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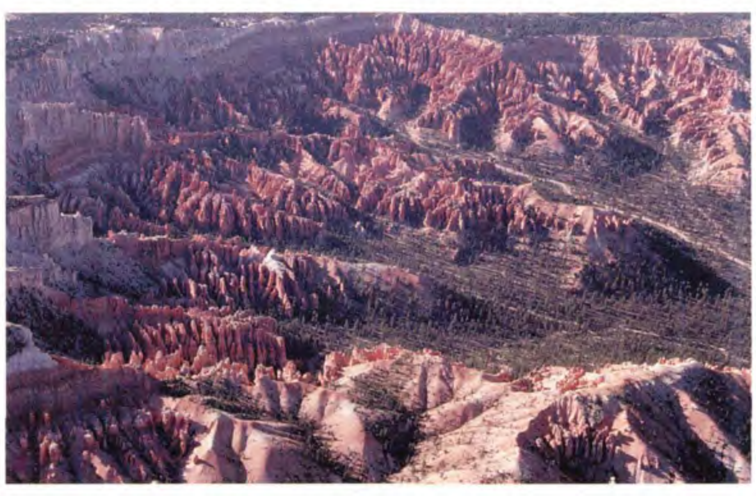

PART 1 ONE

EDITED BY PAUL KARL LINK AND BART J. KOWALLIS

V O L U M E 4 2 • 1 9 9 7

PROTEROZOIC TO RECENT STRATIGRAPHY, TECTONICS, AND VOLCANOLOGY, UTAH, NEVADA, SOUTHERN IDAHO AND CENTRAL MEXICO

Edited by
Paul Karl Link and Bart J. Kowallis

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CONTENTS

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Bart J. Kowallis

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Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.

Middle: Lake Bonneville shorelines west of Brigham City, Utah.

Bottom: Bryce Canyon National Park, Utah.

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Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

Late Pleistocene-Holocene Cataclysmic Eruptions at Nevado de Toluca and Jocotitlán Volcanoes, Central Mexico

J.L. MACÍAS
P.A. GARCÍA
J.L. ARCE
C. SIEBE
J.M. ESPÍNDOLA
Instituto de Geofísica, UNAM, Coyoacán 04510, México, D.F., MEXICO

J.C. KOMOROWSKI
Institut de Physique du Globe de Paris, 4 Place Jussieu, Boite 89, 5252, Paris, Cedex 05, FRANCE

K. SCOTT
U.S. Geological Survey, Cascades Volcano Observatory, 5400 MacArthur Boulevard, Vancouver, Washington 98661

ABSTRACT

This field guide describes a five day trip to examine deposits of Late Pleistocene-Holocene cataclysmic eruptions at Nevado de Toluca and Jocotitlán volcanoes in central Mexico. We will discuss the stratigraphy, petrology, and sedimentological characteristics of these deposits which provide insights into the eruptive history, type of volcanic activity, and transport and emplacement mechanisms of pyroclastic materials. These parameters will allow us to discuss the kinds of hazards and the risk that they pose to populations around these volcanoes. The area to be visited is tectonically complex thus we will also discuss the location of the volcanoes with respect to the tectonic environment.

The first four days of the field trip will be dedicated to Nevado de Toluca Volcano (19°09'N; 99°45'W) located at 23 km. southwest of the City of Toluca, and is the fourth highest peak in the country, reaching an elevation of 4,680 meters above sea level (m.a.s.l.). Nevado de Toluca is an andesitic-dacitic stratovolcano, composed of a central vent excavated upon the remains of older craters destroyed by former events. Bloomfield and Valastro, (1974, 1977) concluded that the last cycle of activity occurred ≈11,600 yr. ago. For this reason Nevado de Toluca has been considered an extinct volcano. Our studies, however, indicate that Nevado de Toluca has had at least two episodes of cone destruction by sector collapse as well as several explosive episodes including plinian eruptions and dome-destruction events. These eruptions occurred during the Pleistocene but a very young eruption characterized by surge and ash flows occurred ca. 3,300 yr. BP. This new knowledge of the volcano's eruptive history makes the evaluation of its present state of activity and the geological hazards necessary. This is important because the area is densely populated and large cities such as Toluca and Mexico are located in its proximity.

ITINERARY

The trip will begin and end at Mexico City's international airport. From the airport we will drive directly to the city of Toluca. There, we will have an overview of the tectonic and geological setting of central Mexico and its volcanoes (Fig. 1).

During the second day, we will visit the summit crater of Nevado de Toluca, where we will discuss its present morphology which has been frequently modified by volcanic

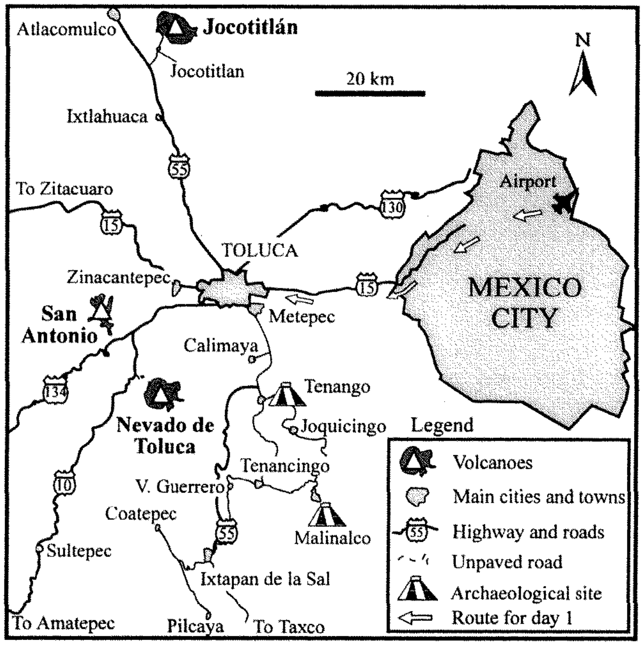

Figure 1. Sketch map showing the location of Nevado de Toluca and Jocotitlán volcanoes. Arrows show the route for Day One.

and glacial activity. From its lower crater rim volcanic landforms and tectonic features around Nevado de Toluca can be observed. In addition, we will examine proximal deposits exposed on the northwestern flanks of the volcano produced by Plinian and dome-destruction style explosions that occurred during the last 40,000 yr. BP. A visit to the Pre-Columbian ruins of Teotenango located on top of a young andesite lava flow at the eastern base of the volcano will conclude our day.

During the third day, we will visit pyroclastic deposits exposed at the northeastern and eastern flanks of Nevado de Toluca. These proximal to medial outcrops comprise mostly units produced by major plinian, dome-destruction, and minor sector collapse events. The plinian events occurred at about 24,000 and 11,600 yr. BP and covered the northeastern volcano slopes. Fallout deposits of the younger event underlie the city of Toluca and have also been found as far as Mexico City and Chalco (at a distance of more than 80 km). The major dome-destruction eruptions occurred circa 37,000 and 28,000 yr. BP, producing block-and-ash flow deposits that reached minimum distances of 15 km from the crater.

On the fourth day, we will visit an impressive sequence of volcanic, fluviatile, and lacustrine deposits widely distributed to the south of the volcano, where they filled a tectonically controlled NW-SE oriented basin. The outcrops exhibit two debris-avalanche deposits that cap a thick sequence of laharic and fluvio-lacustrine beds. At the end of the day, we will visit the Pre-Columbian ruins and monastery of Malinalco.

On the last day, Jocotitlán composite volcano will be visited (Fig. 1). Recent studies (Siebe et al., 1992) have shown that this volcano, formerly believed to be extinct, was active in Pre-Columbian times. Deposits formed after this activity will be inspected near the summit of the volcano. A major Holocene eruption of Jocotitlán emplaced a large debris-avalanche deposit with a pronounced hummocky topography. Many of the outcrops to be visited are related to this debris-avalanche deposit, the emplacement of which may have been triggered by an earthquake in the nearby Acambay graben.

THE TRANS-MEXICAN VOLCANIC BELT (TMVB): AN OVERVIEW

The Trans-Mexican Volcanic Belt (TMVB) is an andesitic continental volcanic arc (Fig. 2). It is about 1200 km long and runs from the mouth of the Gulf of California across central Mexico to Veracruz. Volcanoes of the TMVB are related to the subduction of the Cocos and Rivera plates beneath the North American plate along the Middle American Trench (MAT). Other theories explain the origin of the TMVB by invoking a crustal fracture zone or a mega-shear (Verma, 1984, 1987). The TMVB is only 80 to 200 km from the trench in the Colima region but it is 350 to 400 km distant from the trench at its eastern end (Robin, 1982). The variations in the volcanic arc-trench gap distances are related to the depth of the Benioff Zone beneath Mexico. The inclination of the Benioff Zone in the vicinity of Colima volcano is about 30°, it is as little as 20° beneath Toluca and San Andrés Tuxtla (Nixon, 1982), and the dip is about 30° beneath El Chichón volcano (Stoiber and Carr, 1973).

The initiation of volcanic activity in the TMVB is a matter of controversy. In the western part of the TMVB, Gastil et al., (1979) estimated it to be circa 4.5 m.y., but Allan (1986) placed the oldest calc-alkaline volcanism at 10 m.y. In the central TMVB, volcanism started at 30 m.y. according to Mooser et al., (1974), and in the eastern TMVB, Cantagrel and Robin (1979) suggested that volcanism initiated 20 m.y. ago.

The TMVB is dominated by huge andesitic stratovolcanoes, some of which form north-south volcanic chains that become younger to the south, that is, toward the trench. Examples for this type are: Cantaro-Colima, Iztaccíhuatl-Popocatépetl, and Cofre de Perote-Pico de Orizaba. K-Ar dating of the andesitic calc-alkaline volcanoes Sangangüey and San Juan in the western TMVB indicate that cone construction began circa 0.6 and 0.2 m.y., whereas in the central TMVB (Iztaccíhuatl and Nevado de Toluca), cone growth began 1.7 m.y. ago. This age variation between the

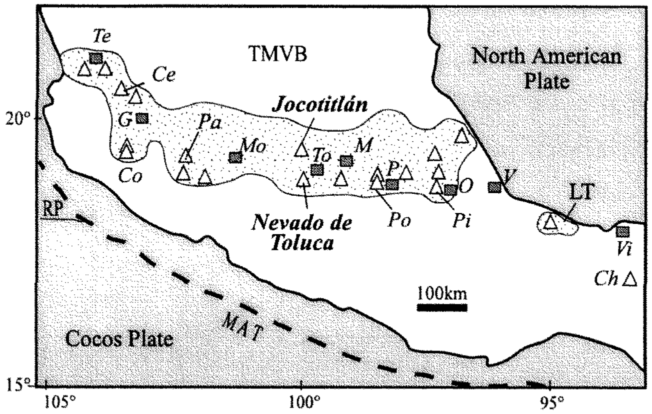

Figure 2. Map showing the location of the Trans-Mexican Volcanic Belt in central Mexico, and its relative position to Los Tuxtlas volcanic area. MAT = Middle America Trench, and RP = Rivera Plate. Some Quaternary volcanoes: Ce = Ceboruco, Co = Colima, Pa = Paricutín, Po = Popocatépetl, Pi = Pico de Orizaba, and Ch = Chichón. Cities: G = Guadalajara, M = Morelia, M = Mexico City, O = Orizaba, P = Puebla, Te = Tepic, To= Toluca, V = Veracruz, and Vi = Villahermosa.

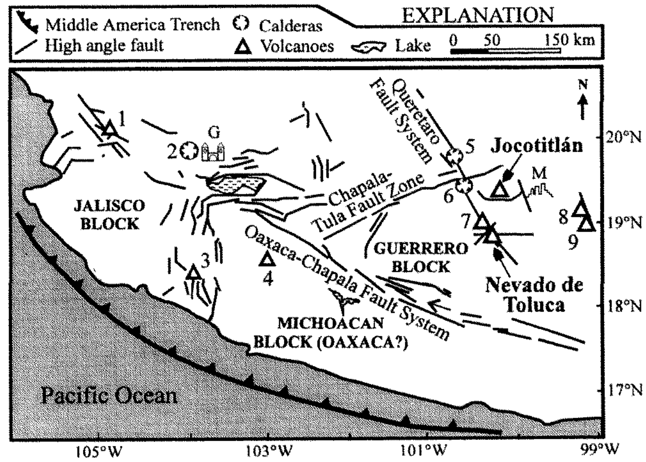

Figure 3. Location of Nevado de Toluca volcano and other volcanic features on the tectonic map of the central part of Mexico (after Johnson and Harrison, 1990). Other Quaternary volcanoes (numbers): 1 = Ceboruco, 3 = Colima, 4 = Paricutín, 7 = San Antonio, 8 = Iztaccíhuatl, and 9 = Popocatépetl. Calderas: 2 = La Primavera, 5 = Amealco, and 6 = Mazahua. Cities: G = Guadalajara, M = Mexico.

birth of the andesitic volcanoes in both areas and the trenchward migration of the volcanic activity may be related to the different subduction rates between the Cocos and Rivera plates (Nixon et al., 1987).

