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Geology of Nevado de Toluca Volcano and surrounding areas, central Mexico

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ABSTRACT

Nevado de Toluca is an andesitic-dacitic stratovolcano of Pliocene-Holocene age located in central Mexico. The volcano is built on a complex sequence of metamorphic and sedimentary formations of Jurassic-Cretaceous age, rhyolitic ignimbrites of late Eocene age, and massive andesitic lava flows of late Miocene. In the northwest corner of the map area, on top of this basement sequence, a complex andesitic-dacitic stratovolcano, San Antonio, and a series of andesitic-dacitic domes and cones of Pliocene–early Pleistocene age were also built. The first andesitic-dacitic emissions of Nevado de Toluca occurred 2.6 Ma and continued during late Pleistocene–Holocene time contemporarily with basaltic to dacitic emissions of the Chichinautzin Volcanic Field in the eastern parts of the map area.

Volcanism in the area has been controlled by the interplay of three fault systems active since late Miocene. These systems, from older to younger, are the Taxco-Querétaro Fault System (NNW–SSE), the San Antonio Fault System (NE–SW), and the Tenango Fault System (E–W). Nevado de Toluca was built at the intersection of these three fault systems, which have influenced its volcanic history as evidenced by at least three sector collapses and several large explosive eruptions. The Pliocene to Holocene volcanism at Nevado de Toluca and the late Pleistocene–Holocene activity at Chichinautzin Volcanic Field, together with the regional tectonic activity and recent seismic swarms, suggest that the Tenango Fault System represents an active segment within the Trans-Mexican Volcanic Belt. The potential reactivation of either this fault system or Nevado de Toluca Volcano would pose earthquake and/or volcanic hazards to more than 25 million inhabitants in the vicinity, including large cities such as Toluca and Mexico.

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INTRODUCTION

The Trans-Mexican Volcanic Belt (TMVB) is a 1200-km-long continental arc, predominantly of andesitic-dacitic composition, extending westward across central Mexico and ending nearly at the Gulf of Mexico (Fig. 1). Volcanoes of the Trans-Mexican Volcanic Belt are generally viewed as resulting from the subduction of the Cocos and Rivera plates beneath the North American plate along the Middle American Trench (MAT) (Ponce et al., 1992; Singh and Pardo, 1993; Pardo and Suarez, 1993, 1995). Other authors suggest that the Trans-Mexican Volcanic Belt is related to a crustal fracture zone or to a mega-shear (Cebull and Shurbet, 1987). More recently Márquez et al. (1999) have proposed the existence of a mantle plume and the subduction of the Cocos and Rivera plates as coexisting mechanisms to explain several geochemical features of the belt. Sheth et al. (2000) argue against this hypothesis, and proposed rather that the Trans-Mexican Volcanic Belt represents a rift-like structure that is experiencing active extension.

Recent petrological studies, particularly Osmium isotopic analyses, reveal that magmatism of the Trans-Mexican Volcanic Belt shows assimilation of the lower crust (Chesley et al., 2000). These results correlate with the study of the Chichinanautzin Volcanic Field (CVF) by Verma (2000), who concluded that andesites and dacites were derived from partial melting of an heterogeneous mafic granulite from the lower crust, while alkaline magmas are mantle derived mafic-magmas.

The beginning of volcanic activity in the Trans-Mexican Volcanic Belt has been controversial. In the western part of the Trans-Mexican Volcanic Belt, Gastil et al. (1979) placed the beginning circa 4.5 Ma, while Allan (1986) placed the oldest known calc-alkaline volcanism at 10 Ma. According to Mooser et al. (1974), volcanism in the central Trans-Mexican Volcanic Belt started 30 Ma ago, whereas in the eastern Trans-Mexican Volcanic Belt, Cantagrel and Robin (1979) suggested a beginning some 20 Ma ago. From stratigraphic studies in western and central Trans-Mexican Volcanic Belt, Pasquaré et al. (1991) found that the oldest units consisted of massive fissure-vent lava flows (basaltic andesites to rhyolites in composition) to which they gave the general name of "Basal Sequence." Two samples from this sequence yielded K-Ar ages of 8.1 Ma (sample from south of Querétaro) and 7.8 Ma (sample from 15 km north of Morelia).

The Trans-Mexican Volcanic Belt is dominated by huge, geologically young andesitic stratovolcanoes, some of which form short north-south volcanic chains younger toward the south, i. e., toward the trench. Examples are Cantaro-Nevado de Colima-Colima, Telapón-Iztaccíhuatl-Popocatépetl, and Cofre de Perote-Las Cumbres-Pico de Orizaba (see Fig. 1). K-Ar data for the andesitic calc-alkaline volcanoes Sanganguey and San Juan in the western Trans-Mexican Volcanic Belt indicate that cone construction began circa 0.6 and 0.2 Ma, whereas in central Trans-Mexican Volcanic Belt (Iztaccíhuatl-Nevado de Toluca) cone growth began 1.7 and 2.6 Ma ago, respectively. This age progression in the onset of growth of the andesitic volcanoes along the Trans-Mexican Volcanic Belt and the trenchward migration of volcanism suggest different subduction rates between the Cocos and Rivera plates (Nixon et al., 1987; Pardo and Suarez, 1995; Ferrari et. al., 1999).

In this work, we present the stratigraphy, distribution, and structural setting of rock units around Nevado de Toluca Volcano and surrounding areas. We summarize the petrological affinities of the stratigraphic units as a basis for elucidation of the volcanic evolution of the region, which in turn bears on the problem of the beginning of volcanic activity in the Trans-Mexican Volcanic Belt. Particular emphasis is given to the complex fault systems in the region, which have affected the basement complex upon which the andesitic-dacitic stratovolcanoes have been built since the late Pliocene. For our study we reviewed several regional geological maps (De Cserna and Fries, 1981; Sánchez-Rubio, 1978; Bloomfield, 1975; Elías-Herrera, 1993; Ramírez-Espinosa, 1977). The study area covers about 4000 km^2, encompassing six quadrangle maps (scale 1:50 000) published by Instituto Nacional de Estadística Geografía e Informática (INEGI). Geological data were collected and compiled with the aid of these topographic maps. The topographic contour lines, geological contacts and faults, and cultural features were then combined into a single digital product at a 1:100 000 scale. For the description of the map units, we follow customary usage in published works as employed by García-Palomo (1998) and García-Palomo et al. (2000).

Tectonic setting of central Mexico

The Trans-Mexican Volcanic Belt consists of three distinctive segments, each with its own tectonic, volcanological, and petrological characteristics (Pasquaré et al., 1987) (Fig. 1). These segments are the western Trans-Mexican Volcanic Belt, dominated by the Colima-Chapala-Tepic triple junction where both alkaline and calc-alkaline volcanic products are present; the central Trans-Mexican Volcanic Belt, characterized by disperse andesitic-dacitic stratovolcanoes, silicic calderas, and monogenetic cone fields where calc-alkaline volcanism is dominant; and the eastern Trans-Mexican Volcanic Belt, characterized by andesitic-dacitic calc-alkaline stratovolcanoes and some alkaline products. Under this scheme, the Nevado de Toluca is located along the boundary between the central and eastern segments.

According to the tectonic model of Mexico proposed by Johnson and Harrison (1990), Nevado de Toluca Volcano is located within the Guerrero Block (Fig. 2). This block is confined to the north by the Chapala-Tula fault system and to the south by the Chapala-Oaxaca fault system. In this model, Nevado de Toluca astrides a series of NNW–SSE trending normal faults, forming a Basin-and-Range like pattern (Demant, 1978; Suter et al., 1992), and a series of E-W trending normal faults (Fig. 2). These two fault systems were originally identified as major fractures in the Toluca–Mexico City area (Mooser, 1969; Mooser and Maldonado-Koerdell, 1961). Based on satellite imagery, Flores (1978) concluded that Nevado de Toluca Volcano lies at the intersection of NW-SE and NE-SW fault systems. However, in these

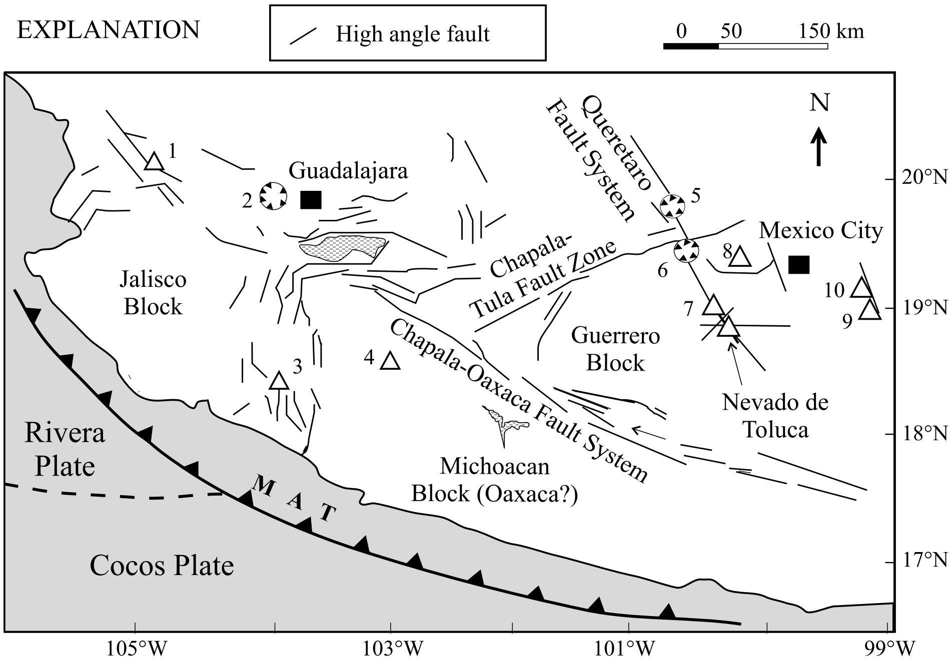

Figure 1. Location of Nevado de Toluca Volcano and other volcanic features of the Trans-Mexican Volcanic Belt (TMVB). Other Quaternary volcanoes are: 1—Ceboruco, 2—La Primavera, 3—Colima, 4—Parícutin, 5—Los Azufres, 6—Amealco, 7—San Antonio, 8—Jocotitlán, 9—Popocatépetl, 10—Iztaccihuati. MAT—Middle American Trench.

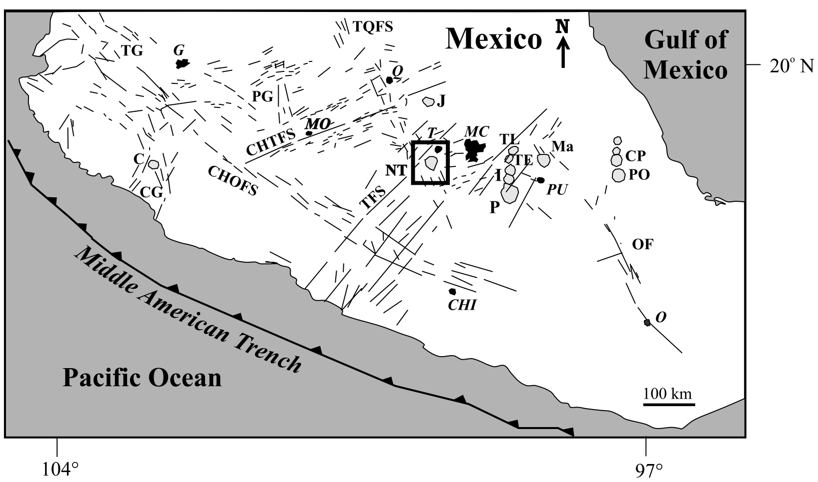

Figure 2. Map showing prominent NE–SW and NW–SE trending fault systems associated with the Trans-Mexican Volcanic Belt (after De Cserna et al., 1988; Johnson and Harrison, 1990; Nieto-Samaniego et al., 1995). The heavy-line box shows the map area in central Mexico. Volcanoes shown are: PO—Pico de Orizaba, CP—Cofre de Perote, NT—Nevado de Toluca, C—Colima, Ma—La Malinche, TE—Telapon, TL—Tlaloc, I—Iztaccíhuatl, J—Jocotitlán, and P—Popocatépetl. Cities shown are MC—Mexico City, T—Toluca, PU—Puebla, Q—Querétaro, O—Oaxaca, CHI—Chilpancingo, MO—Morelia, and G—Guadalajara. Fault systems shown include the Oaxaca fault (OF), the Tenochtitlán fault system (TFS), the Chapala-Oaxaca fault system (CHOFS), and the Chapala-Tula fault system (CHTFS). Other structures are the Tepic Graben (TG), the Colima Graben (CG), and the Penjamillo Graben (PG) (after Siebe et al., 1999).

general studies no data are available on the kinematics of the fault systems. Recently, García-Palomo et al. (2000) concluded that Nevado de Toluca Volcano was built upon the intersection of three fault systems named Taxco-Querétaro (NNW-SSE), San Antonio (NE-SW), and Tenango (E-W), respectively.

Nevado de Toluca Volcano

The Nevado de Toluca Volcano (19° 09′N; 99° 45′W, 4 680 m.a.s.l.), the fourth highest peak in Mexico, is located about 23 km southwest from the city of Toluca, capital of the State of Mexico. Nevado de Toluca is also known as “Xinantécatl,” a Náhuatl term meaning “Nude Man.” Romero-Quiroz (1959) argued that this word does not have solid Náhuatl roots and proposed instead the word Tzinacantépetl, or Bat Mountain. However, García-Martínez (2000), through comprehensive research of the historical archives, recently concluded that the most appropriate Náhuatl name for Nevado de Toluca is “Chicnauhtécatl,” meaning Nine Hills.

Nevado de Toluca is a large andesitic-dacitic stratovolcano of Late Pliocene–Holocene age (Bloomfield and Valastro, 1974; Cantagrel et al., 1981; this work). The northern flanks of the volcano are made of coalescent fans of pyroclastic materials spreading toward the Lerma Basin. This basin encloses the City of Toluca de Lerdo and the lakes of Chiconahuapan and Lerma, which are drained by the Lerma River toward the Pacific Coast. The relief of Nevado de Toluca with respect to the Lerma River basin is 2100 m. The southern flanks of Nevado de Toluca consist of incised valleys that drain to the Chontalcoatlán River and thereafter to the Pacific Ocean. The volcano rises circa 2700 m with respect to the towns of Ixtapan de la Sal and Tonatico located on its southern flanks (Fig. 3).

