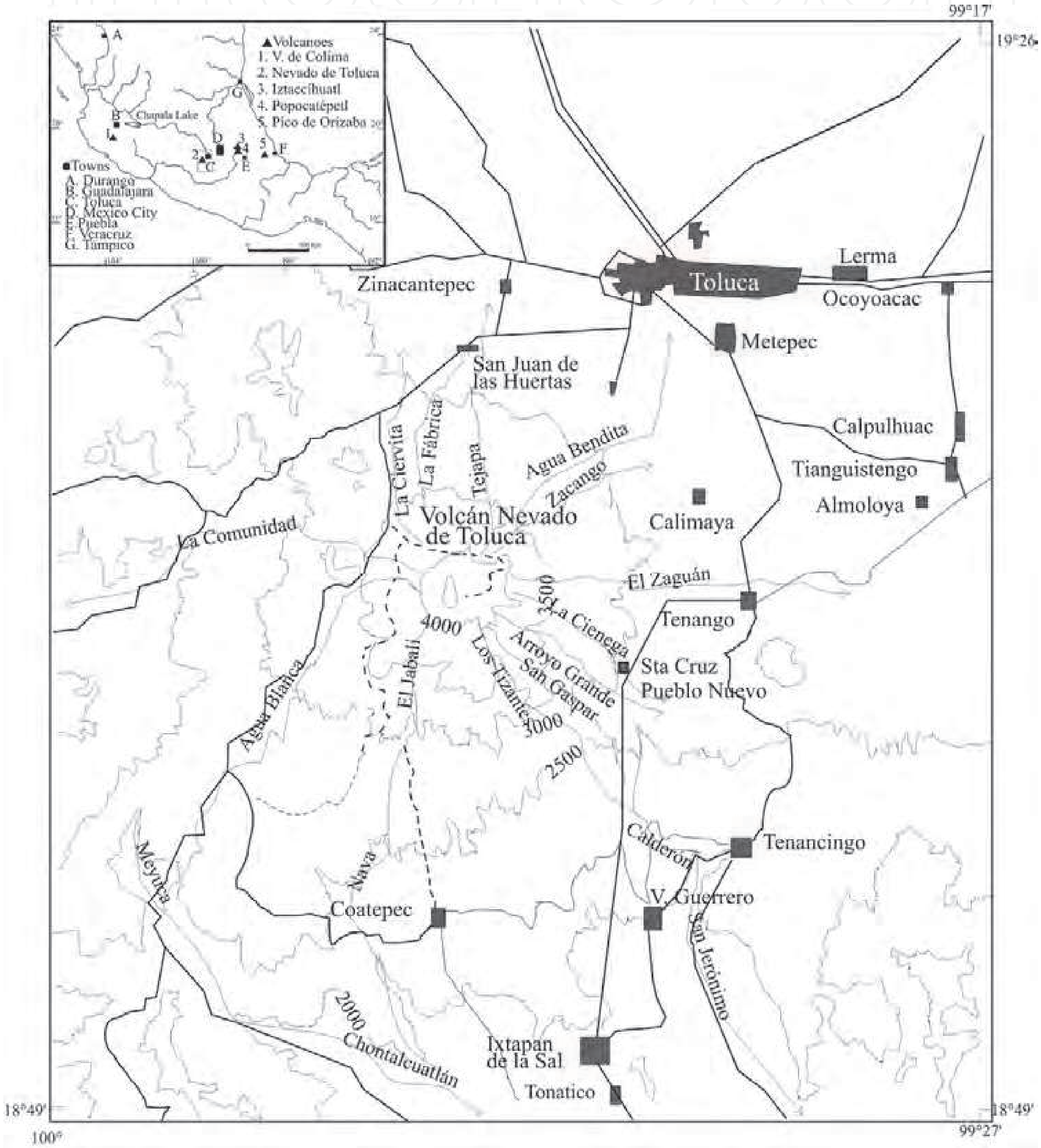

Fig. 8. Nevado de Toluca, location map

Nevado de Toluca Volcanic hazards

Pyroclastic flow Hazards: These deposits are widely spread around the volcano, filling the stream valleys where several settlements are located (Figure 8). The pyroclastic flow deposits cover a minimum area of 630 km^2 and assuming that they have an average thickness of 5 m, the approximate volume is 3.15 km^3 (Macias *et al*. 1997). The maximum distance reached by these deposits is 32 km from the crater towards the south, in the Tizantes and Calderón stream valleys. The block and ash flows form massive units interstratified with surge horizons. The first dome collapse deposited the Zacango Block and Ash flow (37 kyr BP) composed of three massive units with associated surge horizons. The second dome collapse (28 kyr BP) deposited El Capulín Block and Ash Flow. These deposits are distributed around the volcano and cover approximately 630 km^2 with a volume of 2.6 km^3 (Aceves *et al*., 2007).

The pumice flows erupted by the NTV are: the Pink Pumice Flow (43 kyr BP); the White Pumice Flow (26 kyr BP). The MF2 (13.4 kyr BP) pumice flow is a gray ash flow enriched in pumice clasts (<2 cm) and charcoal (Aceves, *et al*. 2007). The Intermediate White Pumice (12.1 kyr BP) is composed of white ribbon pumice clasts and gray to reddish (altered) dacitic lithic clasts, interbedded with a surge (Cervantes 2001). The pumice flows are distributed around the volcano and cover more than 200 km^{2,} with a volume of 0.2 km^3. The pumice flows are related to the Plinian eruptions, many of which result in mudflows and include charcoal and variable amounts of pumice. Some are altered to paleosoils. One of the most pumice-rich flows belongs to the Upper Toluca Pumice Formation (UTP), dated 10,500 yr BP (Macias *et al*. 1997).