The TMVB consists of three distinctive provinces related to their tectonic, volcanological and petrological characteristics. These zones are: (1) The western TMVB, dominated by the Colima-Chapala-Zacoalco triple junction where both alkaline and calc-alkaline volcanic products are present. (2) The central TMVB, which is characterized by huge stratovolcanoes that form a general E-W trending volcanic chain through central Mexico where calc-alkaline volcanism is dominant. (3) The eastern TMVB, which is characterized by andesitic stratovolcanoes where calc-alkaline products are dominant. In this guidebook we will focus only on the central part of the TMVB and specifically on the characteristics of Nevado de Toluca and Jocotitlán volcanoes.

Tectonic Setting of Central Mexico

According to the tectonic model of Mexico presented by Johnson and Harrison (1990), Nevado de Toluca and Jocotitlán volcanoes are located within the Guerrero Block (Fig. 3). This block is confined to the north by the Chapala-Tula fault system and to the south by the Oaxaca-Chapala fault system. In this scheme, Nevado de Toluca overlies a series of NNW-SSE trending normal faults, aligned in a Basin-and-Range like pattern (Demant, 1978), and a series of E-W trending normal faults. These two fault systems were originally identified as major fractures in the Toluca-Mexico area (Mooser, 1969). The existence of a NE-SW fracture system in the Lerma Basin was pointed out by Mooser and Maldonado-Koerdell (1961). This system also seems to be present in a regional context since the so-called "Tenochtitlán Fault System" (De Cserna et al., 1988) has the same orientation across Central Mexico.

NEVADO DE TOLUCA VOLCANO

Location and Present Morphology

Nevado de Toluca volcano (19°09′N; 99°45′W) located 23 Km SW of the City of Toluca represents the fourth highest peak in Mexico reaching an elevation of 4,680 m.a.s.l. Nevado de Toluca or Xinantécatl ("Nude Man" in the nahuatl language) is a large andesitic-dacitic stratovolcano of Late Pleistocene age (Bloomfield and Valastro, 1974; Cantagrel et al., 1981). Nevado de Toluca rises 2100 m above the Lerma River to the north, and 3100 m above the plains of Ixtapan de la Sal and Tonatico. The crater has an E-W elongated form (1–1.5 km in diameter) with a horse-shoe shaped opening towards the east. It contains two lakes (known as the lakes of the Sun and the Moon), which are separated by a dacitic dome intrusion. The floors of these lakes are at 4,200 m.a.s.l. The oval central crater is emplaced on top of two older amphitheater-shaped craters whose remains are still visible on the SE and NE flanks of the volcano. Glacial advances occurring during the Holocene also affected the volcano's morphology (Heine, 1988; Aceves, 1996). Rock glaciars and debris flows derivated

Figure 4. Aerial photograph of Nevado de Toluca (INEGI, 1989). OD = The Ombligo Dome, RG = Rock Glaciar, M = Moon Lake, Mo = Morraine, S = Sun Lake, GV = Glacial Valley.

from glacial activity are well exposed on the external flanks of the present crater as well as inside of it (Fig. 4).

Local Geology Overview

We have mapped and recognized at least 19 stratigraphic units around Nevado de Toluca Volcano which, for the purpose of this guide book, have been grouped into four main sequences (see geological map and composite stratigraphic column in Fig. 5). These units have the following characteristics:

1. The first sequence is composed, from the base upwards, of the volcano-sedimentary metamorphic

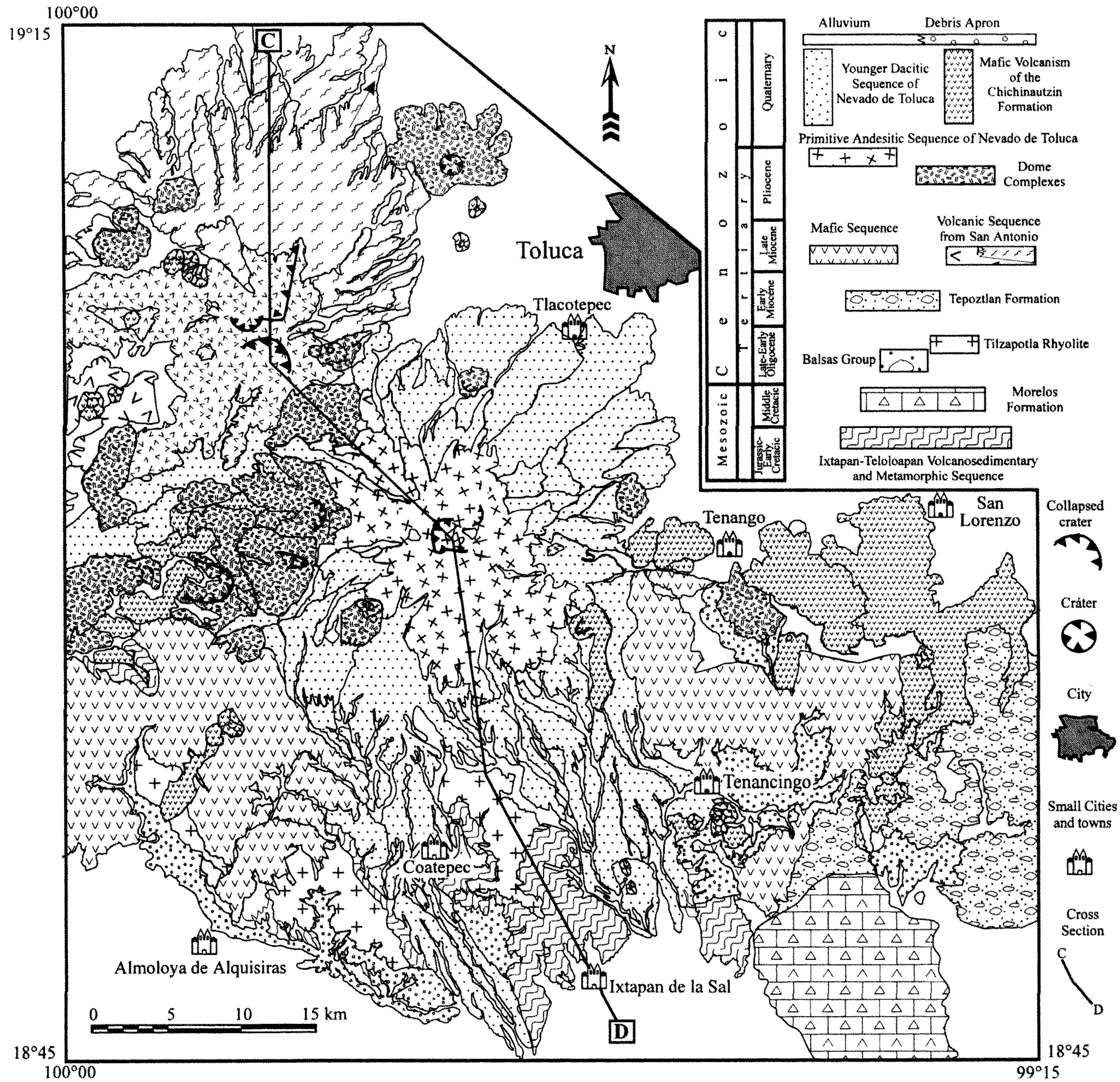

Figure 5. General geologic map of Nevado de Toluca Volcano and its lithologic sequence. Profile C-D is shown in Fig. 7.

Ixtapan-Teloloapan Formation (Campa et al., 1974) which consists mostly of Late Jurassic-Early Cretaceous green schists. This sequence is poorly exposed in the southern portion of the area, where it constitutes the core of horst structures oriented in a NW-SE direction. The Morelos Formation inconformably overlies the Ixtapan-Teloloapan Formation in the S-SE portion of the area. The Morelos Formation consists of massive to thickly bedded limestones and dolomitic limestones rich in fossils of Albian age (Bonet, 1971). The Mesozoic-Tertiary basement is capped by the Balsas Group which consists of conglomerates, lava flows, sandstones, siltstones, and lacustrine deposits of Late Eocene-Early Oligocene age.

2. The second sequence consists of Tertiary volcanic and volcaniclastic rocks. The base of this sequence consists of rhyolites, rhyodacites, dacitic lava flows,

and pyroclastic flow deposits belonging to the Tilzapotla Formation "Riolita Tilzapotla." The age of this Formation has been determined by the K-Ar method at 26 m.y. (Early Oligocene), and by its stratigraphic position in the Oligocene-Miocene (Fries, 1960). The Tilzapotla Formation is discontinuously overlain by the Tepoztlán Formation. It is exposed in the area surrounding the village of Malinalco and in some scattered sites southeast of Nevado de Toluca. The Tepoztlan Formation consists of lahars deposits rich in subrounded porphyritic andesite clasts intercalated with fluviatile deposits. According to Fries (1960), the age of this formation is probably Early Miocene. This unit is capped by a sequence of basalt and andesite lava flows, which are widely distributed across the southwestern slopes of Nevado de Toluca. The exact age of this unit is still unknown.

3. The third sequence is characterized by Quaternary rocks that constitute the volcanic edifice of Nevado de Toluca volcano (Bloomfield, 1974; Cantagrel et al., 1981; Arce, 1996). They are described in detail in the next section.
4. The fourth sequence includes products of cinder cones and lava flows emitted from fissures located in the eastern part of the area. The formation of these volcanic features occurred between 38,000 and 8,000 yr. BP (Bloomfield 1974; 1975).

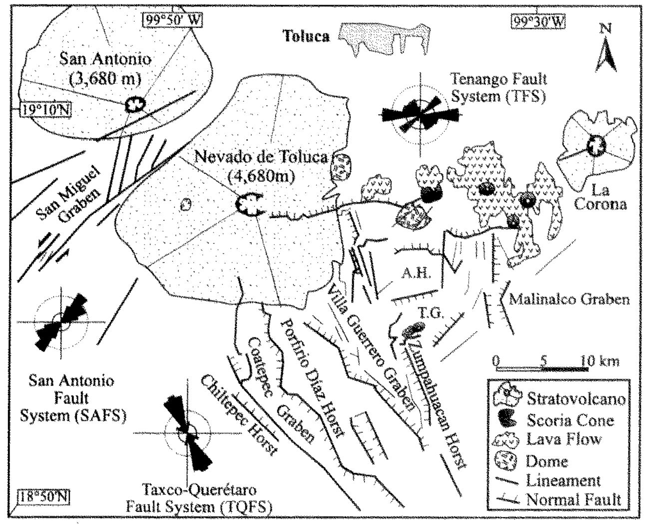

Figure 6. Tectonic setting of Nevado de Toluca Volcano. Rose diagrams represent the orientation of major lineaments in the area. AL = Atlatlahuaca horst, and TG = Tenancingo graben.

Structural Geology

Our studies indicate that Nevado de Toluca is presently affected by three fault systems that intersect at the volcano (Fig. 6). The oldest of these is the Taxco-Queretaro fault system (TQFS) described by Demant (1978). We have called the other two more recent ones, the San Antonio fault system (SAFS) and the Tenango fault system (TFS) (García et al., 1996). These fault systems have the following characteristics:

Taxco-Queretaro Fault System (TQFS)

The TQSF is a tectonic feature of regional extent and is the oldest system in the region. It has important tectonic and volcanological implications because of the alignment of many structures including the Amealco Caldera (Sánchez-Rubio, 1978), the Mazahua Caldera, (Anguita et al., 1991), and the San Antonio and Nevado de Toluca volcanoes (Fig. 6). In the study area, it is represented by a series of horsts and grabens trending N25°W and flanked by faults dipping 70° to 90° and forming cliffs up to 100 m in height. In the western region, the cores of the horsts consist of metamorphic rocks from the Ixtapan-Teloloapan volcanic-sedimentary sequence, while in the eastern region the cores are composed of limestone. In both cases, they are capped by younger volcanic rocks from Nevado de Toluca. The grabens have an average width of 4 km and are filled by volcaniclastic sediments up to 200 m thick. Slickensides on the flanks suggest a complex set of movements since Late Miocene to the Quaternary.

San Antonio Fault System (SAFS)

The SAFS trends NE-SW between the San Antonio and the Nevado de Toluca volcanoes. On a regional scale, this system is characterized by linear features, flatirons, rhomboidal structures, alignment of scoria cones and deformed lava flows. As it can be observed in the idealized cross-section of Figure 7, a complex graben structure here called San Miguel, developed in association with the fault system. At a local scale, the SAFS is evidenced by highly deformed rock masses (crushed and recrystallized) and fault planes showing slickensides. These elements show two stages of movement, initially left-lateral, followed by normal (Fig. 6).

Tenango Fault System (TFS)

This fault system trends E-W and forms the so-called Atlatlahuaca horst. This horst separates the system into two subsets (Fig. 6). In one set, the fault planes dip to the north towards the Toluca basin; in the other, case, they dip to the south, forming the flanks of the Tenancingo Graben. A series of cinder cones with this orientation seems to be associated with this fault system. At least three stages of fault activity are recorded. The first movement is evidenced to the south of San Miguel Banderas by a set of "en echelon" fractures trending N35°W. These faults are at an angle of 45° with respect to the trace of the TFS forefront, indicating right-lateral motion from slickensides. Other structures with the same arrangement but with a N55°E orientation at an angle of 20° to the fault trace, mark the second stage of movement with left-lateral motion. The last stage of activity is of normal type as indicated by the slickensides on the fault planes and the alignment of the cinder cones and dikes.