The summit crater of Nevado de Toluca is roughly elliptical (approximately 2×1.5 km) with its major axis trending E-W; it has a horseshoe shape opened to the east (Fig. 4). The present crater rim is composed of two or more remnants of older crater structures, appearing in air photographs and satellite imagery as straight walls intercepting at high angles. The western crater wall contains remnants of lava flows and domes that are well observed toward the uppermost part of the wall (Fig. 5). The crater contains two lakes (Lake of the Sun and Lake of the Moon) separated by a dacitic dome intrusion known as El Ombligo (Spanish word meaning navel). The surface of floor of these two alkaline lakes (5.6 pH; Armienta et al., 2000) is about 4,200 m.a.s.l., and both contain diatom flora (Caballero-Miranda, 1996). Pre-Hispanic pottery and obsidian blades are commonly found on the surface of the central dome and in the deep waters of the lakes; apparently these pottery shards are the remains of offerings made by the Aztecs or by earlier dwellers such as the Matlazincas (Quezada, 1972).

The volcano's morphology shows the effect of glacial advances during the Holocene (Heine, 1988). Rock glaciers and debris flows derived from glacial activity are well exposed on both flanks of the present crater. Despite some hydrothermally altered areas within the crater, there are no signs of modern hydrothermal activity on the volcano.

STRATIGRAPHY

In our study area we have recognized and mapped seventeen stratigraphic units, as shown in the geologic map and the composite stratigraphic column diagram on the map sheet (located above the legend). A description of each unit follows.

Mesozoic

Guerrero Terrane. The Guerrero Terrane forms most of the western part of Mexico, is one of the largest terranes of the North American Cordillera, and is characterized by an Upper Jurassic-Lower Cretaceous volcanic-sedimentary sequence of arc affinity (Centeno-García et al., 1993). In the study area, the Guerrero Terrane consists of three formations: the Ixtapan-Teloloapan sequence, the Acuitlapan Formation, and the Amatepec Formation. These formations are described below.

The volcano-sedimentary metamorphic Ixtapan-Teloloapan sequence consists of conglomerates, limestones, sandstones, and lava flows affected by greenschist facies metamorphism (Campa et al., 1974). Based on the presence of ammonites and other invertebrates, Campa et al. assigned this unit to late Jurassic-early Cretaceous. This sequence is exposed in the southern portion of the area close to Ixtapan de la Sal, Zumpahuacán, and Coatepec de Harinas, where it consists of long narrow outcrops oriented NW–SE. Its base is not exposed in the area, and it is overlain by Tertiary and Quaternary volcanic rocks.

In the Taxco region, the Acuitlapan Formation consists of interbedded gray to green shales and poorly sorted graywackes formed by feldspar and quartz grains derived from metamorphic and volcanic rocks (Fries, 1966). In the Santa Rosa area, this formation consists of meter-thick interlayering of metamorphosed carbonates, arenites, and lutites. These rocks are well bedded, foliated, rather friable, and weather to a buff or tan color. The calcareous portion is gray and more resistant to weathering than the other lithologies. The main outcrops of this formation are located to the southwest of the study area. According to its ammonite assemblage, the age of this unit is early Jurassic (Tolson, 1993).

The Amatepec Formation (De Cserna, 1983), which is exposed in the southwestern portion of Nevado de Toluca Volcano, consists of dark, bluish-gray to black limestones with centimeter-thick bands of white calcite and quartz. Locally, thin beds of black silicic and slate rocks are intercalated with the limestones, suggesting that the probable protolith of these rocks was pelagic micritic limestone, with thin cherts and shales. The limestone is dark gray, with thin and laminated beds with dark-gray shale intervals. The age of the Amatepec Formation is Cretaceous (Albian-Cenomanian) (De Cserna, 1983).

Guerrero Morelos Platform. The Guerrero Morelos Platform includes the Morelos and Mexcala formations of Tithonian-Coniacian age (De Cserna et al., 1974a). This map unit consists of massive to thickly bedded limestones and dolomitic limestones associated with calcareous terrigenous rocks toward the upper portion of the sequence. In the study area it is exposed around Zumpahuacán, where it forms NNW–SSE trending open anticline-syncline folds with the same alignment. Here, the Morelos Formation is exposed, and consists of light-gray dolomitic limestones with chert bands of massive to metric bedding stratification. The thickness of the unit varies from place to place from few meters up to 1000 m (De Cserna and Fries, 1981). This unit is in normal-fault contact, with the volcanic rocks of the Tepoztlán Formation of middle Miocene age.

Cenozoic: Eocene

Intrusive Felsic Igneous rocks. This unit includes a small stock of quartz-rich porphyritic dacite dated at 55 ± 6 Ma by De Cserna et al. (1974b) (Table 1). This intrusive body is located in the southwestern part of the mapped area close to the towns of Almoloya de Alquisiras and Malinaltenango. They form an elongate dome-like structure with northwesterly trend, the maximum elevation of which (~2,000 m.a.s.l.) rises to about 300 m above the depressions filled with volcaniclastic sediments to the east.

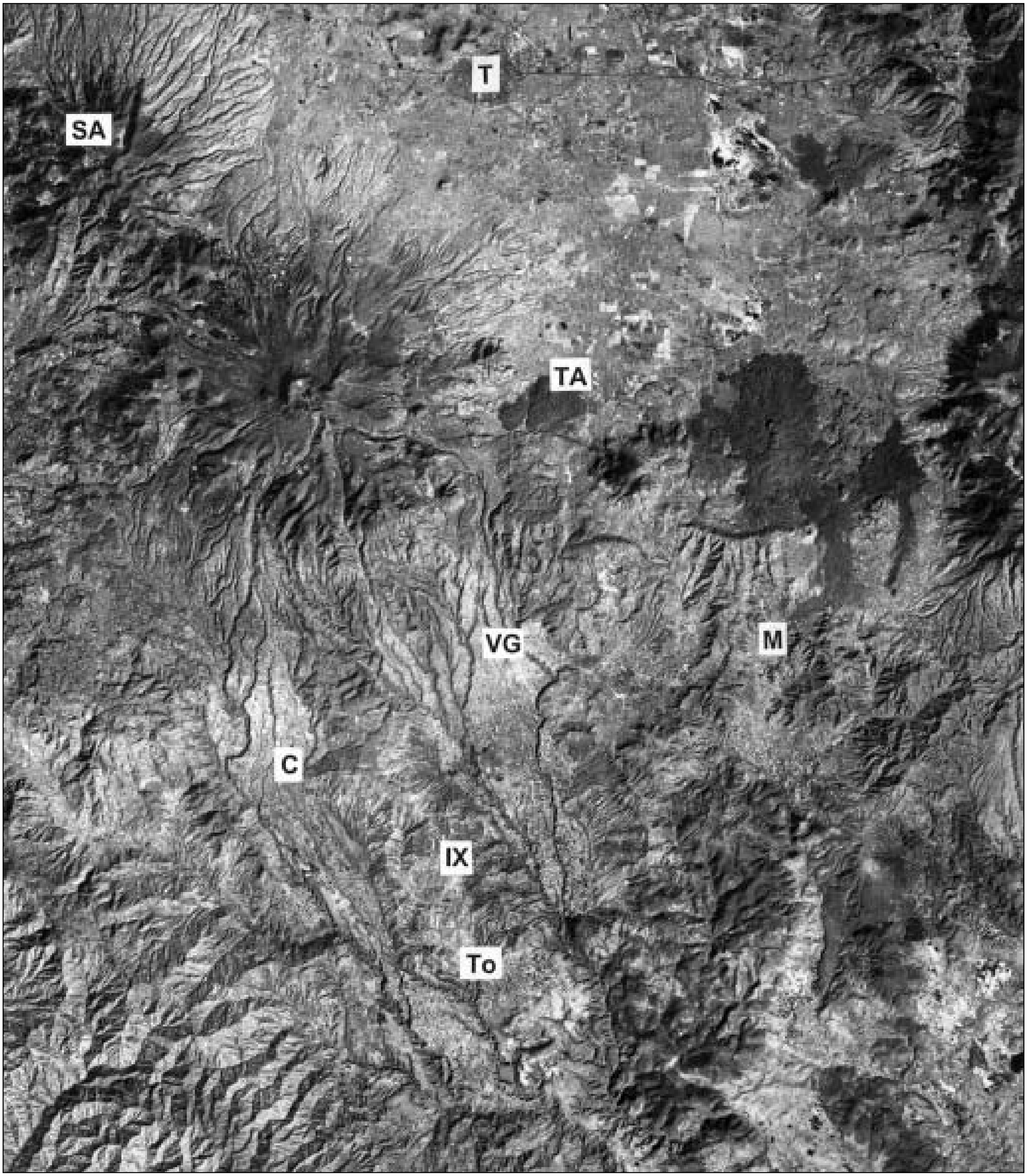

Figure 3. Landsat image of the map area showing NT—Nevado de Toluca, SA—San Antonio Volcano, TA—Tenango Andesite, T—City of Toluca, IX—Ixtapan de la Sal, To—Tonatico, VG—Villa Guerrero, C—Coatepec, and M—Malinalco.

Figure 4. Aerial view to the west of Nevado de Toluca with the crater open to the east. The dacitic central dome “ombligo” appears in the central part of the crater as well as the Moon lake, whose surface stands at ca. 4200 m.a.s.l. (photo by A. Herrera).

Cenozoic: Eocene-Oligocene

The Balsas Formation. The Balsas Formation consists of calcareous conglomerates, lava flows, sandstones, volcanic siltstones, and lacustrine deposits (Fries, 1956; 1960), with a maximum thickness of 500 m (De Cserna and Fries, 1981). This formation ranges in age from Upper Eocene to Early Oligocene and probably represents a late stage of Laramide tectonism that affected the pre-Cretaceous rocks of this region. Its distribution within the map area is limited to scarce faulted and tilted outcrops southeast of the town of Malinalco. Here, the Balsas Formation is represented by red polymictic conglomerates that consist of rounded to subrounded clasts (1-5 cm in diameter) set in a reddish matrix of silty sand. The formation overlies the limestones of the Morelos Formation with an angular unconformity.

The Tilzapotla Formation. The Tilzapotla Formation was originally described as a sequence of rhyolites, rhyodacites, dacitic lava flows, and pyroclastic flow deposits of early Oligocene age as its lower age limit (Fries, 1960). Recently, Morán-Zenteno et al. (1999), in their study of the Tertiary Volcanic Province of Southern Mexico (TVPSM), recognized three series of rocks distributed south of the Trans-Mexican Volcanic Belt: the Taxco volcanic sequence of rhyolitic composition (31-38 Ma, Table 1); the Buenavista-Quetzalapa volcanic sequence of mainly andesitic-dacitic composition (24-31 Ma, Table 1) but including the Tilzapotla Rhyolite; and the Huautla volcanic sequence of dominantly andesitic composition as yet not dated.

Outcrops of this formation are best exposed in the southern part of the map area near the towns of Porfirio Díaz and Chiltepec, where they form large and extensive plateaus, locally intruded by felsic dikes. In these localities, the Tilzapotla Formation is composed of several units of pink ignimbrite, as thick as 300 m, with white pumices and crystals of quartz, plagioclase, and biotite imbedded in a vitric matrix.

Based on its stratigraphic position, Fries (1960) proposed the age of the Tilzapotla Formation as early Oligocene. Rocks from this Formation yielded K-Ar ages of 26 Ma (Fries, 1960), 31.9 ± 0.9 Ma (Morán-Zenteno et al., 1999), and 49 ± 3 Ma (Linares and Urrutia-Fucugauchi, 1981) (Table 1). We obtained a K-Ar date of 38.3 ± 1.0 Ma for a sample from this sequence. This age, together with the areal distribution of these rocks in the southern portion of the study area, just north of the City of Taxco, suggest that this unit correlates with the lower unit (Acamixtla Formation) of the Taxco volcanic sequence dated at 38.2 ± 1 Ma (K-Ar method) (Morán-Zenteno et al., 1999).

The Tilzapotla Formation unconformably overlies the Balsas Formation and is overlain with parallel unconformity by the lava flows of the Basal Sequence.

Cenozoic: Miocene

The San Nicolás Basaltic Andesite. The San Nicolás Basaltic Andesite is composed of a series of dark-gray, vesicular lava flows with thickness as great as 100 m (García–Palomo et al., 2000). They are of basaltic-andesitic composition, aphanitic texture, and contain zeolite-filled vesicles. The rock is hypocrystalline and is characterized by an intersertal texture with scarce phenocrysts of orthopyroxene, clynopyroxene, olivine, plagioclase set in a groundmass rich in microlithes of the same minerals, oxides, and glass. The olivine and pyroxenes have reaction borders to

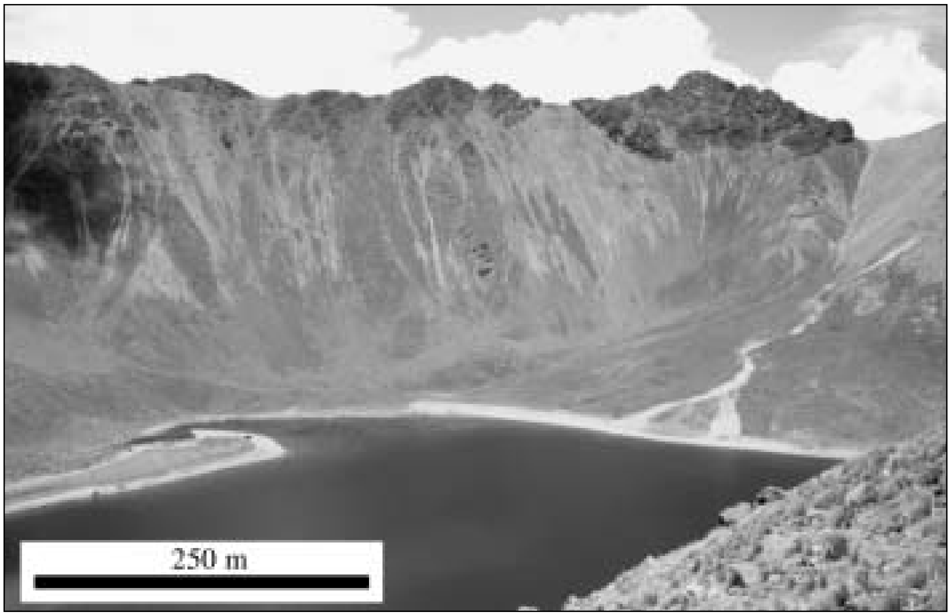

Figure 5. View of the northwest wall of the Nevado de Toluca crater interior showing dark-gray lava flows and domes exposed toward the uppermost portion of the wall. The Sun Lake appears in the foreground of the photograph (photo by J.L. Macías).