Debris avalanches hazards: The debris avalanches have been located towards the south of the NTV in the Meyuca, Calderón Chontalcuatlán and San Jerónimo river valleys. Two units compose the debris avalanches. The oldest unit (DAD1) is massive, with 35% blocks up to 2.5 m in diameter, in a heavy pink partially hardened sand sized matrix. The lithological composition is heterogeneous dacitic, andesitic and schist lithics, with''Jig saw'' blocks (Capra and Macias, 2000). DAD1 is around 10 m thick in Coatepec and continues towards the south to the Valley of the Chontalcuatlan River. The youngest avalanche (DAD2) is composed of two large cohesive debris flows: the Pilcaya (PDF) and the El Mogote (MDF) (Capra 2000). Thickness varies from 6 m in the proximal section to 40 m in the intermediate zone, extending out to a distance of 75 km from the crater. It covered an area of 220 km^2 with a volume of 2.8 km^3 (Aceves *et al*., 2007, Capra 2000).

Lahar hazards: Lahars at NTV are wide spread around the volcano filling new and old valleys. Lahars have rounded and subrounded dacite lithics (15–25 cm), small pumice fragments (<5 cm) fixed in a muddy-sand sized matrix. To the south, the lahar thickness is more than 30 m. The oldest lahars are made up of rounded and subrounded gray and red andesite blocks fixed in red clay sized matrix with scarce pumice fragments. The recent deposits contain subangular and subrounded blocks of gray and red dacite, with pumice fragments, some of which are hydrated, fixed in a siltclay sized matrix. The flow direction of these lahars was controlled by the topography, principally deep tectonic, glacial and fluvial valleys. In distal areas, the lahar deposits were transformed into fluvial mixing with the stream and river waters. To the east, the lahars contain more pumice fragments in a pale brown silt-clay matrix. There is a lahar with large hydrated pumice fragments (20–30 cm), in the Arroyo Grande channel. In this area, many secondary lahars exist, such as the one deposited in 1952 in the Ciénaga channel.