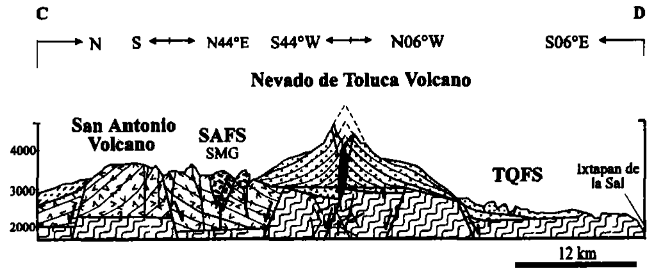

Figure 7. Idealized east-west geologic profile through Nevado de Toluca Volcano. Vertical exaggeration is 3X. Major faults represent relative movements along the San Antonio Fault System (SAFS) and the Taxco-Queretaro fault system (TQFS). SMG is San Miguel Graben. For section location see Figure 5.

ERUPTIVE HISTORY OF NEVADO DE TOLUCA

Previous Work

Since the beginning of the century, the truncated crater of Nevado de Toluca attracted the attention of geologists who described general features of the volcano (Ordoñez, 1902; Otis, 1902; Flores, 1906; Waitz, 1909). The first studies that tried to define the volcanic events that occurred at Nevado, as well as its eruptive history, were those by Bloomfield and Valastro, (1974; 1977), and Bloomfield et al., (1977). In these studies the age of the volcano was determined as Late Pleistocene and two large volcanic eruptions were recognized: A vulcanian eruption that occurred ≈28,000 yr. BP, produced extensive blue-gray lahars, and a plinian eruption that occurred 11,600 yr. BP, emplaced the Upper Toluca Pumice. Between these major episodes of volcanic activity the authors also recognized deposits of other eruptions: A plinian eruption produced the Lower Toluca Pumice fall ca. 24,000 yr. BP, and minor events deposited what they called younger lahars between 28,000 and 20,000 yr. BP. Cantagrel et al., (1981), proposed that Nevado de Toluca was built in two main stages of activity: (I) The first one started ca. 1.5 m.y. ago, with the emission of andesitic lavas that constructed the primitive volcano and the emplacement of thick epiclastic sequences of lahars and fluvial deposits on the southern flanks of the volcano, (II) The second stage of activity started ≈100,000 years ago and was characterized by the intrusion of central domes and their explosive destruction which produced "nuées ardentes péléennes" (blue-gray lithic lahars of Bloomfield and Valastro, 1977). These authors dated a paleosoil below these deposits and obtained a maximum age of 38,000 yr. BP. This stage continued with the formation of "nuées retombantes" (probably corresponding to the young valley-fill lahars of Bloomfield and Valastro, 1977), the two plinian events of 24,000 and 11,600 yr. BP, and ended with the extrusion of the dacitic central dome known as "El Ombligo." New stratigraphic data obtained during the last three years demonstrate that Nevado de Toluca has had a more complex volcanic history than previously thought. Episodes of cone destruction by major sector collapse, dome-destruction events by large magmatic eruptions, and plinian events of variable intensity have been common scenarios during its volcanic evolution. A correlation of the stratigraphic units and events described by previous authors with the new reported units (Arce, 1996, Macías et al., 1996; 1997) is provided in Table 1.

Repeated Sector Collapse

Since the May 18, 1980 eruption of Mount St. Helens eruption during which the volcanic edifice collapsed leading to the emplacement of a debris-avalanche and associated blast, fall, and pyroclastic flow deposits, a large number of similar volcanic deposits have been reported all over the world. In Mexico, the best known examples of these kind of volcanic events are Nevado de Colima and Volcán de Colima (Robin et al., 1987; Luhr and Prestegaard, 1988; Stoopes and Sheridan, 1992; Komorowski, et al., 1993), Jocotitlán (Siebe et al., 1992), Pico de Orizaba (Carrasco-Nuñez et al., 1993), and Popocatépetl (Robin and Boudal, 1987; Siebe et al., 1995). Although Nevado de Toluca was the subject of several geological studies the deposits related to edifice collapse were not recognized before. Today we know that Nevado de Toluca as well as other andesitic Mexican Quaternary stratovolcanoes, collapsed at least on two occasions during its evolution.

Our stratigraphic studies indicate that the old Nevado or "Paleo-Nevado" has been destroyed at least twice by failure of the volcanic edifice, producing debris-avalanche deposits during the Late Pleistocene. On both occasions collapse of the volcanic edifice occurred towards the south. Other Mexican volcanoes have also collapsed towards the south (e.g. Popocatépetl, Nevado de Colima, Volcán de Fuego de Colima, and Pico de Orizaba). The preferred southerly direction of collapse seems to be related to the general tectonic stress pattern within the Trans-Mexican Volcanic Belt.

Table 1. Correlation of stratigraphic units and volcanic events described by several authors at Nevado de Toluca Volcano.

Sample No.	Age (yr. B.P.)	Material Dated	Location	
			N	W
NT95140[3]	3,140+195/–190	Charcoal in pumice flow deposit	19°02′19″	99°54′34″
NT96144B[3]	3,435±50	Charcoal in ash flow deposit	19°13′26″	99°47′22″
KBC-38[1]	11,580±70	Charcoal from thin layer at base of UTP; average of 4 samples		
KBC-40a[1]	13,620±150	Paleosoil (Figure 6)	19°10′	99°39′
KBC-40b[1]	13,870±180	Paleosoil (Figure 6)	19°10′	99°39′
KBC-40c[1]	17,090±220	Humic horizon in Paleosoil just above reworked LTP (Figure 6)	19°10′	99°39′
KBC-25[1]	20,100±140	Paleosoil on Pleistocene lavas below KBC-9; contaminated by modern humus	19°06′	99°56′
KBC-20[1]	21,030±430	Paleosoil on valley lahar (between 2 and 3, Figure 4)	19°05′	99°51′
KBC-19[1]	21,170±170	Paleosoil on Tertiary lavas overlain by lahar: ?=KBC-17 and -18, contamination suspected	19°04′	99°52′
KBC-26[1]	21,790±200	Paleosoil on valley lahar overlain by fluvial sand and gravel (between 3 and 4, Figure 4)	19°11′	99°51′
KBC-9[1]	23,800±490	Charcoal fragments in lithic ash at base of valley lahar (3, Figure 4): 2 samples	19°06′	99°56′
KBC-7[1]	23,940±600	Paleosoil on lahar to E of Nevado: mean of 7 samples		
KBC-42[1]	24,160±420	Thin peaty layer at base of valley lahar, W of Nevado (between 2 and 3, Figure 4)	19°05′	99°51′
KBC-8[1]	24,260±670	Paleosoil on lahar to E of Nevado: mean of 7 samples		
KBC-15	24,400±430	Paleosoil on Tertiary lavas; Sierra de Las Cruces	19°14′	99°23′
KBC-2[1]	24,410±590	Paleosoil on lahar to E of Nevado: mean of 7 samples		
KBC-18[1]	24,440±550	Paleosoil on Tertiary lavas and old lahars to W of Nevado (between 2 and 3, Figure 4)	19°03′30″	99°52′30″
KBC-17[1]	24,590±280	Paleosoil on Tertiary lavas and old lahars to W of Nevado (between 2 and 3, Figure 4)	19°03′	99°52′30″
KBC-4[1]	24,930±670	Paleosoil on lahar to E of Nevado: mean of 7 samples		
KBC-5[1]	25,020±590	Paleosoil on lahar to E of Nevado: mean of 7 samples		
KBC-6[1]	25,250±760	Paleosoil on lahar to E of Nevado: mean of 7 samples		
KBC-3[1]	25,620±680	Paleosoil on lahar to E of Nevado: mean of 7 samples		
NT9545[3]	26,275+1210/–150	Paleosoil below the white pumic flow deposit	19°02′54″	99°39′00″
KBC-41[1]	27,590±650	Paleosoil on fluvial gravel derived from lahar (1 in Figure 4)	19°05′	99°51′
NT9535B[3]	28,140+865/–780	Charcoal in block-and-ash flow deposit	19°13′26″	99°47′09″
NT9521[3]	28,925+625/–580	Charcoal in ash flow deposit	19°00′24″	99°38′56″
NT9550[3]	37,000±1125	Charcoal in block-and-ash flow deposit	19°00′09″	99°38′56″
EN 12[2]	38,000	Paleosoil at Jaral gully		
NT9595[3]	42,030+3530/–2445	Charcoal in ash flow deposit	19°12′52″	99°45′44″

Compiled data from [1]Bloomfield and Valastro (1977), [2]Cantagrel et al (1981), and [3]This work

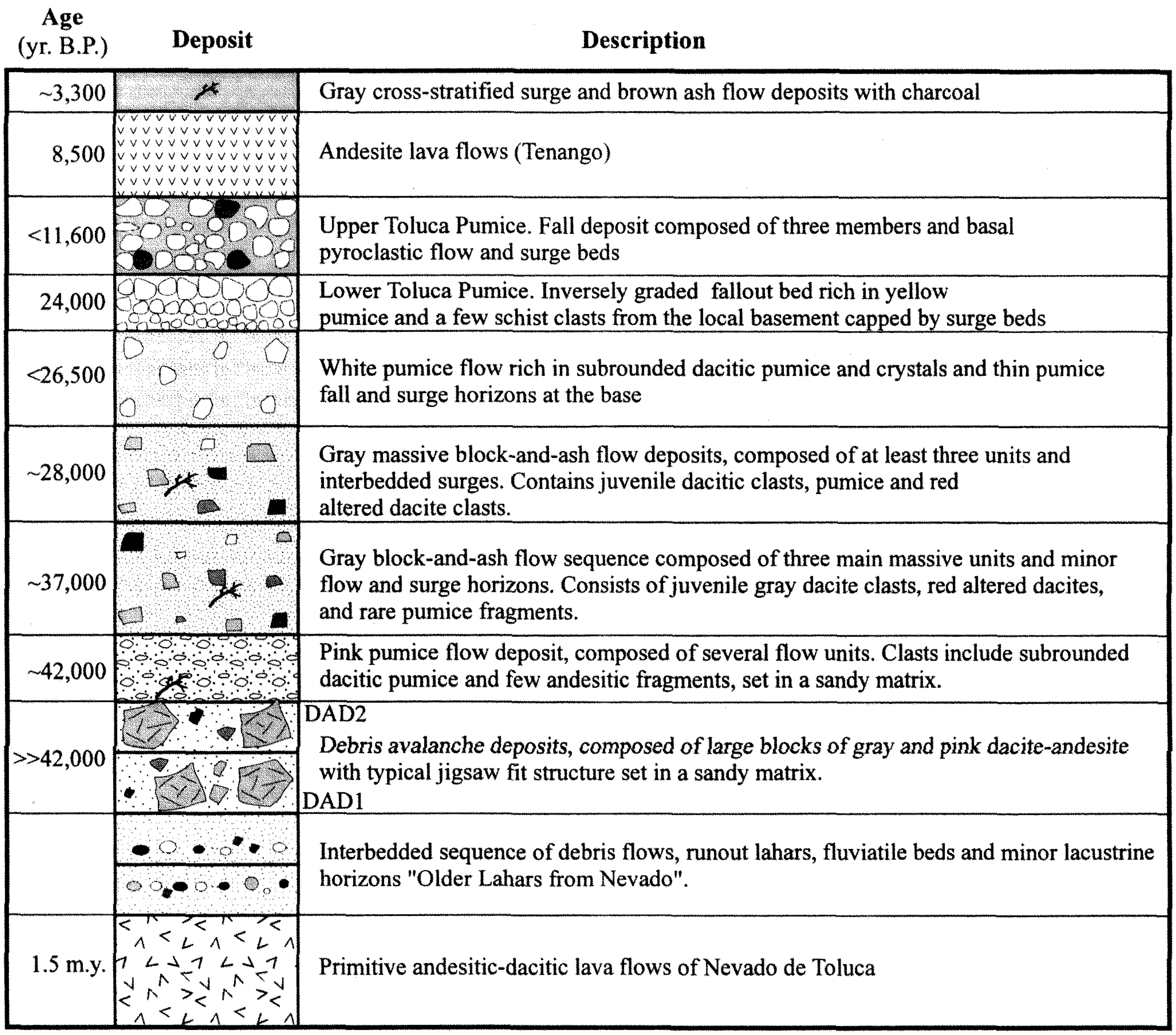

Figure 8. Composite stratigraphic column of Nevado de Toluca Volcano. Data from Bloomfield (1974), Bloomfield and Valastro (1977), Cantagrel et al., (1981), and this paper.