Figure 6. View of the upper part of the Tepoztlán Formation at the pre-Hispanic ruins of Malinalco. Around AD 1400, the archaeological site of Malinalco was used by the Aztecs as a training site for their warriors. This site was carved in lacustrine and hyperconcentrated flow deposits of the Tepoztlán Formation (photo by J.L. Macías).

iddingsite. The primary oxide minerals are titanomagnetite and chromite, and spinel occurs as inclusions in phenocrysts.

These andesites crop out in the vicinity of San Nicolás, a town located SE from Nevado de Toluca, where they overlie the Tilzapotla Rhyolite in sharp erosional contact, which may represent a gap of approximately 10 Ma. García-Palomo (1998) obtained a K-Ar age of 21.6 ± 1.0 Ma for this unit, corresponding to early Miocene (Table 1).

The Tepoztlán Formation. The Tepoztlán Formation consists of massive lahars rich in subrounded porphyritic andesite clasts intercalated with fluvial deposits (Fries, 1960; De Cserna and Fries, 1981). This formation is widely exposed south of the Trans-Mexican Volcanic Belt in the proximities of the towns of Tepoztlán, Cocoyoc, and Oaxtepec. The fluvial deposits show a wide diversity of stratification types (cross-bedded, normal grading, etc.), syn-sedimentary faults, and occasionally, clastic dikes and cut and fill structures as observed at the entrance of the Malinalco pre-Hispanic ruins. This map unit is well exposed in the vicinity of the village of Malinalco and in scattered sites southeast of Nevado de Toluca (Fig. 6). The total thickness of the Tepoztlán Formation varies from 200 to 700 m, although close to Malinalco it pinches out between the San Nicolás Basaltic Andesite and the overlying Basal Sequence. The exact age of this formation is

TABLE 1. K/AR AND OTHER DATES FOR SELECTED ROCKS FROM THE MAP AREA

Map Unit	Sample	Rock Type	Material dated	40*Ar (ppm)	40K (ppm)	40*Ar/K	Age	Ref
12b	NT01	D	WR	0.000148	1.965	0.000075	1.3 ± 0.1 Ma	7
12b	Me19	A	WR				1.3 ± 0.3 Ma	2
11	SJ	B-A	WR	0.000146	1.796	0.000081	1.4 ± 0.1 Ma	1
12b	VnE5	A	WR				1.44 ± 0.07 Ma	2
12b	Ne20	A	WR				1.6 ± 0.15 Ma	2
12a	NT05	A	WR	0.000301	2.017	0.000149	2.6 ± 0.2 Ma	7
8	SN1	A	WR	0.000306	1.754	0.000174	3.0 ± 0.2 Ma	1
9	BMS3	B-A	WR	0.000799	1.84	0.000434	7.5 ± 0.4 Ma	1
5	BI	B	WR	0.000971	0.769	0.001261	21.6 ± 1.0 Ma	1
4	BV-12	I	Hb	0.000831	0.573	0.001450262	24.8 ±1.3 Ma	6
4	BV-17	R	Pl	0.00155	0.869	0.001783659	30.5 ± 1.1 Ma	6
4	TX-10	R	Pl	0.001259	0.68	0.001851471	31.6 ± 1.2 Ma	6
4	TX-25	G	WR	0.008059	4.315	0.001867671	31.9 ± 0.8 Ma	6
4	SOL-5	D	Bt	0.01753	9.372	0.001870465	31.9 ± 0.8 Ma	6
4	TX-21	R	Bt	0.01588	8.364	0.001898613	32.4 ± 0.8 Ma	6
4	TX-16	G	WR	0.01081	5.686	0.001901161	32.4 ± 0.9 Ma	6
4	En19	R	WR				36.9 ± 1.3 Ma	4
4	CH1	R	WR	0.00911	4.045	0.002252	38.3 ± 1.0 Ma	1
4	TX-4	G	WR	0.009415	4.201	0.002241133	38.2 ± 1.0 Ma	6
M48-51	R	WR					49 ± 3 Ma	3
Ig	LG-22	D	Pb/alpha	/mg-hr=2522	Pb=55 (ppm)		55 ± 6 Ma	5

B—Basalt, A—Andesite, D—Dacite, R—rhyolite, G—Glass, I—Ignimbrite, WR—Whole Rock, Hb—Hornblende, Pl—Plagioclase, and Bt—Biotite. [1]García-Palomo et al. (2000), [2]Bloomfield and Valastro (1987), [3]Linares and Urrutia-Fucugauchi (1981), [4]De Cserna and Fries (1981), [5]De Cserna et al. (1974b), [6]Alva-Aldave et al. (1996), and [7]This work.

still uncertain, but Fries (1960) assigned it to Early Miocene. The K-Ar dates of the San Nicolás Basaltic Andesite (21.6 ± 1.0 Ma, Table 1) and the Basal Sequence above it brackets this unit within the middle Miocene (García-Palomo, 1998).

The Basal Sequence. The Basal Sequence consists of interbedded dark-gray lava flows and breccias of andesitic composition (García-Palomo et al., 2000). These rocks commonly have reddish weathered surfaces, show cooling fissures, and reach a total thickness of 400 m. This sequence is extensively exposed in the western and eastern parts of Nevado de Toluca and forms the Tenancingo, Desierto del Carmen, and Chiltepec ranges. Fries (1960) and Elías-Herrera (1993) grouped this sequence within the Andesita Zempoala, a series of undifferentiated rocks of late Miocene-Pliocene age. Our field observations suggest that this sequence is not related to the Andesita Zempoala, because its age and lithologic characteristics are different. Mineralogically, rocks of the Basal Sequence typically have microlithic to ophitic texture; and are composed essentially of plagioclase (andesine-labradorite) and minor amounts of hypersthene and hematite set in a microlithic groundmass composed of the same constituents.

A whole-rock K-Ar date of this sequence yielded an age of 7.5 ± 0.4 Ma which places this unit in late Miocene (García-Palomo, 1998; Table 1). According to its age, and because it unconformably overlies the Tepoztlán Formation (García-Palomo, 1998), the Basal Sequence can be correlated with rock of the basaltic sequence of the Querétaro, Morelia, and Río Grande regions (6-8 Ma) which are inferred to have formed during the early episodes of formation of the Trans-Mexican Volcanic Belt (Pasquaré et al., 1991; Ferrari et al., 1994).

The San Antonio Volcanic Sequence. We group under the name of San Antonio Volcanic Sequence all rocks forming the San Antonio Volcano (Sánchez-Rubio, 1978). The summit of the volcano (19º10' N, 99º52' W; 3,680 m.a.s.l.) has a truncated crater opened to the NE; the volcano is cut by NE-SW trending faults and deep incised valleys (Fig. 3).

The main edifice of San Antonio is composed of a thick sequence of lava flows, overlain by pyroclastic materials consisting of thick pumice-rich plinian fall layers that are overlain by pumiceous pyroclastic flow deposits and surges, such as those observed at Loma de San Francisco (Fig. 7). Sequences of thick block-and-ash flow deposits are also exposed on the northern flanks of the volcano close to the town of Santa María del Monte. A sample from the upper part of the San Antonio sequence yielded an age 3.0 ± 0.2 Ma (Table 1). On the basis of its stratigraphic position, the morphology of the edifice, and the pervasive fracturing and weathering of the rocks, we consider the early stages of formation in middle Miocene.

The San Antonio lavas are porphyritic with as much as 40% phenocrysts, mainly of plagioclase and hornblende, together with lesser amounts of biotite, augite, olivine, or enstatite. The groundmass is hyalopilitic with small crystals of plagioclase, clinopyroxene, and Fe-oxides (Sánchez-Rubio, 1984).

Sierra de las Cruces Sequence. The Sierra de las Cruces Sequence (SCS) is located in the eastern part of the study area and separates the basins of Mexico and Lerma. The Sierra de las

Figure 7. Sequence of pumice fall (black arrows) and pyroclastic flows exposed on the northern flanks of San Antonio Volcano (photo by J.L. Macías).

Cruces Sequence was initially described by Schlaepfer (1968) and Sánchez-Rubio (1984). This range has a general NNW–SSE orientation. It is formed by several andesitic stratovolcanoes such as San Miguel, La Corona, Picacho, Zempoala, and Ajusco. In addition, there are other volcanic structures, mostly domes, calderas, and scoria cones. Every volcano comprised within the SCS is made up of pyroclastic flow and fall deposits, lava flows, and thick sequences of lahar and avalanche deposits associated in occasions with collapse structures. This sequence pinches out against the lacustrine, fluvial, and alluvial deposits of the Lerma Basin. Las Cruces sequence is capped by the younger rocks of the Chichinautzin Volcanic field and rests discordantly on top of the Tepoztlán Formation. The age of the Sierra de las Cruces sequence is considerably variable, going from 13 to 6 Ma in the northern part (Aguirre-Díaz and Carrasco-Hernández, 1999), 7 to 5 Ma at the Catedral caldera (Aguirre-Díaz et al., 1999), 2.87 to 0.39 Ma in the south (Mora-Alvarez et al., 1991), and to 3.4 to 0.6 Ma at Ajusco Volcano (Romero-Teran, 1998).

Pliocene-Pleistocene

Cones and domes complex. A single map unit, designated as monogenetic lava cones and domes, comprises all rocks from a series of monogenetic volcanic structures distributed around Nevado de Toluca and San Antonio volcanoes. The lava cones characteristically have a basaltic andesitic composition and are exposed in the San Miguel region, where they are crudely aligned in a NE-SW direction (García-Palomo et al., 2000). Some of these volcanic centers have open craters with collapse structures toward the southwest (e.g., Las Palomas). The domes are andesitic to dacitic, strongly affected by erosion and fractures, and dispersed throughout the area. The dacites (e.g., San Jose) are holocrystalline with trachytic texture composed of abundant plagioclase microlithes that surround the scarce phenocrysts of plagioclase and pyroxenes, quartz, amphibole, and olivine. Fe-oxides are present as inclusions in phenocrysts and dispersed throughout the sample.

A K-Ar date of the San Jose lava flow was obtained from a whole-rock concentrated yielding an age 1.4 ± 0.1 Ma (Table 1). From this date and its stratigraphic position, we assigned a Pliocene-Pleistocene age to this unit.

Pleistocene-Holocene

Nevado de Toluca Volcano. The first geological studies of Nevado de Toluca Volcano were carried out during the first decade of the twentieth century (Ordoñez, 1902; Otis, 1902; Flores, 1906; Waitz, 1909). These authors described the general features of the volcano, including its morphology, structure, and petrology. Bloomfield and Valastro (1974, 1977) and Bloomfield et al. (1977) were the first authors to define the individual eruptions of the volcano on the basis of radiocarbon chronology. They identified several events: a vulcanian eruption about 28 000 yr. BP that produced extensive blue-gray lahars; a plinian eruption that deposited the Lower Toluca Pumice fall ca. 24 000 yr. ago; and another plinian eruption that generated the Upper Toluca Pumice ca. 11 600 yr. BP.

Cantagrel et al. (1981) divided the rocks forming Nevado de Toluca into two main units. The oldest unit corresponds to a series of light-gray porphyritic andesitic lava flows that constitute the main edifice of the volcano. These rocks are common accessory components in younger volcaniclastic and pyroclastic units and are easy to identify because of their pink-to-red alteration surfaces. The lavas are composed of plagioclase, clinopyroxene, and orthopyroxene set in a glass groundmass (Cantagrel et al., 1981). These deposits crop out near the town of Raíces along the road connecting Coatepec de Harinas and the crater of the Nevado de Toluca. The K-Ar age of these lavas falls between 1.60 ± 0.12 and 1.23 ± 0.15 Ma (Pleistocene) (Cantagrel et al. 1981; Samples Ne20, VnE5, and Me19, Table 1). However, we recently collected a sample from a sequence of lava flows exposed on the southern flank of Nevado de Toluca, which yielded a K-Ar age of 2.6 Ma (sample NT05, Table 1), being in consequence the oldest products of Nevado de Toluca Volcano. These lavas were fed by a N-S dike system now highly dissected and exposed by erosion at several outcrops. These lavas are porphyritic andesites, with plagioclase, clinopyroxene, and resorbed hornblende phenocrysts set in a groundmass composed of glass and plagioclase microphenocrysts. The dikes also cut through an older ignimbrite deposit, unfortunately so altered that further study on its origin is impossible. We also dated a dacitic clast found within a debris avalanche deposit exposed in the southern flanks of the volcano; this clast is very probably a fragment of the younger edifice and yielded an age of 1.3 Ma (sample NT01, Table 1) in agreement with the ages obtained by the above mentioned authors.

The younger unit of Cantagrel et al. (1981) is made up of a complex sequence of pyroclastic deposits that mantle the flanks of Nevado de Toluca Volcano. In the northern part, they form coalescent fans, whereas in the south they were channeled into NW-SE-trending tectonic basins. This unit is composed of volcaniclastic deposits (debris flows and fluvial deposits), a debris avalanche, a debris flow, pyroclastic flow, and surge and fall deposits, all of which were emplaced during the last 100,000 years (Bloomfield and Valastro, 1974, 1977; Bloomfield, 1975; Macías et al., 1997; Capra and Macías, 2000). The activity of Nevado de Toluca between these two periods (~1.5 Ma and <0.1 Ma) was presumably volcaniclastic, according to Cantagrel et al. (1981). Numerous volcaniclastic, laharic, and minor lacustrine deposits are exposed in the southern flanks of Nevado de Toluca, where deep canyons have been cut by erosion. In contrast, the northern flanks of the volcano have a rather youthful morphology covered by younger deposits that bury older rocks. We next summarize the Quaternary stratigraphic record of Nevado de Toluca (Fig. 8).

Older debris avalanche (DAD-1) and cohesive debris flows (PDF and MDF) deposits. Macías et al. (1997) first recognized two debris avalanche deposits emplaced during the Pleistocene toward the S-SE of the volcano (out to a maximum distance of 55 km). The older deposit (DAD-1, Fig. 9) is constituted by a single unit, 10-m thick, massive, matrix supported, and monolithologic with dacitic clasts that vary in diameter from centimeters to 1.5 m. Unfortunately, because outcrops of this older unit are scarce, no additional information is available. In contrast, detailed work by Capra and Macías (2000) showed that the younger sector collapse produced two large cohesive debris flows: the Pilcaya (PDF) and the El Mogote (MDF) deposits. These covered an area of 220 km^2 and involved a total volume of 2.8 km^3 (Fig. 10a). The PDF has a sharp basal contact, and a flat surface. Only in the medial area is hummocky morphology present, with mounds up to 20 m high. Its thickness varies from 6 m in the proximal section to 40 m in the intermediate zone, where thickening is abrupt (Fig. 10b); assuming an average thickness of 20 m, we obtained a total volume of 2 km^3.