These secondary lahars are not related to volcanic activity and represent an increased hazard, because these materials are not consolidated. In torrential periods these materials can be removed by rain, triggering these secondary lahares, which can come up to the low zones affecting the populations who are settled in the mouths of the valleys as it happened to the people of Santa Cruz Pueblo Nuevo. To the north, the ravines are shallower (<30 m). The origin of the secondary lahars are uncompacted volcanic products (ash fall and, pyroclastic flows) mixed with water from the glacial melt and torrential rains (Aceves *et al*., 2007).

Ash fall hazards: Ash and pumice fall deposits cover wide zones around the volcano. The most important deposits are the Upper and Lower Toluca Pumice. For the ash fall hazards map, the distribution and thickness of these deposits were considered as well as the present wind direction for the UTP. These isopach and isopleth maps show dispersal to the northeast. In the Toluca Basin, the maximum thickness measured for the UTP was 40 cm. In order to plot the isopach of 10 cm, map scales of 1:100,000, and 1:250,000 scale were used. The dominant wind direction was obtained from the National Meteorological Service and calculated for a height between 20 and 30 km (Fonseca 2003). The results were: east-northeast from November to March, west-northwest in April and west from May to October (Aceves et al., 2007).

In conclusion, in the last 50,000 yr, NTV had eight vulcanian, and four Plinian eruptions, three large dome collapses, and one ultraPlinian eruption. Block and ash and pumice flows are the most common deposits. The eruptive history of NTV shows cataclysmic events of Plinian and utraPlinian type, beside Vulcanian eruptions, which represent a large hazard for the Toluca Basin. The regions that would be most affected by pyroclastic flows and lahars are: (1) Toluca, Lerma, Metepec, San Mateo Atenco, Santiago Tianguistenco and Capulhuac, located to the northeast of the volcano. These areas concentrate the major population and industrial centers. (2) Calimaya, Zacango, Tenango among several others located to the east of NTV are highly populated and important agricultural areas. (3) To the south, the flower producing centers: Coatepec and Villa Guerrero, and the tourist towns of Ixtapan de la Sal and Tonatico.

Four volcanic hazards types were identified: pyroclastic flows (block and ash flows and pumice flows), lahars, debris avalanches and ash fall. The most destructive (based on energy and frequency) in the NTV are the block and ash flows and the pumice flows, both of them have reached distance of up to 35 km from the volcano summit. The principal affected areas are the northeast and south of the volcano, because these areas have major differences in altitude and present the major development of ravines. Lahars have been present in most of the eruptions. The deep and large valleys located to the east and south of the volcano are the most hazardous areas. The most active valleys are San Jerónimo, Chontalcuatlan, Grande, and El Zaguán Rivers. Debris avalanches present a hazard for areas to the east and south of the volcano, because of the active faults in the area and the instability caused by the difference in altitude, favoring the gravitational collapse of NTV. This type of event has occurred twice in the last 100,000 yrs, the deposits are located to the south of the volcano. The hazards from ash fall, arising from the dominant winds, are: from November to March, they would affect mainly the east and north-east sectors of the volcano, in April affectation would be to the north-west, and from May to October to the west. In case of small and medium eruptions (VEI = 1–3), the affected zone would be the Toluca Basin, but in case of large eruptions (VEI > 4) the affected zone would even include Mexico City.

6. Acknowledgment

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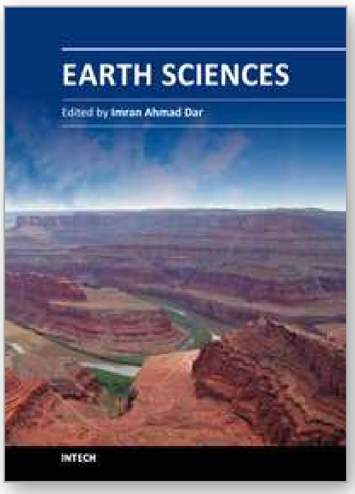

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