Revised Stratigraphy of Nevado de Toluca

Nevado de Toluca volcano has suffered two major sector collapses during the Pleistocene. Renewed volcanic activity, characterized by Plinian and dome-destruction stages, took place at the central crater of the volcano during the Late Pleistocene. Apparently only one minor explosive event occurred during the Holocene. A description of the main eruptive units is shown in Figure 8. From the base to top the units are the following:

Debris-avalanche deposit 1 (DAD1)

This deposit is a massive light-brown unit, up to 10 m thick, with blocks showing jigsaw-fit structures embedded in an indurated coarse sandy matrix (Figs. 9 and 10). This deposit consists of two types of blocks: a porphyritic gray juvenile dacite rich in plagioclase and hornblende phenocrysts set in an aphanitic matrix, and red, altered old dacites from the volcanic edifice with the same mineral composition. Oval-shaped tree casts several centimeters in diameter

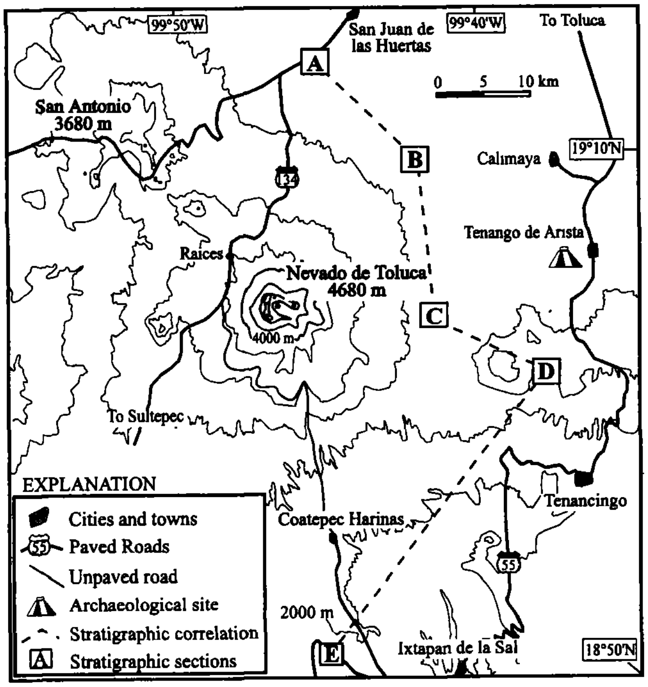

Figure 9. Topographic map of the excursion area. Contour lines every 200 m. Capital letters mark selected stratigraphic sections shown in Fig. 10.

attest to the incorporation of trees during emplacement. The deposit overlies, with a flat basal contact, a poorly-developed paleosoil and a thick sequence (up to 100 m) of lahars, lacustrine, and fluvial deposits. DAD1 spreads south from Nevado de Toluca up to a distance of 45 km from the volcano. It is well exposed around Tonatico and Pilcaya villages (Fig. 11). Assuming that the altitude of Paleo-Nevado was similar to the present volcano (4,680 m.a.s.l.) and that DAD1 has a maximum runout distance of 45 km we obtain a coefficient of friction (Hsü, 1975) or height (H)/length (L) ratio of 0.07. This is one of the lowest H/L ratios for this kind of deposit reported in Mexico. It is similar to the values of 0.04 reported for Nevado de Colima Volcano (Stoopes and Sheridan, 1992), and 0.06 for Popocatépetl Volcano (Siebe et al., 1995). Its age is unknown but it underlies DAD2 and a gray block-and-ash flow deposit dated at about 37,000 yr. BP.

Debris Avalanche deposit 2 (DAD2)

This deposit is a massive light-brown unit comprised of shattered blocks embedded in a coarse sandy matrix. In section E of Figure 10, DAD2 is at least 5 m thick. This deposit is heterolithologic and consists of gray porphyritic dacites, old red-altered dacites both rich in plagioclase and hornblende, older green-altered andesites, basalts, and schists from the local basement. All these blocks display jigsaw-fit structures and some of them have conchoidal fractures. DAD2 does not have an indurated matrix as does DAD1, but it shows the reddish alteration zones typical of debris-avalanche deposits. The deposit rests upon a pale brown paleosoil and is topped by a poorly developed paleosoil. The extent of this unit is similar to DAD1 although it is better exposed (see Fig. 11). It covers an approximate area of 500 km^2. Considering a minimum thickness of 10 m for this deposit, a volume of 5 km^3 was estimated. Around Coatepec Harinas, a 37,000 yr. old block-and-ash flow covers DAD1. Therefore DAD2 must be ≥37,000 years.

Gray Block and Ash Flow Deposits (GBAF)

Two violent eruptions occurred at Nevado de Toluca during the last 40,000 yr. These events produced large magmatic explosions that destroyed old dacitic central domes and excavated the crater that we see today. These domes had volumes ranging between 0.5 and 1 km^3. The explosions emplaced dense block-and-ash flows and minor surge deposits around the volcano (Fig. 12). Because of their similar appearance and components, previous authors described both deposits as a single unit which they referred to as either "older lahar assemblages" (Bloomfield 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 C-14 date from a paleosoil that covers the deposit.

At Barranca Zacango, these deposits are separated by a lacustrine sequence interbedded with paleosoils (see section B in Fig. 10). Charcoal within the older flow deposit gave an age of 37,000 ± 1125 yr. BP, which correlates with the date of 35,600 +2600/–1800 yr. BP for the "gray lahar" of Heine (1978) and an underlying paleosoil dated at 38,000 yr. BP by Cantagrel et al., (1981). Two charcoal samples within the younger 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 1).

Block-and-ash flow deposits (up to 30 m thick) are massive and consist almost entirely 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 mm-sized phenocrysts of plagioclase, hornblende, augite, and minor hypersthene, quartz, and biotite embedded in an aphanitic groundmass of the same constituents. Pumice, as well as dense juvenile lithic clasts have a uniform chemical composition in the range of 65 to 67% in SiO_2 (for further details see Table 2).

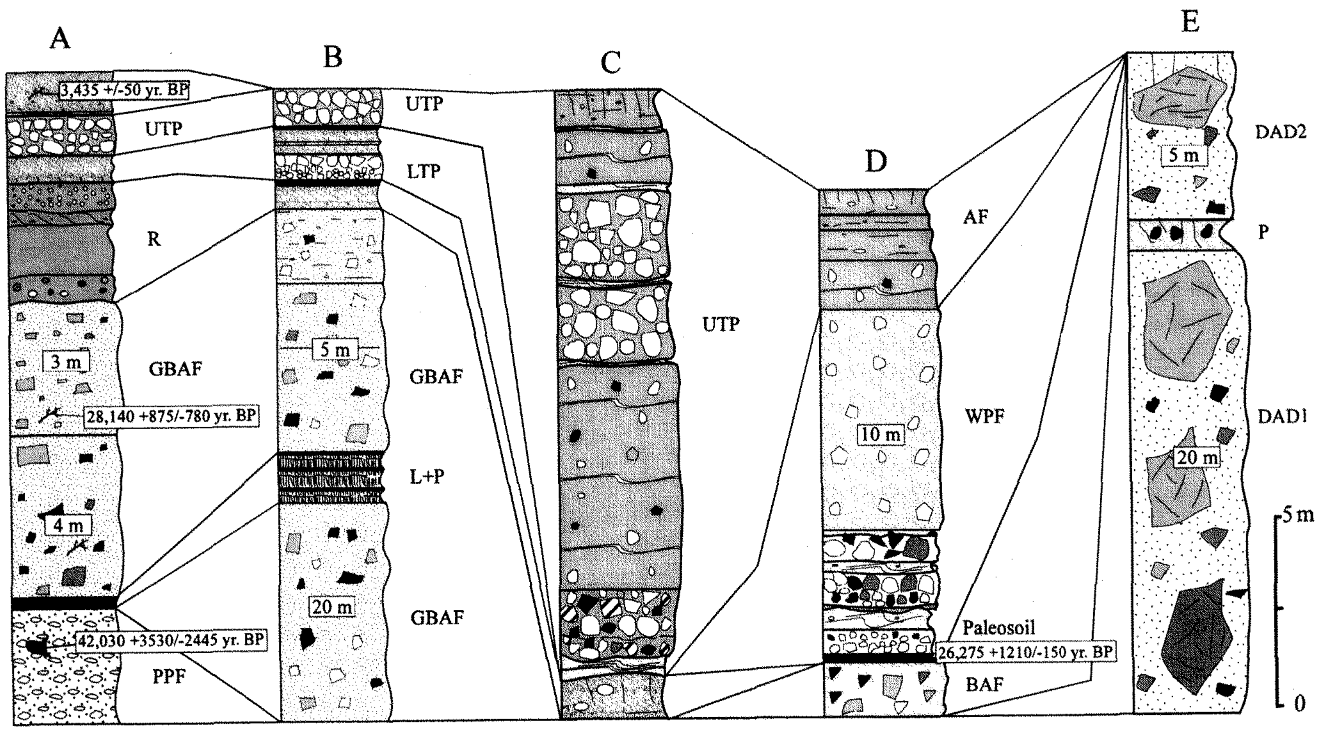

Figure 10. Stratigraphic correlation of main Late Pleistocene-Holocene pyroclastic deposits from Nevado de Toluca. Location of sections is shown in Fig. 9.

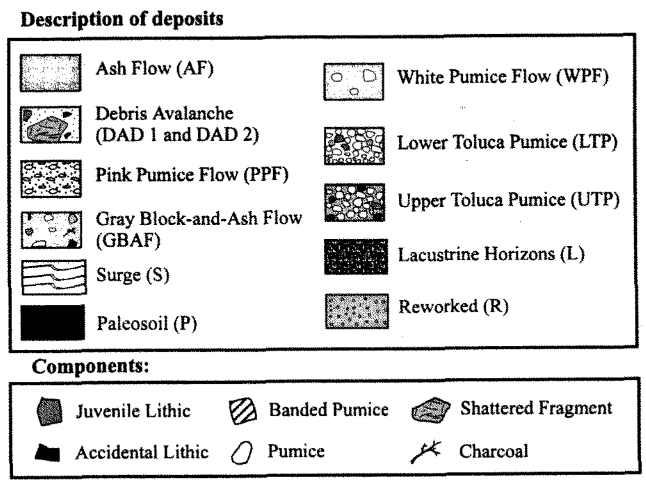

Figure 10. (Continued) Explanation of Nevado de Toluca deposits and their components.

These deposits cover a minimum area of 630 km^2. Assuming a conservative average thickness of 5 m, a minimum volume of 3.15 km^3 is estimated for both deposits. These figures attest to two of the largest dome-destruction style eruptions within the Trans-Mexican Volcanic Belt.

Lower Toluca Pumice (LTP)

This deposit is composed of an ochre fallout deposit with inverse grading and an average thickness of 55 cm. It is separated from the GBAF by an ash flow deposit and a dark-brown paleosoil dated at 24,260 ± 670 yr. BP by Bloomfield and Valastro (1977). The planar contact between the LTP and this paleosoil is observed in section B, Figure 10. The LTP is clast-supported and rich in ochre pumice with lesser amounts of gray dense juvenile dacite, hydrothermally altered lithic clasts, and schist fragments from the local basement. According to Bloomfield et al., (1977), the LTP fallout contains approximately 62% pumice, 27% lithic clasts, and 11% crystals. It covers an approximate area of 400 km^2 and it has a dispersal axis trending NE from the crater (Fig. 13). The above authors calculated its volume at 0.33 km^3 (0.16 km^3 D.R.E.).

In some outcrops the LPT is overlain by cross-stratified surge deposits rich in ochre rounded to subrounded pumice, and a pale brown ash flow deposit. These deposits have a total thickness of 60 cm.

White Pumice Flow Deposit (WPF)

This deposit consists (from bottom to top) of an alternation of thin fallout and surge deposits with a total thickness of 1 m (see location in Fig. 9 and section D in Fig. 10). The fallout horizons (9 and 28 cm) show normal and inverse stratification respectively and are rich in a very fibrous whitish pumice with abundant plagioclase pheno-

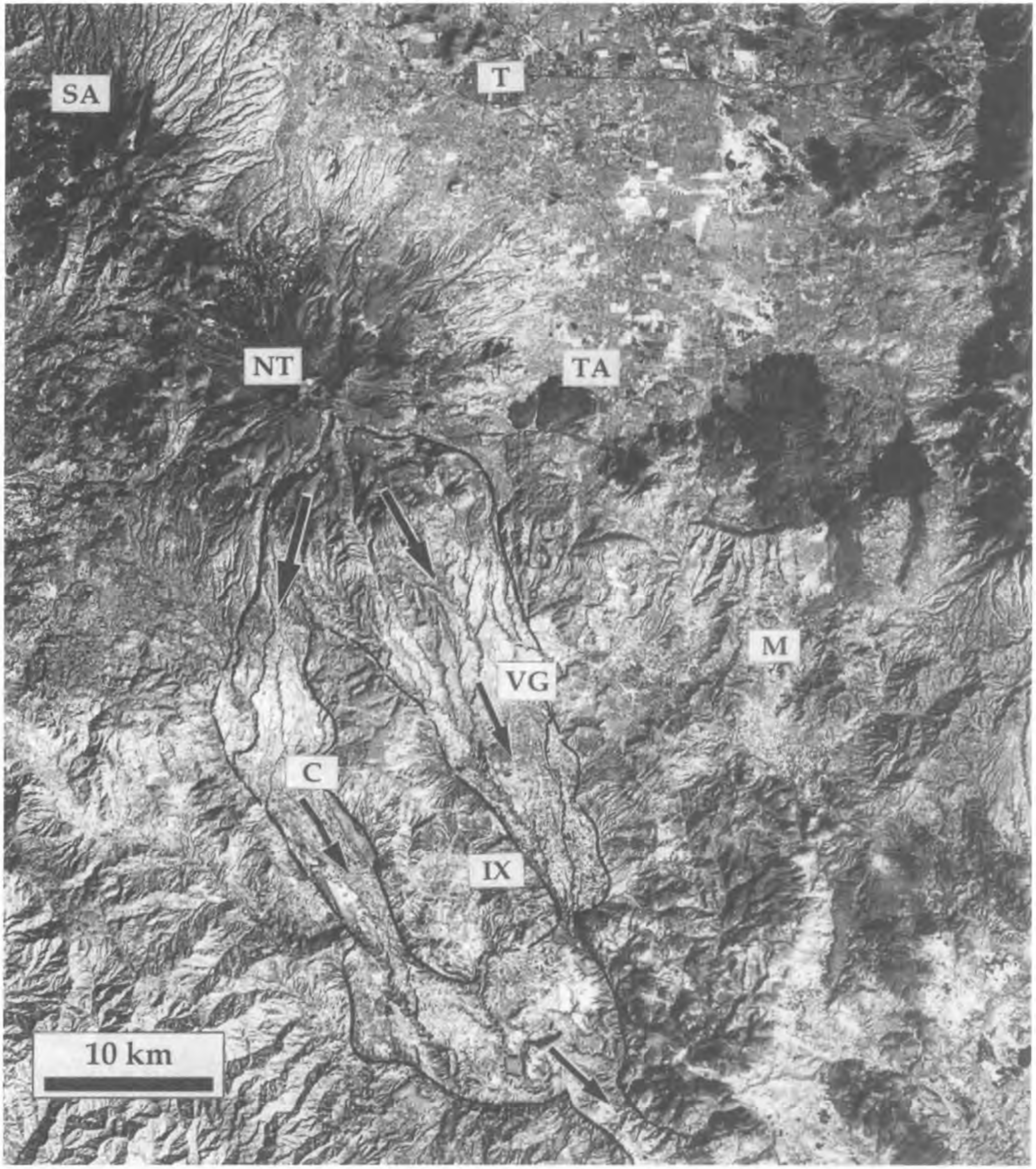

Figure 11. Landsat image of Nevado de Toluca volcano and surrounding area. The solid line marks the distribution of debris avalanche deposits on the southern flanks of the volcano. Arrows show the main path of debris-avalanche deposits. NT = Nevado de Toluca, SA = San Antonio volcano, TA = Tenango Andesite, T = City of Toluca, IX = Ixtapan de la Sal, VG = Villa Guerrero, C = Coatepec, M = Malinalco.