The PDF unit consists of a massive, matrix-supported deposit containing megaclasts up to 15 m in diameter with jigsaw puzzle structures. It is heterolithologic in composition and contains fragments of the andesite and dacite of the older edifice as well as rocks from the local bedrock, such as andesite and basalt of the Miocene Basal Sequence, limestone of the Balsas Formation, schist of the Ixtapan-Teloloapan Formation, rhyolite from the Tizapotla Formation, conglomerate and lacustrine fragments of the Tepoztlán Formation. The matrix is sandy (as much as 80% sand fraction) and contains up to 16% clay (olinite-smectite) in the proximal areas. Sorting improves and mean grain size decreases downstream.

The MDF deposit rests directly on top of the Pilcaya unit (PDF), cropping out at 40 km from the edifice and extending out 75 km with an average thickness of 6 m (Fig. 10B). It covers an area of 120 km^2 for a total volume of 0.8 km^3. It consists of a massive, matrix-supported deposit, with clasts as large as 1 m in diameter of the same composition of the Pilcaya deposit. The matrix is sandy (as much as 78% sand) and contains as much as 6% in clay fraction.

From the textural and sedimentological characteristics of these deposits, we infer that the flank failure occurred because of intense hydrothermal alteration and tectonic dissection of the old edifice of the Nevado de Toluca Volcano. Increase of pore pressure, perhaps combined with seismic activity associated with movements of the Tenango normal fault, could have liquified a portion of the southern part of the edifice, resulting in a debris avalanche that transformed directly into a cohesive debris flow. Subsequent heavy rains then caused the remobilization of the upper part of the PDF, triggering secondary lahars from which the MDF deposited.

Pink Pumice Flow (42 ka). A thick, pink pumice-rich pyroclastic flow deposit is exposed around Nevado de Toluca Volcano. The deposit consists of at least four units composed of rounded to semirounded vesiculated pumice fragments set in a sandy matrix, in which tree trunks have been found (Fig. 11, site 95). This unit represents the oldest radiocarbon-dated material at 42,030 +3530/–2445 yr. BP (Macías et al., 1997). Because no other deposits indicative of dome-destruction events have been found associated with the Pink Pumice Flow, we assume that the eruption that produced it took place under open-vent conditions, most likely after the collapse of the volcano that produced the Pilcaya debris flow.

Block-and-ash flow deposits (37, 32, 28, 26, 14 ka). The volcanic activity of Nevado de Toluca during late Pleistocene has been characterized by cataclysmic eruptions, some of which are related to the partial or total destruction of central dacitic domes. Because these deposits are similar in appearance and components, previous authors considered them as a single unit, which they referred to as either “older lahar assemblages” (Bloomfield

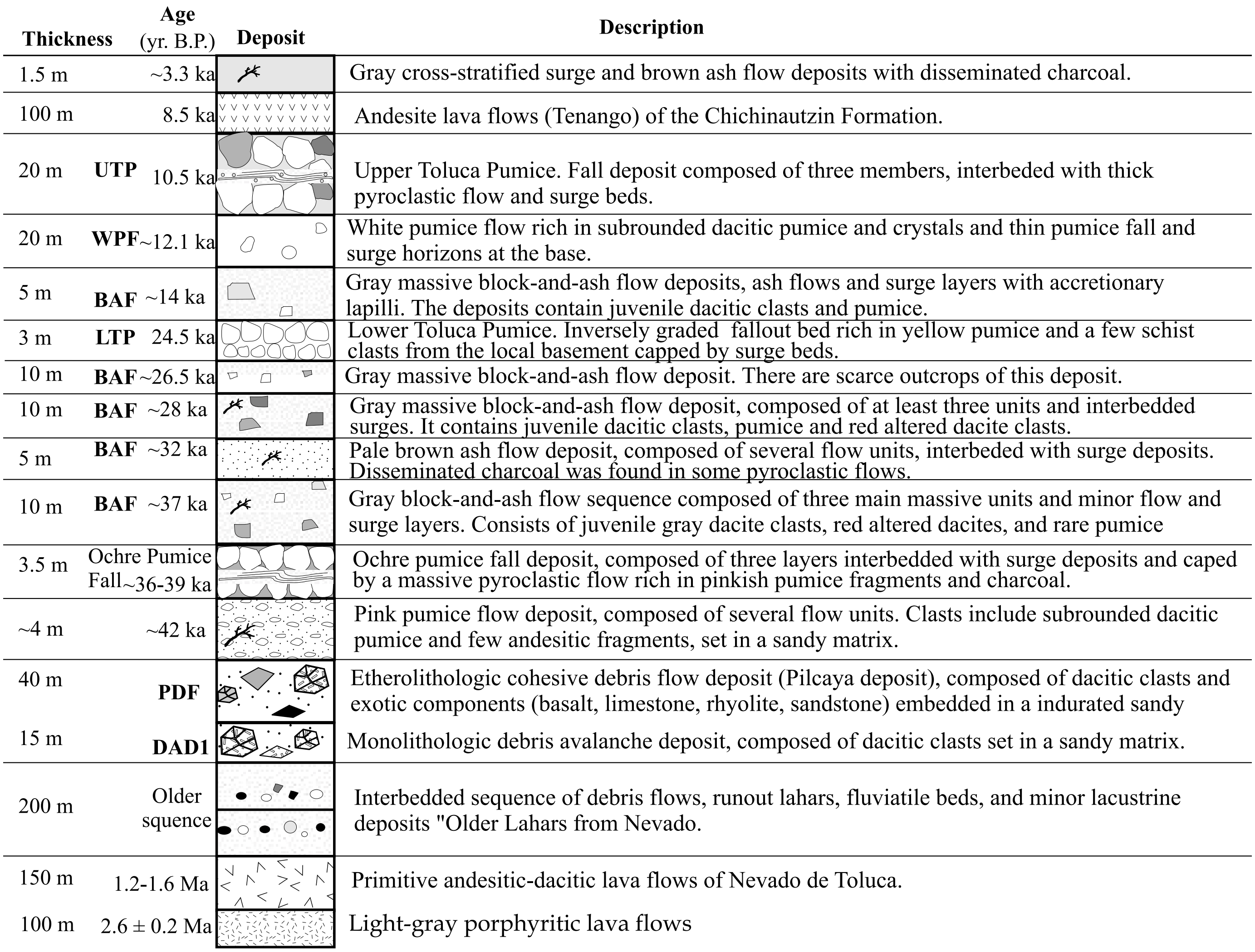

Figure 8. Composite stratigraphic column of Nevado de Toluca Volcano (after Macías et al., 1997).

and Valastro, 1974, 1977) or "Nueés Ardentes" (Cantagrel et al., 1981). Bloomfield and Valastro (1977) estimated the age of the deposits at ca. 28,000 yr. BP, based on a single ^{14}C date from a paleosoil that covers the deposit. However, Macías et al. (1997) identified two block-and-ash flows, the older of which was dated as 37 000 ± 1125 yr. BP, which they correlated with the date of 35 600 +2600/–1800 yr. BP for the "gray lahar" of Heine (1988) and an underlying paleosoil dated at 38,000 yr. BP by Cantagrel et al. (1981). The younger block-and-ash flow deposit yielded ages of 28 140 + 865/–780, and 28 925 + 625/–580 yr. BP. These ages correlate with the upper age limit proposed by Bloomfield and Valastro (1977), who reported an age of 27 580 ± 650 yr. BP for a fluvial gravel on top of the flow deposit (Table 2).

The block-and-ash flows have entirely blanketed and modified the morphology of the volcano's flanks and apron, and at present most of the localities of these deposits are pits used for the extraction of construction materials. The northern flanks of the volcano consist of coalescent tongues of block-and-ash flow deposits that produce a subdued morphology. All other flanks of the volcano are highly dissected and show the action of tectonism and strong erosion, with exposure of the block-and-ash flow deposits cropping out as isolated tongues along major ravines.

From stratigraphic and radiometric age evidence, five block-and-ash flow (BAF) deposits have been identified at Nevado de Toluca with dates of about 37, 32, 28, 26, and 14 ka (see Fig. 8 and Table 2). Eruptions at 37, 28, and 14 ka were produced by the destruction of large central dacitic domes that occupied the volcano's central crater. This interpretation is suggested by the roughly radial pattern of exposures of pyroclastic deposits, although the oldest two also show important ponded deposits. The aspect, texture, composition, and chemistry of juvenile products are very similar for all deposits; therefore, paleosoils and/or charcoal fragments were very useful in identifying individual units.

The 37 and 28 ka deposits consist of massive block-and-ash flow deposits (commonly more than 10 m thick) composed of

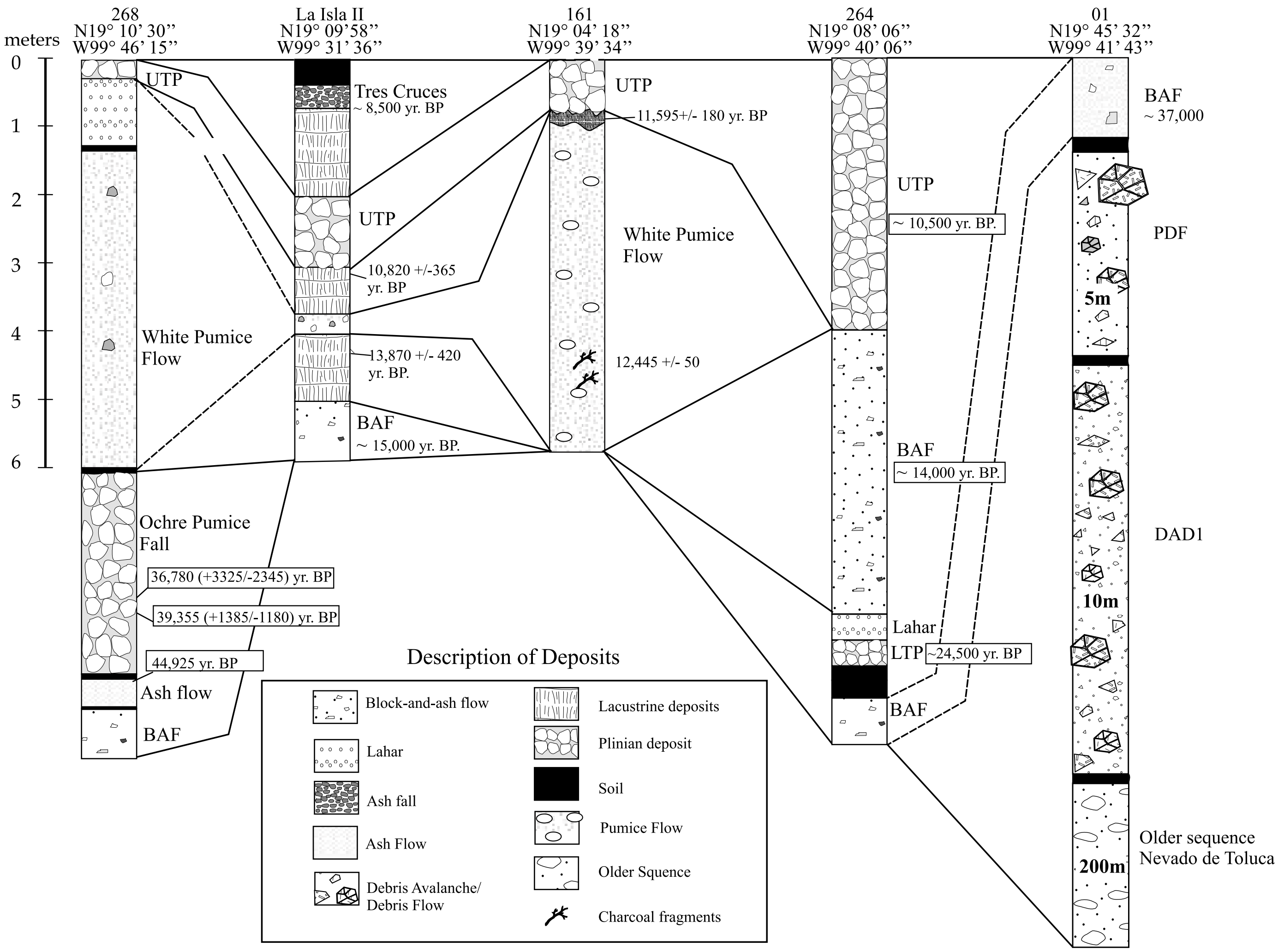

Figure 9. Stratigraphic correlation of the Late Pleistocene deposits around Nevado de Toluca Volcano. Abbreviations of deposits are UTP—Upper Toluca Pumice, LTP—Lower Toluca Pumice, BAF—Block-and-ash flow, PDF—Pilcaya Debris Flow, and DAD1—Debris Avalanche Deposit 1.

more than three flow units of which the uppermost has a pink-red color, probably suggesting oxidation due to contact with the ambient air. These flow deposits contain charred logs and fumarolic pipes, and are associated with minor pyroclastic surge deposits. Both flow deposits are composed of gray porphyritic juvenile lithics with minor amounts of pumice, glassy lithic clasts, and red-oxidized dacite clasts from the volcanic edifice. The juvenile lithic clasts have millimeter-sized phenocrysts of plagioclase, hornblende, augite, and minor hypersthene, quartz, and biotite embedded in an aphanitic groundmass of the same constituents. Pumice and dense juvenile lithic clasts have a uniform chemical composition in the range of 65 to 67% in SiO_2 (Table 3 and Macías et al., 1997).

The 14 ka block-and-ash flow deposit differs strikingly from the other two because it has a more radial distribution around the volcano. A typical proximal section of this unit consists, from the base upward, of a gray cross-bedded surge deposit (15 cm thick) overlain by two massive gray block-and-ash flow units made of gravel to boulder size lithics set in a coarse sand-size matrix with a total thickness of 10 m (Fig. 12, Section 268). In other localities (e.g. Section 35), the basal surge is rather thick (30-40 cm) with well-developed cross bedding and accretionary lapilli as large as 1 cm in diameter, capped by a massive pink ash flow deposit with few gravel size lithics embedded in a fine sand matrix (Fig. 11). In distal areas (20 km northeast from the vent), this unit has been found in subaerial exposures (Newton and Metcalfe, 1999) and in drill holes at the margins of Lake Chiconahuapan (Caballero et al., 2001) (Fig. 11). At this distance, the 14 ka event is represented by a gray, massive ash flow about 90-cm thick composed of fine sand- to silt-size particles. Organic-rich material collected some 50 cm above this layer at pit La Isla II yielded an age of 13 870 +445/–420 yr. BP; for which Caballero et al. (2001) assigned an approximate age for this unit of >14 000 yr. BP. However, at Site 256, a paleosoil sample lying below the block-and-ash flow deposit yielded an age of 13 160 ± 89 yr. BP. Therefore the age of this event remains uncertain.

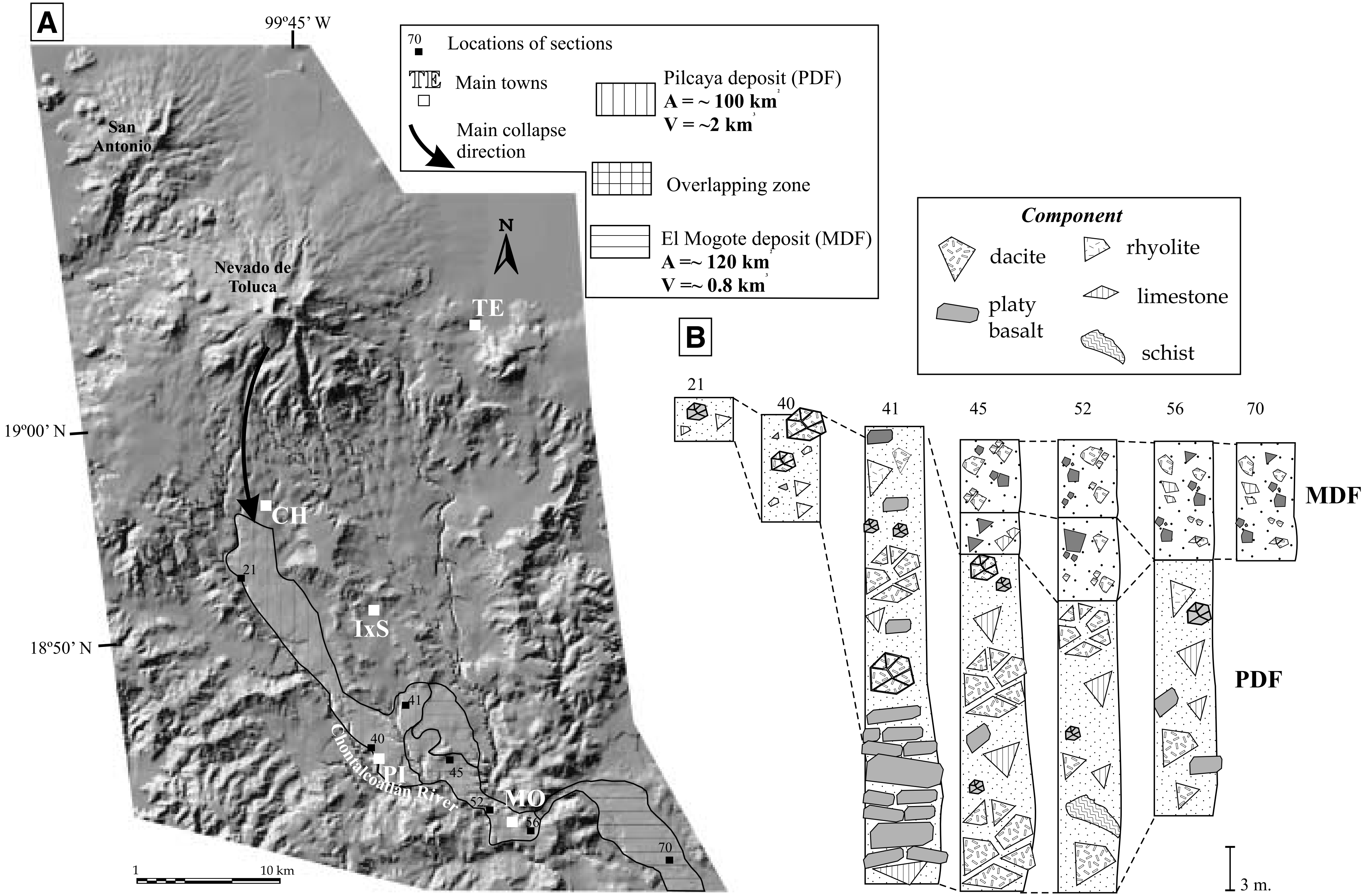

Figure 10. A: Digital elevation model showing the distribution of the Pilcaya (PDF) and El Mogote (MDF) cohesive debris-flow deposits on the southern flanks of Nevado de Toluca Volcano. TE—Tenago, CH—Coatepec Harinas, IxS—Ixtapan de la Sal, PI—Pilcaya, and MO—El Mogote. B: Stratigraphic correlation of selected sections of the Pilcaya and El Mogote deposits (for locations see Figure 10A).

Massive block-and-ash flows deposits represent the other two events dated ca. 32 and 26 ka; however, they have a poor distribution around Nevado de Toluca. The scattered nature of outcrops of these deposits probably reflects direct explosions or partial collapse of the central dacitic domes or to burial by subsequent pyroclastic deposits.

Pumice Fall Deposits

Previous work described two plinian eruptions at the Nevado de Toluca volcano. They were dated in ~24 500 and ~11 600 yr. BP and named Lower Toluca Pumice and Upper Toluca Pumice, respectively (Bloomfield and Valastro, 1974, 1977). Radiocarbon ages were determined for paleosoil and carbonized material collected below the deposits; however, no charcoal material was collected in the deposits themselves. In this work, we recognize four plinian eruptions (older to younger): Ochre Pumice Fall (~36 000–37 000 yr. BP), Lower Toluca Pumice (~24 500 yr. BP), White Pumice Flow (12 100 yr. BP), and Upper Toluca Pumice (10 500 yr. BP) (see Table 1). Of these four units, only the Ochre Pumice Fall was not previously reported (Macías et al., 1997).

Ochre Pumice Fall (OPF). The Ochre Pumice Fall occurs on the northern slope of Nevado de Toluca Volcano ~ 5 km from the summit (Fig. 9, Section 268). From bottom to top, it consists of an alternating sequence of pumice fall layers and surge and flow deposits as follows: pumice fall layer (22 cm), surge deposit (10 cm), thin pumice fallout (7 cm), surge and ash flow deposits (62 cm total thickness), pumice fall (25 cm), and surge horizon (10 cm). The fall layers (Fig. 12) consist of ochre vesiculated pumice fragments and rare accidental lithic clasts. The sequence is crowned by a pink pyroclastic flow deposit rich in gravel-size pumice fragments set in a sand to silt size matrix (3–5 m thick). Two charcoal samples from the second surge horizon and from the base of the next fall layer yielded approximate ages of 39 355 +1385/–1180 yr. BP, and 36 780 +3325/–2345 yr. BP. These dates bracket the age of the eruption as between 36 and 39 ka ago.

Lower Toluca Pumice (LTP). The Lower Toluca Pumice is composed of an ochre fallout deposit with reverse grading and an average thickness of 55 cm. It is separated from the 28 ka BAF by an ash flow deposit and a dark-brown paleosoil, dated at 24 260 ± 670 yr. BP by Bloomfield and Valastro (1977). The Lower Toluca Pumice is clast-supported and rich in ochre pumice, with lesser amounts of clasts of gray dense juvenile dacite, hydrothermally altered lithic clasts, and schist fragments from the local basement. According to Bloomfield et al. (1977), the Lower Toluca Pumice fallout contains approximately 62% pumice, 27% lithic clasts, and 11% crystals. It covers an approximate area of 400 km^2 and has a dispersal axis trending northeast from the crater. The above authors calculated its volume at 0.33 km^3 (0.16 km^3 D.R.E. = dense rock equivalent).

However, the most complete exposures of this deposit (Fig. 11, Section 62) show that the Lower Toluca Pumice is more complex than previously described. The base of the unit always consists of the pumice fall layer proper (LTP), which is overlain by pale-brown cross-stratified surge deposits as thick as 35 cm, rich in ochre rounded to subrounded pumice and lithic clasts. The unit is then covered by a pale-brown ash flow deposit 42 cm thick, which commonly shows clear signs of reworking toward the top that ends with a poorly developed paleosoil.

White Pumice Flow (WPF). The White Pumice Flow consists, from bottom to top, of three fallout members, and at least two pyroclastic flow units (Fig. 9, Section 161). The lower fallout member (55 cm thick) has asymmetric grading (reverse to normal) and poor sorting; it is rich in white pumice fragments, lesser lithics, and abundant crystals of biotite, hornblende, and plagioclase. The middle fallout member (7 cm thick) is composed of fine sand grains (lithics, pumice, and crystals of hornblende, biotite, and plagioclase), and it shows high-angle cross-lamination (laminae dark and white). The upper fallout member (12 cm thick) has asymmetric grading and is composed of coarse gravel of pumice, lithics (more than the basal members), and crystals. At Section 161 it developed high-angle cross-stratification, suggesting wind reworking during deposition (Fig. 13). Thin cross-stratified pyroclastic surges are interbedded with the fallout layers. On top of the fallout sequence lays the white pumice flow deposit, which consists of two massive units; both have a minimum thickness of 15 m and contain pumice and lithic fragments as large as 35 and 20 cm in diameter, respectively. The pumice is dacitic (65.67% in SiO_2) and rich in phenocrysts of plagioclase, hornblende, biotite, and quartz. The White Pumice Flow has been found mainly on the southeast slopes of the volcano, with very thick exposures close to Villa Guerrero and Tenancingo. This unit correlates with the Lower Almoloya Tephra found in a pit drilled in the northwestern edge of the Chiconahuapan Lake (Newton and Metcalfe, 1999); these authors dated an organic rich horizon below this layer at 12400 ± 60 yr. BP. The White Pumice Flow is underlain by a paleosoil dated at 26 275 +1210/–150 yr. BP (Macías et al., 1997); however, recent findings of charred logs within the pumice flows at different outcrops (Fig. 11, Sections 161 and 200), yielded ages of 12 414 +290/–280, and 12 040 ± 92 yr. BP (see Table 2). Because the lower limit of the Lower Almoloya Tephra has been dated at 12 400 ± 60 yr. BP, we consider the approximate age of the White Pumice Flow eruption to be closer to the 12 040 ±92 yr. BP date, although additional dating needs to be carried out to establish a more definite age.

Upper Toluca Pumice (UTP). The Upper Toluca Pumice represents the largest plinian eruption at Nevado de Toluca Volcano. Bloomfield and Valastro (1974, 1977) subdivided the Upper Toluca Pumice into two members (Lower and Upper); however, recent detailed studies of this deposit demonstrate that the eruption was rather complex (Macías et al., 1997; Arce, 1999). Extensive field data attest that the Upper Toluca Pumice is composed of four fallout horizons (PC0, PC1, PC2, and PC3), that correspond to four plinian columns ~ 25, 37, 42, and 28 km in height (Arce, 1999). Four pyroclastic flows (F0, F1, F2, and F3) and two pyroclastic surges (S1, and S2) are included in this

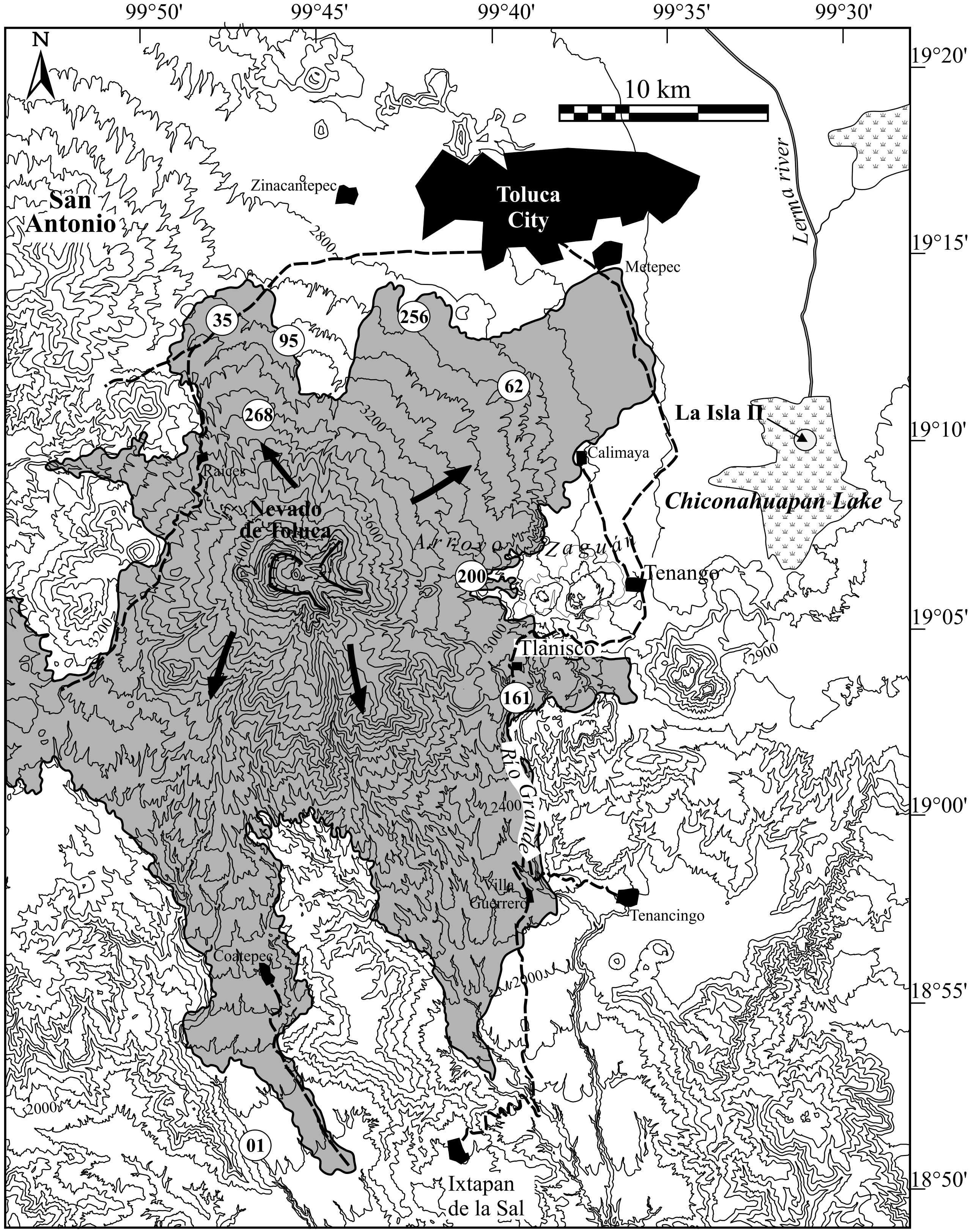

Figure 11. Distribution of block-and-ash flow deposits around Nevado de Toluca Volcano. The locations of some key stratigraphic sections discussed in the text are indicated by a numbered open circle. Contour intervals every 100 m.

TABLE 2: RADIOCARBON AGES OF PYROCLASTIC DEPOSITS OF NEVADO DE TOLUCA VOLCANO.