crysts and minor amounts of disseminated biotite. The surge laminae consists of gray silt. On top of the fallout and surge sequence lies the white pumice flow deposit. The flow deposit is massive, has a minimum thickness of 7 m and contains pumice and lithic fragments up to 35 and 20 cm in diameter respectively. The pumice is dacitic (65.67% in SiO_2) and rich in phenocrysts of plagioclase, hornblende and quartz. The WPF has been found mainly on the SE slopes of the volcano with very thick exposures close to Villa Guerrero and Tenancingo. It covers a minimum area of 62 km^2. We have not obtained enough data to provide a volume estimate. The WPF is underlain by a paleosoil dated at 26,275 +1210/−150 yr. BP.

Upper Toluca Pumice (UTP)

Bloomfield and Valastro (1974, 1977), described the Upper Toluca Pumice from outcrops located on the northern and eastern slopes of Nevado de Toluca. These authors subdivided the UTP into two members (Lower and Upper), which were divided by a thin band of dark ash. Bloomfield et al., (1977), described the UTP, giving additional details of the two fall members plus some descriptions of associated deposits. We will next describe the characteristics of the rather complex UTP (column C in Fig. 10).

From base to top, the UTP is composed of a pumice fall layer up to 1.50 m thick, rich in pink pumice, gray juvenile dacite clasts, red-altered andesitic lithics, and banded pumice. This unit is overlain by a thick sequence (about 15 m) of pink, pumice-rich pyroclastic flow and surge deposits with cross-stratification, dunes, and antidunes. These deposits are composed mostly of pumice with minor amounts of gray juvenile dacite, red-altered andesitic lithic clasts, and green-altered dacite clasts set in a sandy matrix. This pyroclastic sequence (fall, flow and surges) is well exposed in barranca del Zaguan on the eastern flank of Nevado de Toluca where it is found *underlying the lower Member of the UTP.* Since no hiatus, erosive surface or paleosoil is evident between both units we believe that these deposits were emplaced during the initial phases of the eruption that emplaced the UTP. These deposits are probably those described by Palacio-Prieto (1988) at barranca del Zaguan as pumice-rich lahars, and by Bloomfield and Valastro (1977) SE of Tlamisco 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 as an independent event with respect to the UTP eruption.

Overlaying this sequence is the UTP as described by Bloomfield and Valastro (1974) with only some slight differences. UTP consists from bottom to top of a dark-gray medium-sand surge deposit 21 cm thick, an eroded pumice fall (maximum thickness 10 cm), a light-brown silty surge (4 cm thick) with well-developed pumice lenses, a pumice fall 1.4 m thick, composed of white angular pumice *that corresponds to the Lower Member* of Bloomfield and Valastro (1974; 1977), a sequence, up to 54 cm thick, of fall and surge beds, and a pumice fall up to 1.78 m thick *or the Upper Member* of Bloomfield and co-workers. The sequence continues with a series of pyroclastic flow and surge deposits of pink color with variable thickness between 4 and 10 m (Fig. 14). According to Bloomfield et al., (1977) the fallout members of the UTP have a main dispersal axis oriented N65°E covering an area of approximately 2000 km^2 and a minimum volume of 3.5 km^3 (1.54 km^3 D.R.E.) (See Fig. 15).

The different fall horizons comprising the sequence are white in color and consist of the following components: pumice (ca. 85%), dark gray juvenile dacite and minor red-altered dacite lithic clasts (both ca. 15%) and crystals (1%). The maximum diameter of the pumice and lithics is 25 cm and 15–20 cm respectively. In proximal areas these members are separated by surge horizons 10 to 30 cm thick and covered by ash flow deposits of variable thickness. In distal areas they become thin sandy layers rich in juvenile lithics, accidental lithics clasts, and crystals (thickness <5 cm). The chemical composition of juvenile components ranges from 61 to 65% SiO_2 (see Table 3). Bloomfield and Valastro

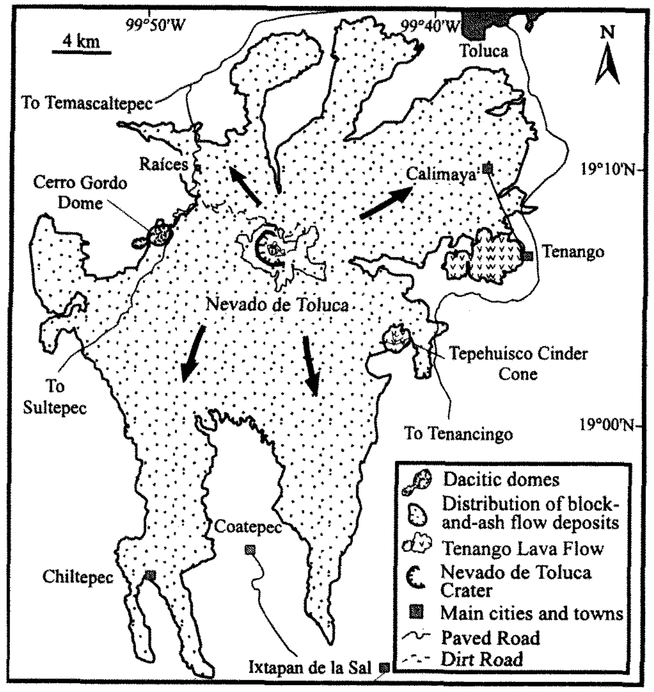

Figure 12. Aerial distribution of block-and-ash flow deposits around Nevado de Toluca emplaced Ca. 37,000 and 28,000 years B.P.

Table 2. Summary of C-14 and K-Ar dates performed on rocks and organic material of Nevado de Toluca Volcano.

Volcanic Event	Type of Deposits	Bloomfield and Valastro (1974)	Bloomfield and Valastro (1977)	Bloomfield et al. (1977)	Cantagrel et al. (1981)	(This Work)
Construction of the primitive volcano	Andesitic lava flows	Late Pleistocene	Dacitic lava flows Late Pleistocene older than 28,000 yr. B.P.	———	Andesitic lava flows 1.4 m.y. (An average of four K-Ar dates)	———
Generation of volcaniclastic sediments	A sequence of lahar, fluviatile, and minor lacustrine horizons	———	———	———	Older Lahar Sequence Related to construction of the primitive volcano	Older lahar sequence >42,000 yr. B.P.
Cone collapse	Debris Avalanche (DAD1)	———	———	———	———	DAD1, >42,000 yr. B.P.
Cone collapse	Debris Avalanche (DAD2)	———	———	———	———	DAD2, >42,000 yr. B.P.
Column collapse?	Pink pumice flow (PPF)	———	———	———	———	Pink pumice flow, ≈ 42,000 yr. B.P.
Dome destruction	Grey block-and-ash flow (GBAF)	———	———	———	Pumice flows (Caldera formation ≈ 28,000 yr. B.P.?)	GBAF ≈ 37,000 yr. B.P.
Dome destruction	Grey block-and-ash flow (GBAF)	Older widespread lahar ≤ 25,000 yr. B.P.	Grey older lahar assemblages ≈ 28,000 yr. B.P.	———	Nueés ardentes (destruction of dome ≈ 28,000 yr. B.P.)	GBAF ≈ 28,000 yr. B.P.
Plinian eruption	Lower Toluca Pumice (LTP)	LTP ≤ 24,500 yr B.P.	LTP, ≈ 24,500 yr. B.P. Area: 400 km^2 Volume: 0 25 km^3	LTP, ≈ 24,500 yr. B.P. Area: 400 km^2 Volume. 0.33 km^3 (0.16 km^3 DRE)	LTP ≈ 24,500 yr. B.P.	LTP ≈ 24,500 yr. B.P.
Plinian event?	White pumice flow (WPF)	Younger lahars?	Younger valley lahars? ≈ 21,410–27,590 yr. B.P.	———	———	WPF <26,000 yr. B P.
Plinian eruption	Upper Toluca Pumice (UTP)	UTP ≈ 11,600 yr. B.P. Area: 1,700 km^2 Volume: ≈ 0.125 km^3	UTP, ≈ 11,600 yr. B.P. Area. 2,000 km^2 Volume: 3.5 km^3	UTP, ≈ 11,600 yr. B.P. Area: 2,000 km^2 Volume. 3.5 km^3 (1.54 km^3 DRE) Column hieght >40 km	UTP ≈ 11,600 yr. B.P.	UTP ≈ 11,600 yr. B.P.
El Ombligo dome extrusion	Central dacitic dome	≤ 11,60 yr. B.P.	≤ 11,600 yr. B.P.	———	≤ 11,600 yr. B.P.	≤ 11,600 yr. B.P.?
Minor explosive event	Ash flows and surges	———	———	———	———	≈ 3,300 yr. B.P.

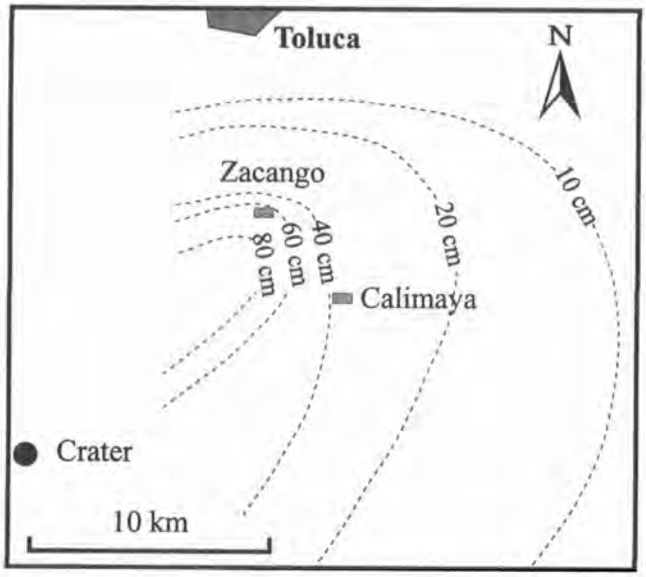

Figure 13. Isopach map of the Lower Toluca Pumice (After Bloomfield et al., 1977).

(1974; 1977) provided a minimum age of 11,600 yr. BP based on C^{14} dates collected at the base of the unit (Table 2).

Petrography of Products

Despite slight variations among products of different events, both juvenile lithic clasts and pumice contain the same mineral assemblage, which consists of euhedral plagioclase phenocrysts, hornblende, two pyroxenes (augite and minor hypersthene), and biotite in a glassy groundmass composed of the same constituents plus oxides (magnetite, and titanomagnetite). Plagioclase phenocrysts represent the most abundant crystalline phase of the Toluca products. They are up to 1 cm in length with an average size of 2–3 mm. Their chemical composition varies from Labradorite to Oligoclase (An_{30}–An_{55}) although the average chemical composition is Andesine. Dark-green calcium-rich hornblende crystals (up to 3 mm long) are the most abundant mafic phase in the Nevado de Toluca products. Minor amounts of dark-green augite and hypersthene crystals are present as phenocrysts in juvenile products; they are more common as microphenocrysts embedded in the groundmass. Biotite crystals are not present in all Nevado de Toluca products. Crystals, 1–2 mm in diameter are common within the 37,000 yr. old block-and-ash flow deposit and as microphenocrysts within pumice of other deposits. Minor amounts of magnetite, titanomagnetite, and apatite are present as microlites in all Toluca products. The composition of glass in pumice fragments is commonly rhyolitic (SiO_2 70–76%).

Figure 14. Photograph of an outcrop of the Upper Toluca Pumice on the eastern slopes of Nevado de Toluca. PS = Pyroclastic surge, PF = Pyroclastic flow. The lower (LM) and upper member (UM) as described by Bloomfield and Valastro (1974). White arrow points at person standing on the edge of gorge.