Sample No.	Lab. No.	Age (yr. BP)	Material dated	Location	Ref.
NT95140	A-8880	3,140 +195/-190	Charcoal in pumice flow deposit	19°02′19″, 99°54′34″	1
NT96144B	A-9175	3,435±50	Charcoal in ash flow deposit	19°13′26″, 99°47′22″	1
MX9787C	A-9926	4,200±110	Charcoal in dark-organic paleosoil	19°01′55″, 99°30′00″	2
MX97455	A-9708	9170+160/-155	Charcoal in brown paleosoil	19°05′59″, 99°26′01″	2
NT9570-A	A-9173	10,445±95	Charcoal in pyroclastic flow of UTP	19°17′30″, 99°21′00″	2
La Isla-2	A-9778	10,820±365	Charcoal in lacustrine sediment, jus below UTP		3
KBC-38	Tx-1658	11,580±70	Charcoal from thin layer at base of UTP; average of 4 samples	19°04′00″, 99°22′00′	4
NT97200	A-9781	12040±92	Charcoal in White Pumice Flow deposit		2
NT96161	A-9472	12,415+290/-280	Charcoal in White Pumice Flow deposit	19°04′05″, 99°39′20″	2
KBC-40a	Tx-1660	13,620±150	Paleosoil	19°10′00″, 99°39′00″	4
KBC-40b	Tx-1661	13,870±180	Paleosoil	19°10′00″, 99°39′00″	4
NT97193	A-9776	15,340+155/-150	Lacustrine organic horizon below block-and –ash flow deposit	19°13′37″, 99°28′45″	3
MX9887D	A-9921	16,215+135/-130	Paleosoil	19°01′55″, 99°30′00″	2
KBC-40c	Tx-1662	17,090±220	Humic horizon in Paleosoil just above reworked LTP	19°10′00″, 99°39′00″	4
KBC-25	Tx-1604	20,100±140	Paleosoil on Pleistocene lavas below KBC-9; contaminated by modern humus	19°06′00″, 99°56′00″	4
KBC-20	Tx-1599	21,030±430	Paleosoil on valley lahar	19°05′00″, 99°51′00″	4
KBC-19	Tx-1598	21,170±170.	Paleosoil on Tertiary lavas overlain by lahar: ?=KBC-17 and -18, contamination suspected	19°04′00″, 99°52′00″	4
KBC-26	Tx-1605	21,790±200	Paleosoil on valley lahar overlain by fluvial sand and gravel	19°11′00″, 99°51′00″	4
KBC-9	Tx-1725	23,800± 490	Charcoal fragments in lithic ash at base of valley lahar , 2 samples	19°06′00″, 99°56′00″	4
KBC-7	Tx-1523	23,940± 600	Paleosoil on lahar to E of Nevado: mean of 7 samples	19°12′00′, 99°39′00″	4
KBC-42	Tx-1664	24,160±420	Thin peaty layer at base of valley lahar, W of Nevado	19°05′00″, 99°51′00″	4
KBC-8	Tx-1524	24,260± 670	Paleosoil on lahar to E of Nevado: mean of 7 samples	19°10′00′, 99°39′00′	4
KBC-15	Tx-1594	24,400±430	Paleosoil on Tertiary lavas; Sierra de Las Cruces	19°14′00″, 99°23′00″	4
KBC-2	Tx-1518	24,410± 590	Paleosoil on lahar to E of Nevado: mean of 7 samples	19°04′00′, 99°39′00″	4
KBC-18	Tx-1597	24,440± 550	Paleosoil on Tertiary lavas and old lahars to W of Nevado	19°03′30″, 99°52′30″	4
KBC-17	Tx-1596	24,590± 280	Paleosoil on Tertiary lavas and old lahars to W of Nevado	19°03′00″, 99°52′30″	4
KBC-4	Tx-1520	24,930± 670	Paleosoil on lahar to E of Nevado: mean of 7 samples	19°09′00″, 99°37′00″	4
KBC-5	Tx-1521	25,020± 590	Paleosoil on lahar to E of Nevado: mean of 7 samples	19°09′30″, 99°37′30″	4
KBC-6	Tx-1522	25,250± 760	Paleosoil on lahar to E of Nevado: mean of 7 samples	19°09′30″, 99°39′30″	4
KBC-3	Tx-1519	25,620± 680	Paleosoil on lahar to E of Nevado: mean of 7 samples	19°12′00″, 99°41′00″	4
NT9545	A-8485	26,273-1208/-1050	Paleosoil below the white pumice flow deposit	19°02′54″, 99°39′00″	1
NT97204-B	A-9782	26,610±320	Charcoal in block-and-ash flow deposit	19°07′05″, 99°40′50″	2
KBC-41	Tx-1663	27,590±650	Paleosoil on fluvial gravel derived from lahar	19°05′00″, 99°51′00″	4
NT9535B	A-8244	28,140+865/-780	Charcoal in block and ash flow deposit	19°13′26″, 99°47′09″	1
NT9521	A-8388	28,925+625/-580	Charcoal in ash flow deposit	19°00′24″, 99°38′56″	1
MX9787A	A-9927	31,450+660/-610	Brown paleosoil	19°01′55″, 99°30′00″	2
NT9535-1	A-9315	32,730±50	Paleosoil below block-and-ash flow deposit	19°13′26″, 99°47′22″	2
NT9521-A	A-8389	32,860+2025/-1615	Charcoal in block-and-ash flow deposit		2
NT98268-C	A-10000	36,780+3325/-2345	Charcoal in ochre pumice fall deposit	19°10′30″, 99°46′20″	2
NT9550	A-8486	37,000 ± 1125.	Charcoal in block and ash flow deposit	19°00′09″, 99°38′56″	1
NE 12	CGR-4955	38,000	Paleosoil at Jaral gully		5
NT9595	A-8657	42,030+3530/-2445	Charcoal in ash flow deposit	19°12′52″, 99°45′44″	2

Compiled data from: [4]Bloomfield and Valastro (1977), [5]Cantagrel et al. (1981), 1Macías et al., (1997), [3]Caballero et al., (2000), and [2]This work.

TABLE 3. CHEMICAL ANALYSIS OF SELECTED SAMPLES FROM THE MAP AREA

Sample	CH33	CH46	CH47	CH49	CH84	SJ	BS3	BI	NT30	NT54	NT84	NT90
SiO2	61.04	60.67	61.25	61.63	56.7	64.46	60.08	52.69	60.89	65.06	63.47	62.73
TiO2	0.75	0.77	0.8	0.8	0.82	0.58	0.78	0.79	0.77	0.58	0.65	0.70
Al2O3	15.92	16.12	15.97	16.01	16.07	15.72	15.5	16.33	16.44	16.21	16.60	16.32
Fe2O3	5.59	5.72	5.43	5.58	6.54	4.09	5.8	7.87	5.72	4.08	4.95	5.13
MnO	0.09	0.09	0.09	0.09	0.1	0.07	0.09	0.13	0.09	0.07	0.08	0.07
MgO	4.91	4.69	4.37	4	6.07	2.2	5.61	6.74	3.51	2.09	2.55	3.56
CaO	5.62	6.08	6.02	5.69	6.9	4.35	5.76	8.04	5.86	4.18	4.73	4.89
Na2O	4.38	4.24	4.25	4.39	3.99	4.18	4.02	3.68	4.22	4.34	4.39	4.32
K2O	1.56	1.62	1.7	1.86	1.41	1.98	1.95	0.83	2.20	2.29	1.98	1.86
P2O5	0.19	0.24	0.26	0.26	0.24	0.17	0.3	0.17	0.28	0.16	0.19	0.20
LOI	-0.01	-0.01	-0.01	-0.01	0.12	1	0.08	0.86	0.14	1.43	0.57	0.66
Total	99.97	100.11	99.99	100.29	98.96	98.81	99.97	98.12	100.1	100.49	100.2	100.45
Ba	389	529	587	528	495	390	466	197	605	448	455	463
Rb	0.1	35	51	44	34	27	22	18	47	50	48	44
Sr	465	573	661	571	545	729	822	381	720	493	514	500
Y	17	17	18	18	18	16	16	17	20	15	18	20
Zr	137	169	176	174	149	135	161	94	175	149	149	152
Th	2.7	3.6	4.3	4	3.3	3.1	3.4	0.8	5.9	4.6	4.1	4
Pb	12	10	14	12	9	8	10	5	0	0	0	5
Zn	63	66	67	71	69	75	70	76	57	47	52	62
Cu	21	22	21	19	35	24	25	49	12	6	12	17
Ni	106	87	76	67	126	38	148	161	13	17	20	49
V	101	102	99	105	119	73	104	167	123	74	94	96
Cr	193	200	167	145	262	71.7	240	384	57.3	38.8	62.9	113
Hf	3.4	4.2	5.2	4.4	4	3.5	4	2.5	5.1	2.6	2.7	2.7
Cs	1.4	1.5	1.1	1.3	0.8	0.7	1	0.4	1.2	2.7	1.6	1.8
Sc	13.5	14.4	14.1	14.1	17.5	9.1	13.3	20.8	15.1	9	13.1	14.1
Ta	0.5	0.9	1.2	0.6	0.4	0.3	0.3	0.3	0	0	0	0
Co	48.4	54.9	51.5	56.7	43.9	16.6	22.6	33.8	33.9	16.9	19.9	20.5
Be	1	1	1	1	1	1	2	1	2	1	1	2
U	1.1	1.4	4.3	1.7	1.1	0.9	1	0.1	2.2	1.5	2.2	1.5
W	260	271	283	322	139	23	1	14	124	34	39	37
Mo	1	1	1	3	1	2	2	2	3	2	2	4
Au	1	1	1	1	2	2	2	3	44	0	0	0
La	14.9	24.6	28.1	25.1	21.6	18.5	22.3	7.3	28.3	15.7	19.7	21.8
Ce	37	58	61	60	50	30	46	18	57	31	36	37
Nd	18	28	31	27	24	17	22	11	27	15	18	21
Sm	3.85	4.88	5.66	5.14	4.69	3.19	4.53	2.86	5.98	3.28	4.34	4.6
Eu	1.21	1.57	1.49	1.65	1.53	1.02	1.45	1	1.63	1.04	1.29	1.28
Tb	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.8	0.4	0.5	0.7
Yb	1.74	1.82	1.76	1.98	1.83	1.13	1.41	1.5	1.9	1.43	1.88	1.95
Lu	0.26	0.27	0.26	0.28	0.23	0.17	0.22	0.24	0.28	0.22	0.28	0.29
N	19° 13′	19° 04′	19° 07′	19° 06′	19° 01′	19° 09′	19° 05′	18° 58′	19° 03′	19° 01′	19° 02′	19° 03′
W	99° 26′	99° 25′	99° 28′	99° 31′	99° 27′	99° 58′	99° 37′	99° 30′	99°47′	99° 47′	99° 45′	99° 43′

Note: Major elements reported in weight percentages, minor and trace elements in ppm.

Samples are: CH—Holocene scoria cones and lava flows of the Chichinautzin Volcanic Field, SJ—San José, cones and domes complex, BS3—Basal Sequence, and BI—San Nicolás Basaltic-Andesite.

All samples were analyzed for major elements by Inductively coupled plasma-direct current (ICP-DC), and for trace elements by Instrumental neutron activation analysis (INAA), at Activation Laboratories, Ancaster, Canada.

deposit (Fig. 14). The fallout layers of the Upper Toluca Pumice covered portions of the Lerma and Mexico City basins with layers ~1 m and 10 cm thick, respectively; such areas presently contain major population centers of Toluca and Mexico City, which have a combined population of more than 25 million. These deposits are composed mostly of pumice with minor amounts of gray juvenile dacite, red-altered andesitic lithic clasts, and green-altered dacite clasts. This pyroclastic sequence (fall, flow, and surges) is well exposed at El Zaguan gully on the eastern flank of Nevado de Toluca. The pyroclastic flow deposits are probably those described by Palacio-Prieto (1988) at El Zaguan gully as pumice-rich lahars, and by Bloomfield and Valastro (1977)

Figure 12. Panoramic view of Site 268 where the Ochre Pumice Fall deposit is well exposed on the northern flanks of Nevado de Toluca Volcano.

southeast of Tlanisco as “pink valley-fill lahars.” Cantagrel et al. (1981) also saw similar deposits in some cuts of the Rio Grande and correctly catalogued them as “coulées pyroclastiques ponceuses” although they considered them an independent event apart from the Upper Toluca Pumice eruption.

The chemical composition of juvenile products is dacitic, ranging from 61 to 65% silica (Macías et al., 1997; Arce, 1999). The pumice and juvenile lithic clasts consist of crystals of plagioclase, orthopyroxene, and hornblende with minor biotite and oxides set in a glassy vesiculated groundmass.

Bloomfield and Valastro (1974, 1977) obtained a minimum age of 11 600 yr. BP on the basis of ^{14}C dates obtained from samples collected at the base of the unit (Table 2). New radiocarbon dates of a sample found within the basal pyroclastic flow deposit yielded an age of 10 445 ± 95 yr. BP (Macías and Arce, 1997; Arce, 1999). These data, along with a radiocarbon date of 10 820 ± 365 yr. BP for a sample from the La Isla II drill hole taken just below of the Upper Toluca Pumice layer (Caballero et al., 2001) and the revised data available in the literature, suggest that the Upper Toluca Pumice eruption occurred some 10 500 years ago.

The Chichinautzin Volcanic Field

The Chichinautzin Volcanic Field (CVF) represents the youngest volcanic activity in the area and consists of a series of predominantly basaltic-andesitic scoria cones (e.g., Tres Cruces Volcano, Holotepec) and fissure-fed lava flows (e.g., Tenango). These volcanic edifices, which constitute only the western part of the Chichinautzin Volcanic Field are located in the easternmost portion of the study area. The age of the volcanic centers of the Chichinautzin Volcanic Field varies from 38 000 to 1500 years BP (Bloomfield 1974, 1975; Martin del Pozzo, 1982; Velasco-Tapia and Verma, 2001; Siebe, 2001). The Upper Toluca Pumice deposit, which was produced by a large plinian eruption of Nevado de Toluca some 10 500 yr. BP, represents an excellent marker to distinguish between late Pleistocene and Holocene rocks within this western edge of the The Chichinautzin Volcanic Field (Fig. 15A). Based on stratigraphic relations, it is obvious that fissure-vent lava flows and cinder cones related to the E–W Tenango fault system are mainly Holocene. Alternatively, scattered scoria cones in the Lerma Basin are pre-Upper Toluca Pumice and are bracketed between 38 000 and 10 500 yr. BP.

The late Pleistocene stratigraphic sequence of this region of the Chichinautzin Volcanic Field can be further subdivided into two groups based on the stratigraphic position of the scoria fallout layers derived from the Negro Cone that has a main dispersion axis to the NW. A paleosoil below this fallout horizon yielded an age of 19 530 ± 160 yr. BP (Bloomfield, 1975); therefore, the oldest group of cones includes Quilotzi and Pehualtepec, while the younger group, with ages between 19 530 and 10 500 yr. BP, includes Capulhuac, Cuautl, and others (Fig. 15B).

Geochemistry

Twelve new chemical analyses of major, trace, and rare-earth elements were performed on the volcanic rocks in the study area. These results, combined with those of previous work, represent a total of 53 calc-alkaline and 18 alkaline rocks plotted on the classification diagram of Figure 16 (Bloomfield and Valastro, 1974; Macías et al., 1997, Morán-Zenteno et al., 1999; Marquez et al., 1999; Wallace and Carmichael, 1999; Verma, 1999). Young products belonging to Nevado de Toluca Volcano and older units have calc-alkaline affinity (Fig. 16). However, a few samples from the central and eastern parts of the Chichinautzin Volcanic Field

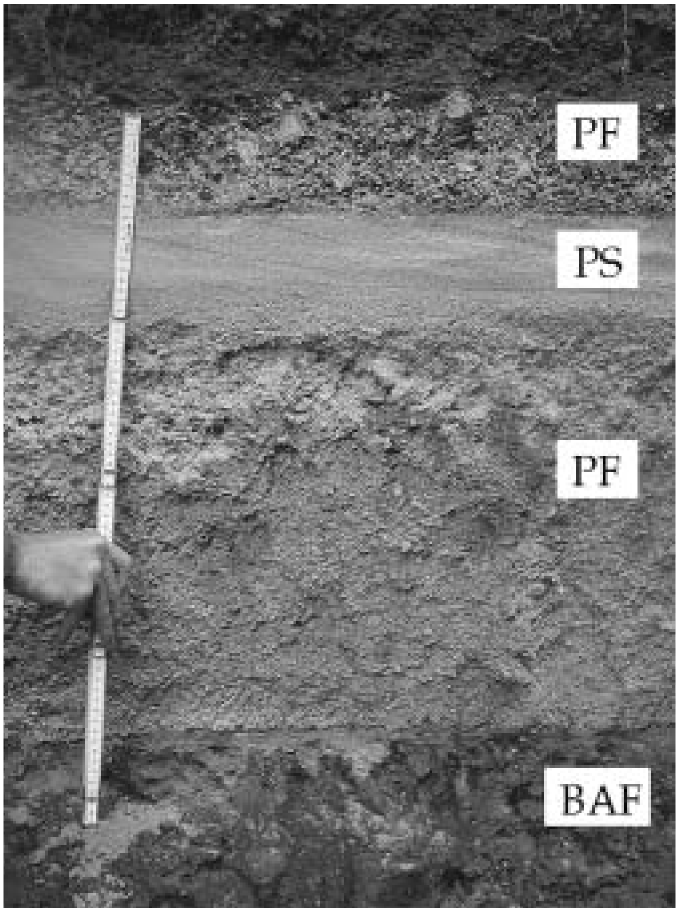

Figure 13. Detailed view of the base of the White Pumice Flow (WPF) sequence consisting of alternate layers of poorly sorted pumice fall layers bracketing a high-angle cross-stratified fall horizon that we attribute to reworking by strong winds during deposition (see coin for scale).

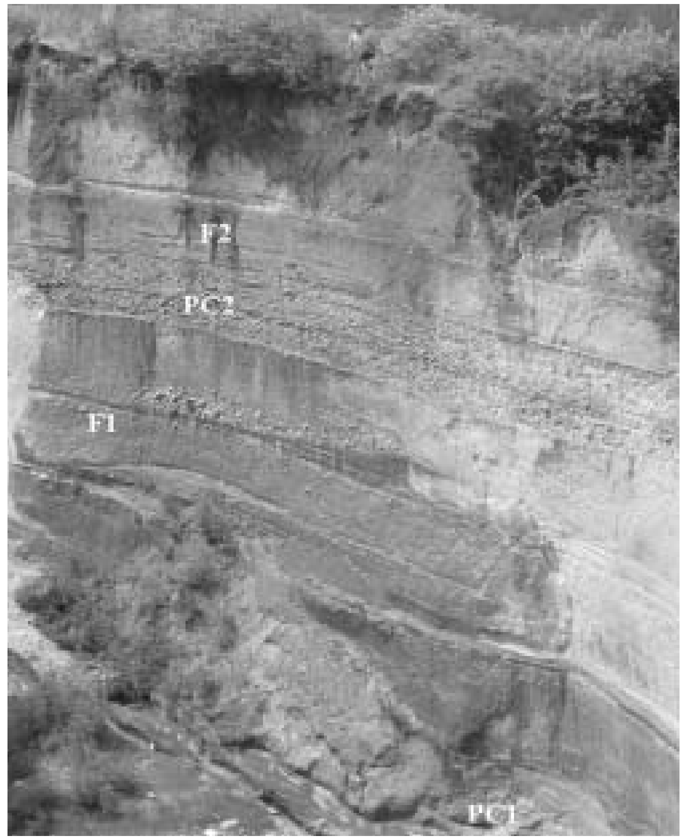

Figure 14. Composite stratigraphic section of the Upper Toluca Pumice (UTP), which consists of a complex set of pyroclastic fall, surge, and flow deposits. The upper and lower members of the UTP described by Bloomfield and Valastro (1974) are shown.

overlap the alkaline field (Bloomfield, 1975; Márquez et al., 1999; Wallace and Carmichael, 1999).

The Nevado de Toluca samples plot in the andesite and dacite fields, ranging from 55 to 67% SiO_2. Rocks of the western Chichinautzin Volcanic Field have mainly andesitic composition, in particular the Holocene scoria cones and fissure-fed lava flows. The rocks of the Tilzapotla Formation are mainly rhyolites and represent the most differentiated eruptive products in the area (Fig. 16). The San Nicolas Basaltic Andesite plots in the left part of the basaltic andesite field, while the Basal Sequence falls in the andesitic field.

The andesites and dacites of Nevado de Toluca Volcano have MgO values (1.5–3.5 wt%) and slightly differ from the andesites and dacites of the Chichinautzin Volcanic Field (4–7.2 wt% MgO), as was previously recognized by Wallace and Carmichael (1999). Alkaline products of the Chichinautzin Volcanic Field have MgO values between 6 and 10 wt% that plot in the upper left corner of Figure 17A. Three clusters of samples grouped according to their MgO concentrations are evident in Figure 17A: Toluca andesites, Toluca dacites, and Chichinautzin calc-alkaline, alkaline and the older Basal Sequence, and San Nicolás Basaltic Andesite rocks. Other Harker diagrams, however, show that Nevado de Toluca samples plot separately from the Chichinautzin calc-alkaline and alkaline rocks and the Basal Sequence and San Nicolás Basaltic Andesite samples (Fig. 17B–D). A similar behavior is observed in the abundances of Ni, V, and Cr among the trace elements, with the San Nicolás Basaltic Andesite being the more mafic sample (Fig. 17C). The silica versus alkalis diagrams clearly show the alkaline rocks of the Chichinautzin Volcanic Field to be distinct from the rest of the samples (Fig. 17E–F).

Figure 18 shows the spider diagram for ten of our twelve chemical analyzed rocks, in which the Nevado de Toluca volcanics define a gray-shaded pattern. The Nevado de Toluca rocks fit well in respect to the Trans-Mexican Volcanic Belt with LREE (La, Ce, and Nd) enrichments between 30 to 60 times and depletions of HREE (Tb, Yb, and Lu). The San Jose Dacite (1.3 Ma) follows the same pattern as the Nevado de Toluca rocks. The youngest calc-alkaline Chichinautzin samples are slightly enriched in light REE with respect to the Toluca samples; surprisingly, the Basal Sequence (7.5 Ma) shows a similar pattern. The only sample that diverges from this general trend is the San Nicolas Basaltic Andesite (21 Ma), which shows smaller

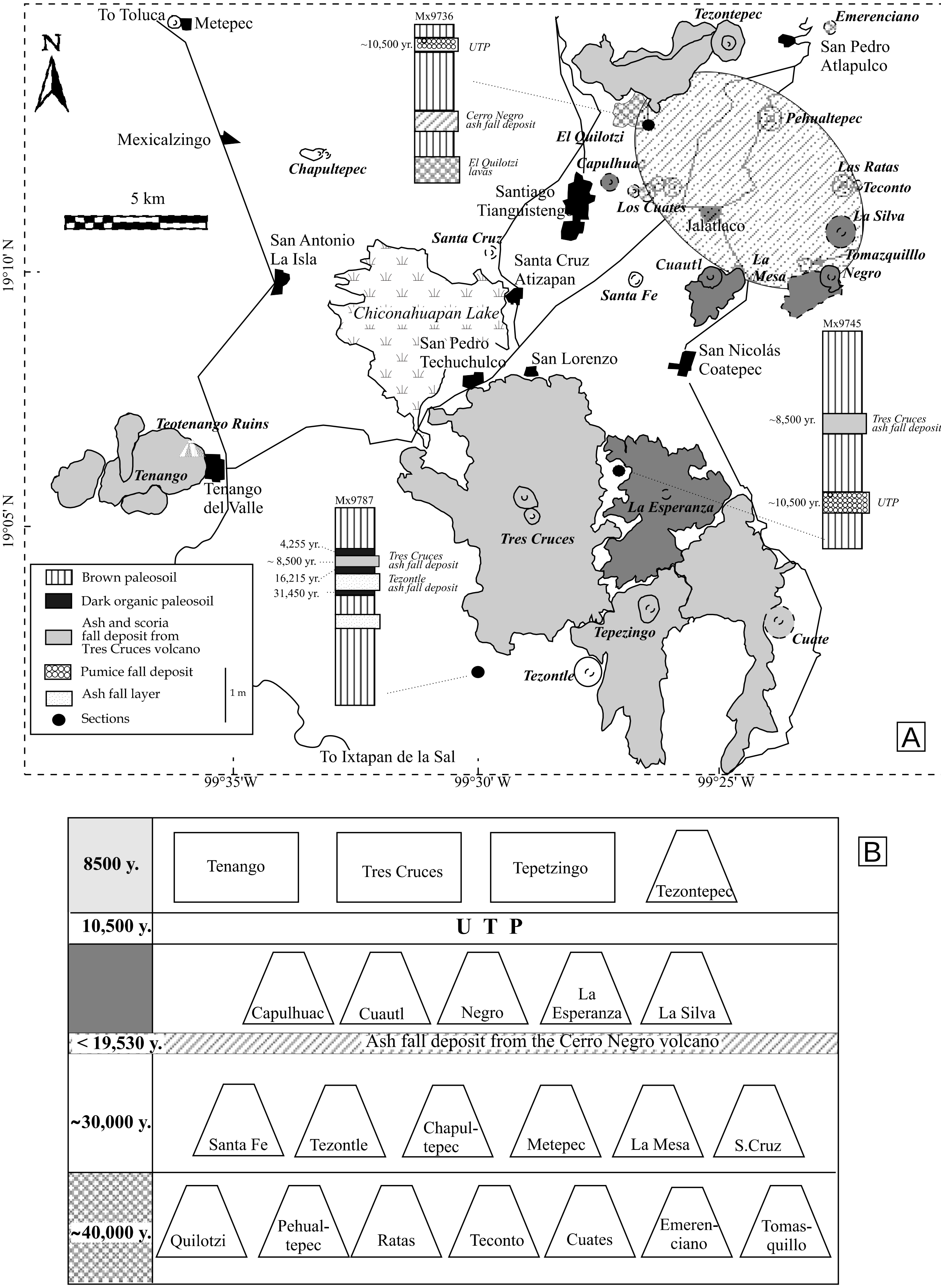

Figure 15. A. Simplified geological map of the Chichinautzin Volcanic Field (CVF) in the Lerma basin zone, east of the Nevado de Toluca Volcano. B. Stratigraphic relations of the cinder cones and lava flows are based on their ages (Bloomfield, 1975; this work) and their relative positions with respect to the Upper Toluca Pumice fall deposit.

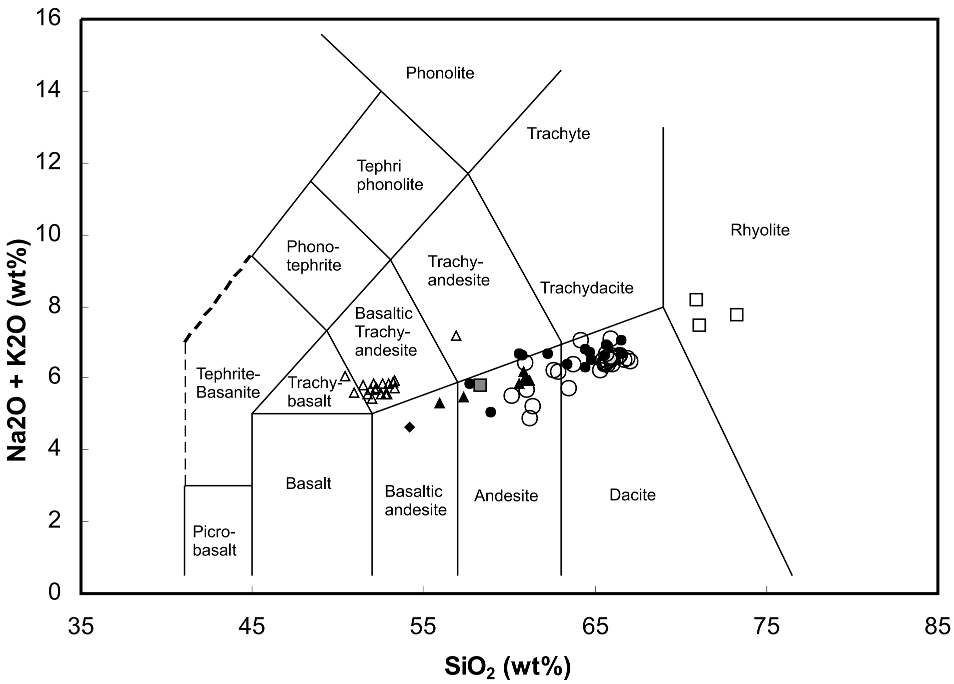

Figure 16. Silica versus alkali diagram of Le Bas et al. (1986) andesitic and dacitic rocks from Nevado de Toluca are shown by the small black (Cantagrel et al., 1981) and empty gray circles (Macías et al., 1997; this work). Other symbols plotted are open triangles, the alkaline rocks of Chichinautzin Volcanic Field (CVF) (Wallace and Carmichael, 1999); black triangles, Holocene lava flows, and cinder cones from the CVF (this work); solid diamond, the San Nicolás Basaltic Andesite (SNBA); black square, the Basal Sequence (BS); open diamond, San José dacite; and open squares, the Tilzapotla rhyolite (Morán-Zenteno et al., 1999).

enrichments of light REE in regard to the mantle and a similar pattern of the heavy REE with respect to the Basal Sequence falling within the Nevado de Toluca trend.