Chemistry of Rocks

Chemical analyses of 65 rocks compiled from various authors are shown in Fig. 16. Nevado de Toluca rocks are andesitic to dacitic in composition and plot in the field of the calc-alkaline magmatic series in the SiO_2 vs. Na_2O+K_2O diagram (Cox et al., 1979, Fig. 16a). Nevado de Toluca rocks have chemical compositions typical of calc-alkline suites of continental margins (Whitford and Bloomfield, 1976), and particularly of the TMVB. Fissural lava flows and scoria cones are andesitic to dacitic in composition and fall in the field of the K-rich alkaline series although some of them plot in the calc-alkaline field. In Figure 16b is shown the SiO_2 vs. K_2O diagram of Gill (1981), all rocks of Nevado de Toluca plot in the field of

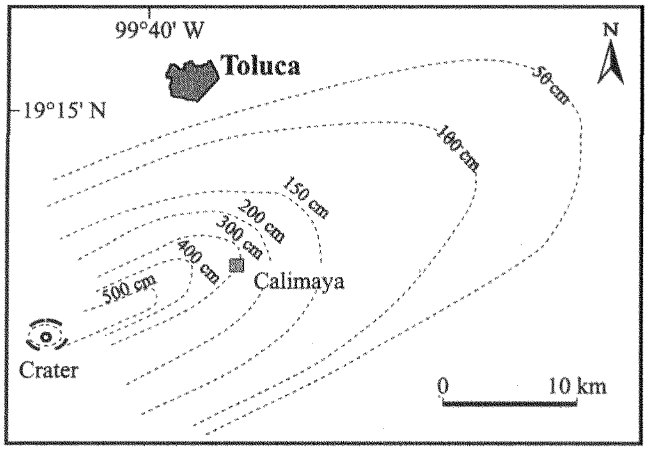

Figure 15. Isopach map of the Upper Toluca Pumice (After Bloomfield et al., 1977).

the K-medium calc-alkaline series while the peripheral group extends over the calc-alkaline fields with medium and high K concentrations.

Two stages of construction at Nevado de Toluca: A simplified model

Cantagrel et al., (1981) concluded that Nevado de Toluca was erected in two main stages: (1) Formation of the primitive andesitic volcano (some 1.5 million years ago) with the emission of lava flows and lahar deposits. (2) Pyroclastic activity during the last 100,000 years. The authors based their division on previous studies of Bloomfield and coworkers, and their own petrologic data and field observations. However, our preliminary results indicate that Nevado de Toluca has had a more complex evolution, with several stages of cone construction and subsequent destruction that were previously not recognized. A two stage volcanic history of Nevado de Toluca is much too oversimplified, as deduced from the following considerations:

1. At least four events of partial collapse have occurred at Nevado de Toluca during the Quaternary. Clear evidence for two events exists on the southern flanks of the volcano where debris-avalanche deposits underlie deposits that are 37,000 years old. These deposits have not been reported previously. At this time we do not know whether the collapses are related to magmatic activity but it is that each collapse constitutes the end of a constructional cycle.
2. Previous workers focused their studies on the recent stratigraphic sequence (<40,000 years). Despite of extensive field work, theoretical considerations (Bloomfield and Valastro, 1974; 1977; Bloomfield et al., 1977), and petrologic data (Cantagrel et al., 1981), the available stratigraphic information is not enough to fully understand the processes involved in each magmatic event.

HAZARDS IMPLICATIONS

Our preliminary results indicate that Nevado de Toluca is located in a complex tectonic framework consisting of three fault systems that transect the volcanic structure. These fault systems have been active several times in the past, displacing Holocene pyroclastic deposits. Therefore, it would not be surprising if tectonism played an important role in the migration of magmatic melts along these reactivated fault planes. These melts either stagnated in the magmatic reservoir of Nevado de Toluca where they evolved into andesitic and dacitic compositions (55–68% SiO_2) that generated explosive eruptions at the volcano summit or they rose rapidly through zones of weakness erupting K-rich basaltic andesites to andesitic products (52–61% SiO_2) that have formed cinder cones and fissure lava flows around the volcano (Fig. 6). The most recent example of fissure activity is represented by the "Tenango Andesite" that erupted through the E-W Tenango fault system only 8,500 yr. ago (Bloomfield, 1974). In 1980 an earthquake swarm occurred just NE of the fault plane (Yamamoto and Mota, 1988). These authors interpreted these movements to be associated with the E-W fault system. This evidence suggests that the Tenango fault system is active. This fact is not surprising, since the E-W fault system is typical of the TMVB and has been considered active along many of its sections (e.g. the Acambay graben, Suter et al., 1995).

A Potential Plinian Scenario

A common scenario during the Quaternary volcanic history of Nevado de Toluca has been the partial collapse of its cone. Late Pleistocene activity at Nevado de Toluca consisted of large dome-destruction eruptions dated at ca. 37,000 and 28,000 yr. BP, and plinian eruptions dated at ca. 42,000, ≤26,000, 24,000 and 11,600 yr. BP. The latter event formed a plinian column that rose to stratospheric heights dispersing fallout beds in the direction of prevailing winds to the NE (Bloomfield et al., 1977). This horizon has been identified in the basin of Mexico City and named the "Tripartite Pumice" by Mooser, (1967). This unit can be traced as far as Chalco more than 80 km from the source (Lozano-García and Ortega-Guerrero, 1994). Future plinian activity at Nevado de Toluca could endanger hundreds of towns including the city of Toluca, just 22 km from the volcano.

Because previous workers concluded that the youngest activity at Nevado de Toluca took place 11,600 years ago, the volcano has been regarded as extinct. The discovery of

Table 3. Selected chemical analyses of rocks from Nevado de Toluca Volcano.

Sample Unit	NT9511 WPF	NT9532 C. Gordo	NT9533b GBAF(o)	NT9533b GBAF(p)	NT9558 UTP (l)	NT9558 UTP (p)	NT9562 GBAF-37	NT96151 GBAF-28	NT96152 GBAF-28	NT9562 LTP (p)	NT9596 Ombligo	and-ne16 Lava	and-ne20 Lava	KB89-72 And
SiO2	65.67	66.41	65.27	65.03	65.7	63.24	65.9	67.21	66.28	55.28	64.28	59.9	62.9	59
TiO2	0.59	0.61	0.62	0.63	0.63	0.66	0.64	0.53	0.58	0.68	0.6	0.85	0.6	0.68
Al2O3	15.95	16.31	16.2	16.53	16.07	17.11	16.61	16.68	16.16	18.52	16.08	16.9	16.6	17.22
Fe2O3	3.78	3.96	4.22	4.1	4.11	4.33	3.89	3.35	3.97	4.96	4.16	3.05	1.85	1.33
FeO												2.39	2.03	4.25
FeOT												5.13	3.69	5.45
MnO	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.09	0.08	0.09	0.06	0.45
MgO	1.51	1.7	1.89	1.91	1.73	1.74	1.62	1.52	1.73	1.95	1.71	3.4	2.9	4.34
CaO	3.9	4.11	4.19	4.38	4.15	4.3	4.09	3.99	4.06	4.25	4.21	5.5	4	6.3
Na2O	4.21	4.52	4.27	4.4	4.32	4.24	4.34	4.32	4.47	3.17	4.46	4.65	4.3	4.14
K2O	2.12	2.09	2.06	2.05	2.75	2.73	1.99	2.37	2	1.25	1.86	1.9	2.35	2.2
P2O5	0.13	0.15	0.15	0.16	0.17	0.18	0.1	0.11	0.15	0.19	0.2			
LOI	2.6	0.45	1.72	1.69	1.73	2.93	0.03	0.32	–0.05	8.22	0.96	0.3	0.2	0.03
Total	100.53	100.37	100.65	100.96	100.59	100.53	99.31	100.96	99.47	98.57	98.6	99.61	99.26	100.23
Ba	520	536	531	526	516	543	483	496	536	383	495			
Rb	47	37	42	39	10	38	38	52	30	29	50			
Sr	464	528	513	549	492	535	710	673	482	506	503			
Y	14	14	15	14	13	14	5	11	14	17	13			
Zr	118	145	145	141	140	146	143	180	166	179	137			
Th	3.8	3.4	3.7	3.6	3.3	3.5	11	10	3.7	3.8	3.2			
Pb	7	5	5	5	9	19	11	13	9	6	5			
Zn	90	62	69	64	75	73	64	59	72	69	77			
Cu	54	11	4	2	8	10	1	15	5	15	10			
Ni	2	3	7	7	8	8	4	6	11	11	11			
V	48	55	64	57	44	43	75	66	60	77	57			
Cr	23.2	24.3	31.7	26.2	27.5	31.1	26	29	35.1	33.3	25.7			
Sc	6.9	7.3	8.3	7.9	7.1	7.3	8	7	8.1	10.4	7.5			
Co	6.5	7.4	8.6	7.9	7.4	8.1	10	8	8.8	8.6	8.8			

KB = Bloomfield (1974)
and-ne = Cantagrel et al (1981)
NT = This work
Letters are l = juvenile lithic, p = pumice, and o = obsidian (vitric lithic)

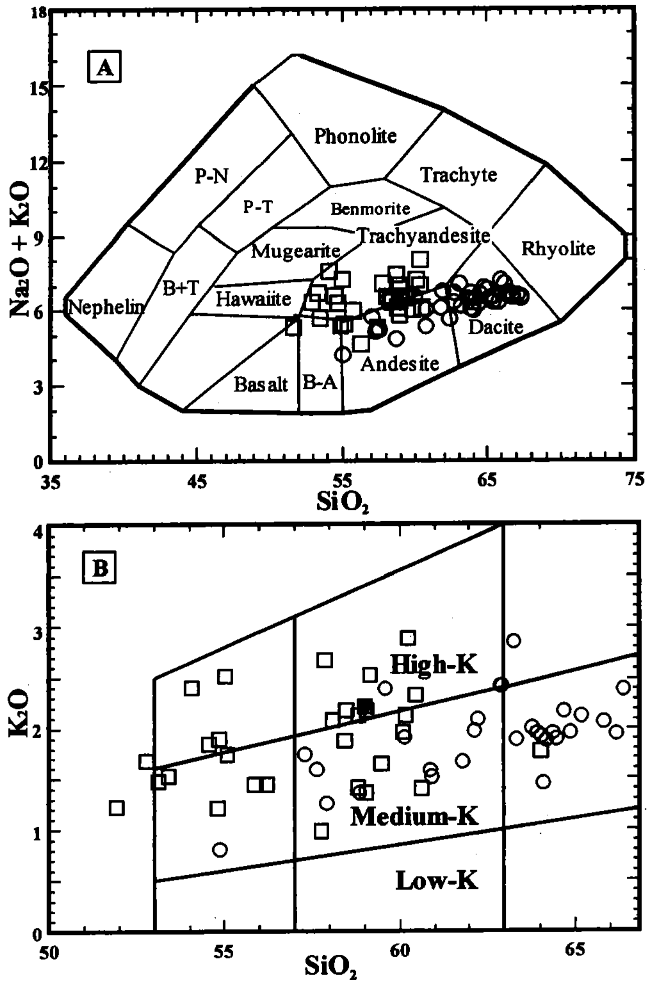

Figure 16. A: SiO_2 vs. Na_2O+K_2O composition diagram of 62 volcanic rocks belonging to the Nevado de Toluca volcanic complex (circles) and peripheral scoria cones and fissural lava flows (squares). Gary-filled diamond is the Tenango Lava Flow. Data compiled from Bloomfield (1974; 1975), Cantagrel et al., (1981), and this work. B: SiO_2 vs. K_2O diagram of the same rocks (Gill, 1981).

deposits of an eruptive event dated by us at ca. 3,300 BP invalidates this assumption. Is Nevado de Toluca really an extinct volcano? If not, what are the potential hazards that the volcano poses to the nearby populations in case of renewed activity?

FIELD TRIP STOPS

Road Log

Day 1. Tuesday, October 14.

We will have introductory lectures on the geology of central Mexico, and Nevado de Toluca Volcano.

Day 2. Wednesday, October 15.

This day we will examine the morphology of the crater of Nevado de Toluca. In our way back, we will also visit outcrops on the northwestern slopes showing Late-Pleistocene-Holocene pyroclastic deposits (Fig. 17).

km

00.0 From the city of Toluca take highway 134 west to Temascaltepec. After 17 km, stop at an excellent spot with a general view of the northern slopes of the volcano. Continue on the same road until km 29.7 and make a left turn on road 10 to Sultepec. Drive 8 km and after the town of Raices take a left turn into the unpaved road that leads directly into the crater through its eastern opening. Here, stop and have a look of the dacitic central dome "El Ombligo" and the northern crater walls (Fig. 17).

57.8 **Stop 2-1. (N19°06′31″; W99°45′28″)**
Nevado de Toluca crater.
The Nevado de Toluca crater contains a dacitic dome dubbed "El Ombligo" that separates the crater into two parts. These two areas are the seat of two lakes called Laguna del Sol (Sun) and Laguna de la Luna (Moon). The surface of the lakes have an elevation of 4,200 and 4,220 m.a.s.l. respectively. The "El Fraile" peak (4,680 m.a.s.l.) located on the southeastern rim of the crater constitutes the summit elevation of Nevado de Toluca. The internal and external walls of the crater show signs of intense erosion by glacial activity (Heine, 1976, 1988; Aceves, 1996). Another common characteristic is the presence of rock-fall debris aprons from the unstable upper parts of the crater.

Stop 2-2. (N19°05′59″; W99°45′07″)
Hike to the southern lower rim.
Hike to the southeastern peak of the crater (4,400 m.a.s.l.). From this point, enjoy the view of the southern slopes and recognize major volcanic and tectonic features in the surroundings lowlands. A series of furrows produced by glacial activity can be observed nearby.

Return to the bottom of the crater and take the unpaved road back to Raices. After 2.3 km, a great panoramic view of the Lerma Basin that circles the city of Toluca and surrounding towns can be obtained.

60.1 **Stop 2-3. (N19°05′59″; W99°45′07″)**
Panoramic view of the Lerma Basin
Volcanic and tectonic features including the Holocene andesite lava flow of Tenango can also be observed. At this site the Upper Toluca Pumice

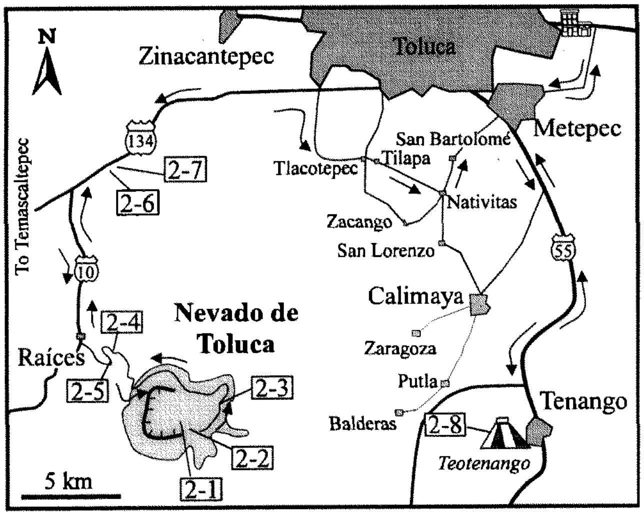

Figure 17. Map of the route for the second day. Numbered squares represent sites to be visited.

rich in pumice with minor amounts of altered red accidental fragments of dacitic rocks and juvenile gray dacitic lithic clasts, crops out.

Continue down the road for 11.8 km. On the left side, stop at a small outcrop that exhibits proximal deposits belonging to the UTP, produced by the last large Plinian eruption.

71.9 **Stop 2-4. (N19°07′50″; W 99°46′51″)**
Proximal deposits of the UTP
Here the UTP consists of three fall layers separated by surge deposits. The whole unit rests upon a pinkish morrain deposit (Fig. 18).

Follow the dirt road for 2 km and stop near the "Los Venados" shelter at a large outcrop on the left side of the road.

73.9 **Stop 2-5. (N19°08′01″; W 99°47′32″)**
Block-and-ash flow deposits (Fig. 18).
This exposure shows at the base the gray block-and-ash flow deposit composed of at least three flow units. The units consist of boulder to gravel sized fragments in a sandy matrix. The sequence is covered by units of reworked material and the UTP. The flow deposits might correlate with either one of the two large widespread flow deposits dated at 37,000 and 28,000 yr. BP.

Continue on the unpaved road for 4 km until the junction with road 10, which connects Sultepec with Toluca, turn to the right and drive through the town of Raices. Proceed on the same road for 7.8 km and reach the junction with road 134. There, turn to the right towards Toluca. After 2.6 km on the right side of the road there is an entrance to a large sand and gravel quarry.

77.9 **Stop 2-6. (N19°13′26″; W 99°47′22″)**
In the quarry are exposed from the base to the top: a pumiceous pyroclastic flow deposit (dated at another locality at ca. 42,000 yr. BP), a gray block-and-ash flow deposit (dated here at 28,000 yr. BP) that consists of several interbedded flow and surge units, that show excellent cross-stratification and pinch out structures (Figs. 19a and 19b). The sequence is topped by the UTP represented here by a single fallout bed.

77.9 **Stop 2-7 (A few meters northward within the same quarry)**
This site exhibits the same gray block-and-ash flow deposit as well as minor surge deposits on top (Fig. 18). The flow deposit consists of three massive flow units (10–20 m thick), of which the upper one is characterized by a pinkish-red color. The most remarkable feature at this site is the presence of a brown ash flow rich in charcoal dated at ca. 3,500 yr. BP which is interbedded with gray surge deposits. This deposit represents the youngest explosive event recognized so far at Nevado de Toluca (Fig. 20). A similar age of 3,100 yr. BP was obtained from an ash flow capping the sequence on the western side of Nevado de Toluca volcano. The thickness of these deposits at a distance of 15 km from the crater suggest that this event was of considerable magnitude.

Return to road 134 towards the city of Toluca. Drive 4.7 km to the town of Metepec. Take road 55 which connects Toluca and Ixtapan de la Sal to the south, drive 14.6 km to the town of Tenango de Arista. Make a right turn through the town and follow the directions to get to the archaeological site of Teotenango, located on top of the Tenango lava flow.

125.2 **Stop 2-8. (N19°16′15″; W 99°35′40″)**
Teotenango Ruins and Tenango andesite lava flow
This site is located 15 km NE of the Nevado de Toluca crater (Fig. 17). The flow consists of four aa andesite lava lobes which rise more than 250 m above the surrounding plain. The rocks have a SiO_2 content of 56–62% and are composed of microphenocrysts of olivine and augite imbedded in a groundmass of andesine, augite and interstitial glass. Charcoal and charcoal-rich paloesoil samples below the Tenango flow yielded an average age of 8510 ± 160 yr. BP. (Bloomfield, 1974).

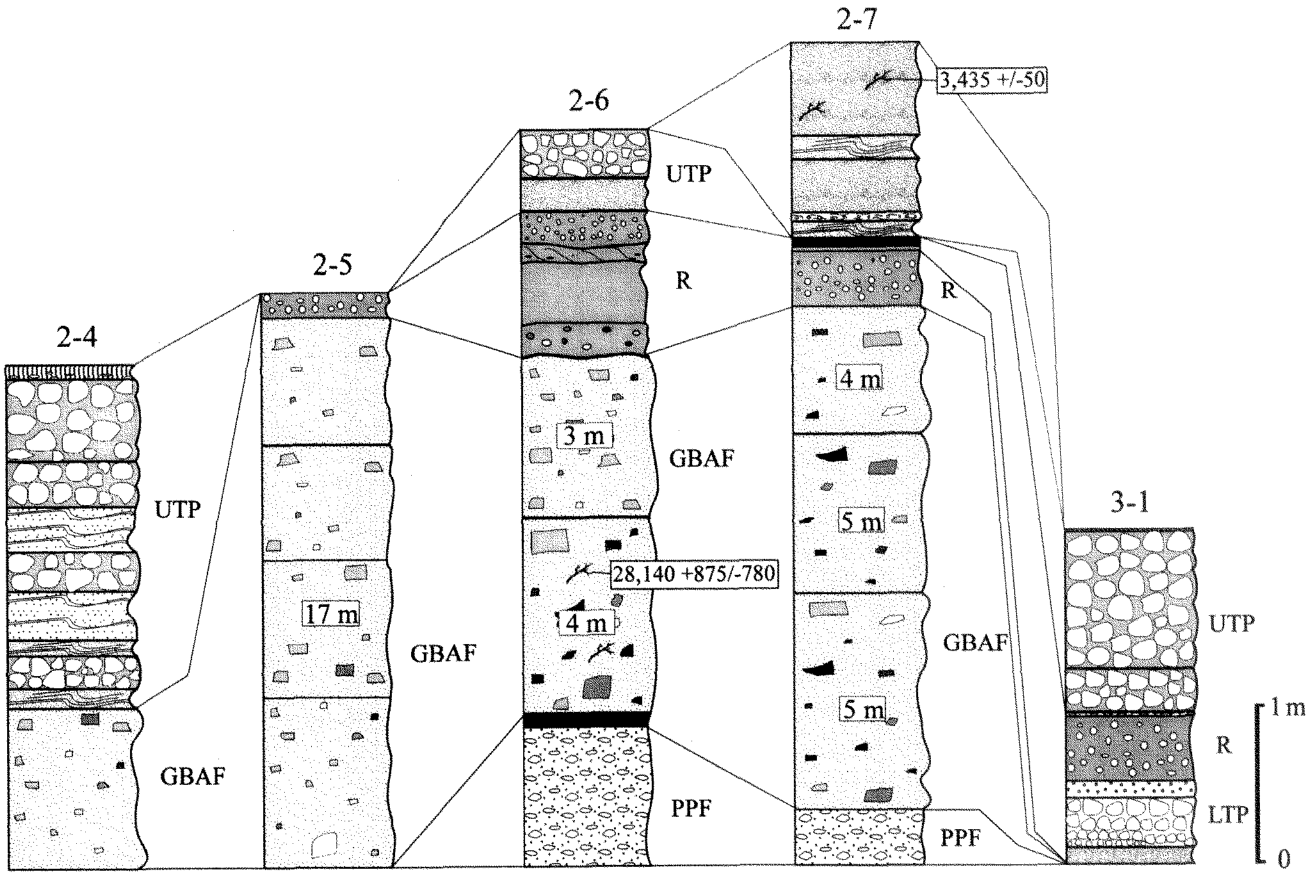

Figure 18. Stratigraphic correlation between outcrops at stop sites 2-4 to 3-1. For legend see Fig. 10.

The lava flow constitutes the substrate on which the fortified Pre-Hispanic city of Teotenango was built. This site was first inhabited around 1000 B.C. (Pre-Classic Period of the Mesoamerican archeological time scale) by the "Teotenancas," a tribe related to the Otomi and Toltec cultures (Piña Chan, 1972). Archaeological excavations revealed that the city itself was constructed around A.D. 750–900 when inhabitants that used to live in small agricultural villages moved to the Tetépetl hill. Between A.D. 900 and 1200 the city reached its maximum architectonic development when important portions of the city, such as the ball court, were constructed. Around A.D. 1200 the Teotenancas were conquered by the Matlazincas who dominated the Toluca basin, and constructed important cities. Between 1474 and 1476, Teotenango was conquered by the Aztecs (during the reign of the emperor Axayácatl). After the Spanish conquest, Martín Dorantes moved the people living in the ancient city to the base of the lava flow and founded the present city of Tenango de Arista.

From this site, return on road 55 towards the city of Toluca, turn right into road 134 towards Mexico and reach again the Holiday Inn Hotel.

Day 3. Thursday, October 16.

This day will be devoted to the inspection of pyroclastic deposits on the north and northeastern slopes of Nevado de Toluca (Fig. 21).

km

0.0 From the city of Toluca take highway 134 west which leads to Temascaltepec. Drive 13.6 km and make a left turn to take the road to San Juan Tilapa. Drive 2.7 km and reach Tilapa. Drive through the town and at the exit take the road towards Nativitas. Drive 1.4 km and reach the road that leads to the Zacango Zoo. Drive on this road 1.5 km and arrive at stop 3-1 (Fig. 18).

19.2 **Stop 3-1. (N19°12′45″; W99°39′29″)**
This exposure exhibits from the base to the top: an ash flow deposit with soil development towards

Figure 19a. View of outcrop 2-6 showing the 28,000 B.P. gray block-and-ash flow deposit (PF = pyroclastic flow, PS = pyroclastic surge) on top of the pink pumice flow deposit dated at 42,000 years BP.

Figure 19b. Close view of the 28,000 BP block and ash flow deposit (section 2-7). Arrow points at carbonized tree log which is 50 cm long.

the top, the LTP, a brown matrix-supported lahar with embedded subrounded pumice, the UTP, and covering the sequence the modern soil (Fig. 22). At this location, the UTP consists of two main fall members (lower and upper fall members as described by Bloomfield and Valastro, 1974) separated by thin surge layers that can be correlated to those surge deposits observed at stop 2-4.

Continue 1.2 km on the same road and arrive at the Zacango Zoo. There, turn right, and take the road to San Marcos de la Cruz for 0.8 km. Turn right again and drive 1.7 km on the dirt road that leads to the Zacango quarry. Take the little entrance on the left which leads to the quarry. This is stop 3-2 (Fig. 22).

22.9 **Stop 3-2. (N19°11′18″; W99°39′29″)**
Late Pleistocene Nevado de Toluca products.
This quarry exhibits an amazing outcrop of pyroclastic deposits produced by Nevado de Toluca during the last 40,000 yr. BP (Fig. 22). The base of the quarry exposes a thick (10–20 m) gray block-and-ash flow deposit composed of several flow units rich in porphyritic dacite lithic clasts in a sandy matrix. The upper flow unit shows gas escape pipes. Because of its stratigraphic position, an age of 37,000 yr. BP has been assigned to this unit. Overlying the flow deposit, there is a sequence of lacustrine beds interbedded with dark-gray paleosoils. The section continues upwards with a gray block-and-ash flow deposit (5 m thick) composed of gray dacite and pumice lithic clasts embedded in a sandy matrix. Because of its stratigraphic position and base on a date of 27,590 ± 650 yr. BP from a paleosoil on top of this unit (Bloomfield and Valastro, 1977), we have assigned it an age of 28,000 yr. BP. Therefore, this deposit correlates with the younger flow deposit observed at stop 2-7. Further up section, there is a thick, well-developed paleosoil with desiccation cracks. This paleosoil was also dated by Bloomfield and Valastro (1977) and yielded an age of ca. 24,500 yr. BP (Fig. 23). On top of this paleosoil rests LTP and associated surge beds. The sequence continues with a thick paleosoil on top of which rests the UTP that comprises a pink ash flow deposit as well as the fall members.