Tectonic setting of the Nevado de Toluca region

The Nevado de Toluca Volcano is localized by the intersection of three complex fault systems of different age, orientation, and kinematics (García-Palomo et al., 2000). These systems, from older to younger, are the Taxco-Querétaro Fault System (trending NNW) located south of the volcano; the San Antonio Fault System (NE–SW) that runs between the San Antonio and Nevado de Toluca Volcanoes; and the Tenango Fault System (E–W) located to the east of the volcano. Our field data, consistent with previous work, suggest that these systems have coexisted since the late Miocene. In addition, the stratigraphy, chronology, and kinematics of fault planes indicate the occurrence of at least three main deformation events that have affected central Mexico since late Miocene. During early Miocene, an extensional phase with the same deformation style as the Basin and Range tectonics of northern Mexico caused the formation of horsts and grabens south of Nevado de Toluca and the intrusion of subvertical dikes oriented NW–SE and NNW–SSE. During middle Miocene, a dominantly transcurrent event generated NE–SW faults with two main components of motion. The first movement corresponds to a left-lateral strike-slip fault (σ_3 oriented NW–SE) that then turned into a normal fault through a counterclockwise rotation of σ_3 close to a N–S position. The latest deformation phase started during late Pliocene, involving an oblique extension (σ_3 oriented NE–SW) accommodated by E–W right-lateral faults that changed to normal faults by the shifting of σ_3 to a N–S orientation. Late Pleistocene-Holocene monogenetic volcanism, explosive central eruptions of Nevado de Toluca Volcano, and present-day seismicity in the region and in central Mexico are all related to these faults.

Volcanic history of the Trans-Mexican Volcanic Belt in the map area

The oldest rocks in the area, while of similar age, belong to two different tectonic environments. During Late Jurassic–Early Cretaceous, Mexico was bounded on the west by an island arc trench system that resulted from subduction of the Farallon and Kula plates beneath Mexico (Coney, 1982). The eruptive output from these volcanic arcs are represented in our map area by the Ixtapan-Teloloapan sequence and the Acuitlapan and Amatepec Formations that belong to the Guerrero Terrain (Campa and Coney, 1983; De Cserna and Fries, 1981; De Cserna, 1983). Geological conditions in the east, however, were different; there the development of a calcareous reef platform (Guerrero-Morelos Platform) and sedimentation of the Morelos Formation occurred. These deposits represent a marine transgression associated with the opening of the Gulf of Mexico. Soon afterwards, the inshore part of the platform was exposed to clastic flysch sedimentation (Mexcala Formation) from the continental emergence in the region.

During late Mesozoic-early Tertiary, the continental landmass underwent compression from the southwest as a consequence of accretion of the insular arcs to Mexico during the Laramide orogeny (Coney, 1978). This compressional phase caused the insular rocks composed of the Ixtapan-Telolopan

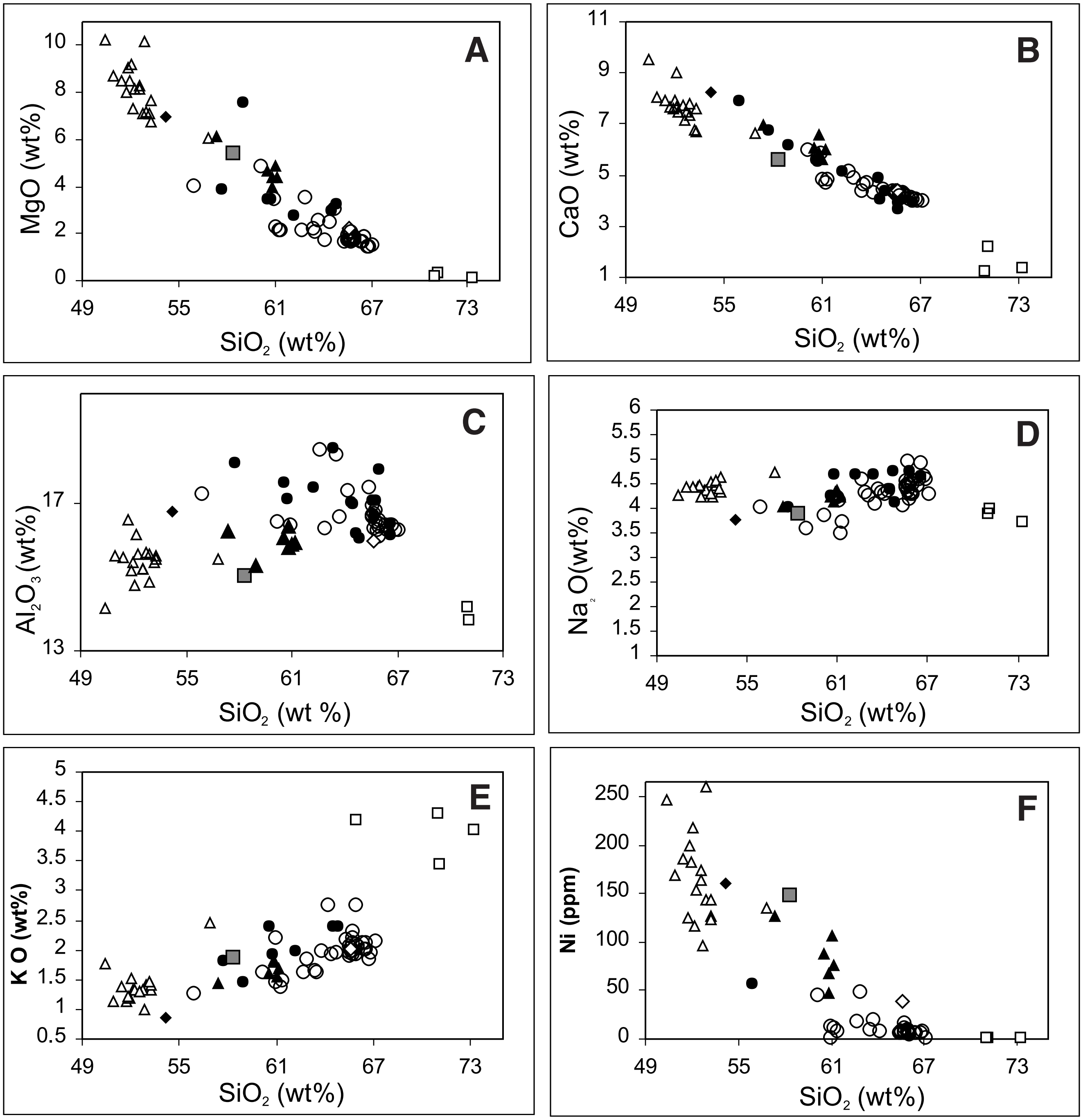

Figure 17. Binary diagrams of major and trace elements, symbols as in Figure 16. Alkaline rocks from the Chichinautzin Volcanic Field plot in the left side of the diagrams. The Nevado de Toluca volcanics from the San Nicolás Basaltic Andesite to the younger products follow a linear trend in MgO, CaO, and K_2O toward higher silica concentrations, and the Tilzapotla Rhyolite that are the most silic rocks.

sequence to override the calcareous formations of the Guerrero-Morelos platform through a N–S thrust fault. The Laramide orogeny caused substantial continental emergence, and subsequent marine regression continued through the Eocene with the end of the marine sedimentation and the beginning of continental deposition of the red beds of molasse deposits (Balsas Formation) (Fries, 1956, 1960). During this time, the southwestern part of the map area was subjected to the intrusion of a felsic igneous body.

During the Oligocene, the Farallon plate continued to be subducted beneath the continent, with the ensuing generation of a wide continental volcanic arc along western Mexico. In the northwestern part of Mexico, it formed the Sierra Madre Occidental (McDowell

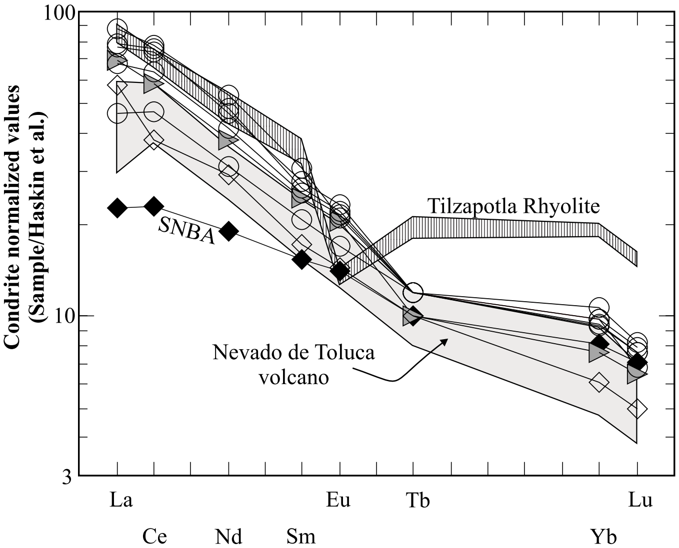

Figure 18. Chondritic REE patterns of selected samples using the normalization values of the Haskin et al. (1966) symbols as in Figure 16. The gray pattern represents the field of juvenile products of dacitic composition of Nevado de Toluca Volcano (Macías et al., 1997). The hachured pattern represents the field of the Tilzapotla Rhyolite (Moran-Zenteno et al., 1999)

and Clabaugh, 1981); in the southwestern part, it formed the Tertiary Volcanic Province of Southern Mexico (Alba-Aldave et al., 1996; Martiny et al., 1996). The last sequence involved the volcanic rocks of the Taxco-Huautla region (Morán-Zenteno et al., 1999), which includes the rhyolitic volcanics of the Tilzapotla Formation exposed south of Nevado de Toluca Volcano.

During the early Miocene, the tectonic conditions in western Mexico apparently changed and resulted in a hiatus of volcanic activity (Morán-Zenteno et al., 1999). However, in our map area, about 21 Ma, the apparently effusive volcanism that produced the San Nicolas Basaltic-Andesite took place, suggesting a volcanic phase during this time. Nevertheless, the scarcity of outcrops and data for this episode precludes a good understanding of its role in the volcanic-tectonic evolution of the region.

During middle Miocene, volcanism occurred in scattered areas of central Mexico along the present Trans-Mexican Volcanic Belt. In the map area, intense volcaniclastic sedimentation during this time deposited the Tepoztlán Formation; its outcrops, hundreds of meters thick, are exposed in the southeastern part of Nevado de Toluca and Zempola volcanoes. Primary structures and the distribution of the Tepoztlán Formation suggest that this unit was emplaced by an older volcano located somewhere north of the deposits.

Late Miocene was characterized in the area by an episode of erosion without deposition followed by the formation of large andesitic-dacitic stratovolcanoes forming the Las Cruces Volcanic Range, located just to the east of Nevado de Toluca. During this time, the Chortis Block was moving along a left-lateral fault from its former position south of Mexico to its present position in Central America, initiating an important geodynamic reorganization of the Pacific plates (De Cserna, 1969). Evidence of this movement are the mylonitic bands observed along the coast of Guerrero (Tolson, 1998), the brecciated calcareous rocks of early Cretaceous age (Mills, 1998), and the diminishing age of the magmatic rocks of the Sierra Madre del Sur (Morán-Zenteno et al., 1999). From this process of plate reorganization spawned the Acapulco trench on the Guerrero coast and a compressive deformation in central Mexico, as suggested by strike-slip faults such as those found in the regions of Morelia and Guadalajara (Ferrari et al., 1994), Hidalgo (Suter et al., 1991), and in the San Antonio Fault System in the study region (García-Palomo et al., 2000).

The construction of extensive lava-flow plateaus in several sectors of the Trans-Mexican Volcanic Belt marks a striking episode of widespread volcanism during Late Miocene; these plateau-forming rocks have been recognized around the cities of Guadalajara, Querétaro, and Toluca (Ferrari et al., 1994; García-Palomo et al., 2000). This widespread effusive activity, which produced mainly calc-alkaline products, might represent the beginning of the volcanic activity that resulted in the Trans-Mexican Volcanic Belt, as suggested by Pasquaré et al. (1991).

During the Pliocene, the subduction of the Cocos and Rivera plates beneath Mexico produced the volcanic activity of the Trans-Mexican Volcanic Belt across central Mexico; it probably also is associated with a distensive tectonic regime as previously discussed. During Late Pliocene, sporadic activity mostly resulted in cinder cones and domes, and a few fissure-fed lava flows. San Antonio Volcano is the oldest stratovolcano in the map area, with its activity beginning approximately in Middle Miocene and involving effusive and explosive events that deposited voluminous block-and-ash flow deposits and plinian fall units. During the Pliocene, numerous monogenetic cones and domes erupted within the vicinity of the San Antonio Volcano. Nevado de Toluca Volcano began to develop during this time ([a]2.6 Ma), with the extrusion of thick andesite lava flows that constructed the central edifice. Between 1.2 Ma and 42 000 yr. BP, the activity was dominated by the emplacement of thick laharic sequences, some of which were associated with major collapses of the volcanic edifice. While the specific triggering mechanisms for collapse cannot be deduced from field evidence, the abundance of highly altered materials in the deposits suggests that intensive hydrothermal alteration significantly weakened the edifice, thereby contributing to periodic structural failure. The collapse-generated volcaniclastic deposits were emplaced within the southern sectors of the volcano and channeled into the grabens of the Taxco-Querétaro fault system. Approximately 42 000 years ago resumption of explosive activity produced a thick sequence of pumice and block-and-ash flow deposits, that formed extensive fans around the volcano. According to our revised stratigraphy, at least five dome-destruction events and four plinian eruptions have occurred since. The Lower Toluca Pumice and the Upper Toluca Pumice tephra fall from plinian eruptive columns blanketed extensive areas; isopachs of these deposits show dispersal axes toward the population centers of Toluca and Mexico City. While the explosive activity of Nevado de Toluca (< 42 000 yr.) was developing, numerous monogenetic cinder cones also erupted in the Lerma and Toluca basins (Chichinautzin Volcanic Field). Holocene fissure-vent lava flows, such as the Tenango Andesite, were also deposited in this period. The most recent volcanic activity recognized in the area (3300 yr. BP) was a minor magmatic eruption at Nevado de Toluca Volcano, which emplaced a surge and a pyroclastic flow deposit on its northeast flank.

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