Drive back to Santa María Nativitas (4.5 km). Follow the same road and drive through the towns of San Lorenzo (2 km) and Calimaya (4.6 km), and at 8.3 km reach the road that connects the towns of Tenango and Putla. Turn right and drive 3.8 km to the town of Putla. Drive through the town and take the road towards San Cruz Pueblo Nuevo for about 2.4 km. There take the road to the right to San Miguel Balderas for another 1.1 km and cross the town. On its northwestern edge there is a dirt road to the Zaguan gorge located on the eastern flanks of the volcano. Drive 8.8 km until the end of the dirt road. There you will observe the Upper Toluca Pumice which is made up of a thick (20 m) complex sequence of pyroclastic flows and surge deposits covered by the fall members as described by Bloomfield and Valastro (1977) (see Fig. 14). Take the same dirt

Figure 20. A. Photograph of the upper part of section 2-7 showing the 3,300 yr. old deposits of Nevado de Toluca Volcano. Figure A shows a general aspect of the outcrop, arrow points at the base of the deposit. B: Close-up of the deposit showing from bottom to the top a thin layered sequence of pyroclastic surges, a clast-supported lapilli-sized surge bed, and a massive fine lapilli to sandy ash flow rich in charcoal (arrow). Scale bar is 40 cm.

road back to San Miguel Balderas and at about 1 km park your car on the left side of the road at a little gully. This is stop 3-3.

56.4 **Stop 3-3. (N19°06′36″; W99°41′33″)**
Upper Toluca Pumice

This outcrop (Fig. 22) shows at its base a sandy brown bed overlain by a pumice fall layer rich in white angular pumice, banded pumice, gray dacite, and hydrothermally altered lithic clasts. This bed is covered by a sequence of pumice-rich pyroclastic flow and pyroclastic surges deposits displaying regressive dune forms. The uppermost part of the section is composed of the three fall members of the UTP. Because of no clear discontinuities have been observed between the basal part (fall bed, flow and surge deposits) and the upper part (UTP fall members as described by Bloomfield and Valastro, 1977), we do believe that both parts represent a single sequence associated to the same eruption that produced the UTP ca. 11,600 yr. BP.

Continue on the dirt road and after 1.8 km reach a gully. This is stop 3-4.

59.0 **Stop 3-4. (N19°07′16″; W99°40′57″)**
Debris Avalanche Deposit 3

This section (Fig. 22) shows from the base to the top a thick gray block-and-ash flow deposit rich in dacite clasts embedded in a sandy matrix, which is overlain by a debris-avalanche deposit (DAD3). DAD3 is composed of shattered gray dacite clasts and m-sized red blocks. The blocks display jig-saw-fit and are more frequent towards the top of the deposit. Because these units are not separated by an erosive unconformity, it is possible that they were emplaced during the same eruption whose age is still unknown but might be related to the 37,000 yr. BP or to the 28,000 yr. B.P events. On top of DAD3 are the fallout layers of the LTP and UTP units which are separated by paleosoils.

Take the dirt road to San Miguel Balderas and Putla and continue 10 km until junction with road 55 which connects the cities of Toluca and Tenango. Turn right and after 0.6 km make a right turn and take the toll road to Ixtapan de la Sal. Drive 14.2 km and at a narrow curve, pull over and park on the right side of the road. Stop 3-5 is located on the left side of the road. Be careful when crossing the road.

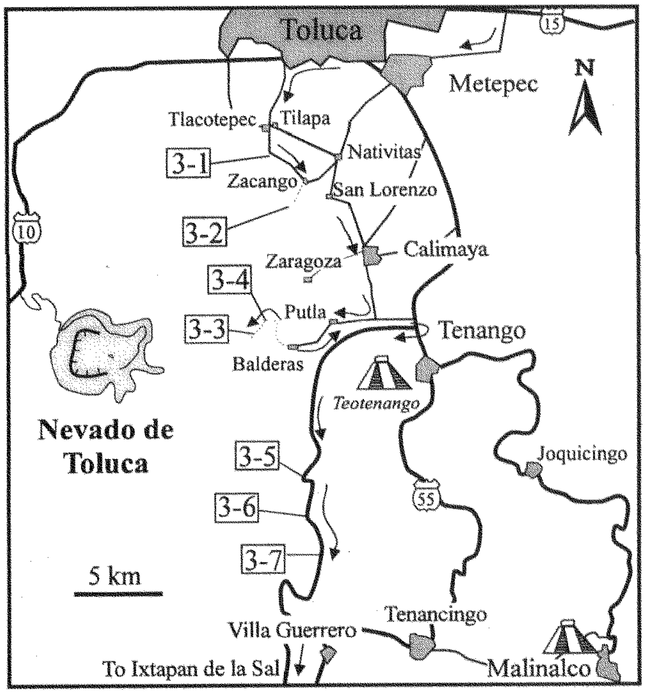

Figure 21. Map of the route for Day 3. Numbered squares represent sites to be visited.

86.0 **Stop 3-5. (N19°02′48″; W99°39′45″)**
White Pumice Flow Deposit
This outcrop shows from the base upwards a gray block-and-ash flow deposit that is capped by a paleosoil. This paleosoil was dated at 26,275 +1210/–150 yr. BP (Figs. 22 and 24a). The White Pumice Flow sequence rests on top of this paleosoil. It is composed of a white, clast-supported pumice fall layer covered by gray sandy-silty surge horizons and pumice-rich flow units. On top is a massive pumice flow deposit composed of lapilli-to-gravel sized pumice clasts embedded in a sandy matrix (Fig. 24b).

Continue on the same road for another 2.5 km and park on the right side of the road. Here, a debris-avalanche deposit is exposed on a tall road cut on the left side. This is stop 3-6.

88.5 **Stop 3-6. (N19°01′39″; W99°38′44″)**
Debris-Avalanche Deposit
This exposure shows a pinkish monolithologic debris-avalanche deposit composed of gray dacite blocks which display jigsaw-fit structures surrounded by a sandy matrix. The age of this deposit is still unknown.

Continue on the same road and after 3.7 km reach a large quarry on the right side of the road. This is stop 3-7.

92.2 **Stop 3-7. (N19°00′09″; W99°38′56″)**
Block-and-Ash flow deposit 37,000 years old.
This quarry shows a great view of a ponded gray block-and-ash flow deposit more than 20 m thick (Fig. 2). The flow deposit consists of more than 6 flow units and it is composed of gray porphyritic dacite, minor pumice and accidental lithics set in coarse sandy matrix. A charcoal sample found within this deposit yielded an age of 37,000 ± 1025 yr. BP.

Continue 21.8 km on the same road and arrive at Ixtapan de la Sal, where we will stay at Hotel Villa Vergel.

Day 4. Friday, October 17.

This day will be devoted to the inspection of the southern slopes of Nevado de Toluca where features related to major sector collapse of the volcano dominate the landscape (Fig. 25).

km

0.0 From Ixtapan de la Sal take the road to Coatepec Harinas and drive 10.8 km until you reach a triple road junction. Turn left into road 7 to Zacualpan, drive through Puerta Grande and after 4.5 km stop and enjoy the panoramic view of the Coatepec graben. Proceed 2 km on the same road and reach stop 4-1, which, is located on the right side of the road at a dangerous curve. Stop your car at the entrance of a dirt road.

17.3 **Stop 4-1. (N18°45′32″; W99°41′43″)**
Debris-Avalanche deposits (DAD1 and DAD2)
This exposure exhibits at the base the older lahar sequence mentioned by Cantagrel et al., (1981). The sequence is composed of fluviatile beds, debris flow deposits and run-out lahars (Fig. 26). The sequence is overlain by a poorly developed brown soil. Above this is a pinkish-red debris-avalanche deposit 1 (DAD1) which is 10 m thick and rests with a flat non-erosive contact above the paleosoil (Fig. 27a). DAD1 consists of gray and red-altered dacite blocks set in a coarse sandy matrix with a few tree casts. Blocks are gravel to boulder in size and show jigsaw-fit structures. DAD1 is overlain by a brown paleosoil which in turn is overlain by the debris-avalanche deposit 2 (DAD2). In parts of this outcrop, DAD2 lies directly on top of DAD1 (Fig. 27b). DAD2 is pinkish in color and has a maximum thickness of 5 m in this section. It is heterolithologic and has the same lithic components as DAD1. In addition, it con-

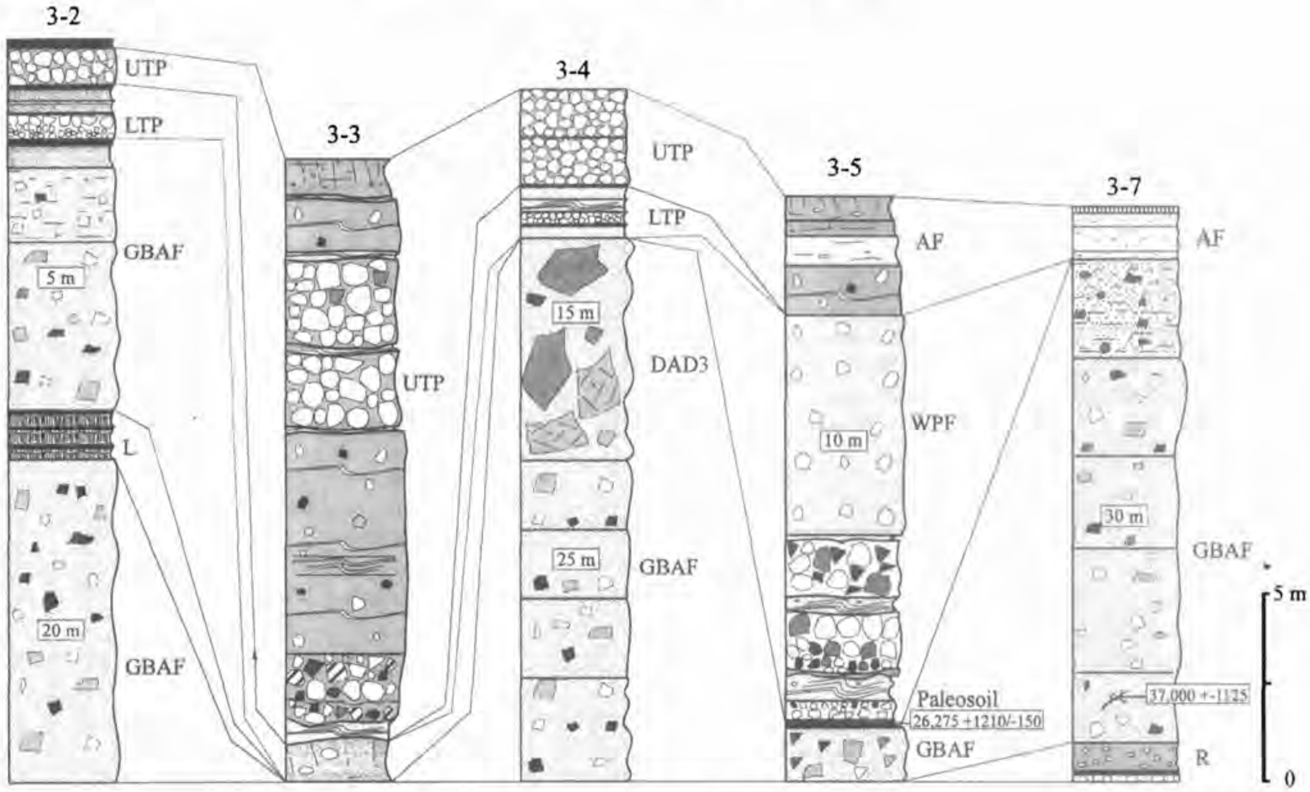

Figure 22. Stratigraphic correlation between outcrops at stops 3-2 to 3-7. For legend see Fig. 10.

tains a wide variety of lithic clasts picked up from the substrate (e.g. schists and highly altered dacites from the local basement). Gravel- and boulder-sized blocks show jigsaw-fit structures and conchoidal fractures. This sequence is older than the gray block-and-ash flow deposit dated at 37,000 yr. BP.

Take road 7 back to Ixtapan de la Sal and after 7.7 km reach the junction to Coatepec Harinas. Proceed to Ixtapan de la Sal and after 0.2 km turn right into road 12 that leads to Pilcaya. Drive through Coazusco and after 9.10 km reach La Concepción. There, turn right on the dirt road to La Concepción quarry. Drive 1.1 km to the quarry, which is stop 4-2.

35.4 **Stop 4-2. (N19°55′35″; W99°42′53″)**
Sequence of Lahar Units

This quarry shows a thick sequence of fluviatile cross-stratified beds interbedded with lahars and lacustrine beds. The lahars contain rounded pebbles of gray and red dacite clasts embedded in a homogeneous sandy matrix. A lahar unit in the middle part of the section filled a small channel. This deposit thins out towards the channel walls where the deposit grades into a massive homogeneous sand-sized horizon. In the center of the channel it is much coarser with gravel-sized clasts in a sandy matrix (debris flow). The age of this deposit is not well constrained (Fig. 26).

Drive back to La Concepción and make a right turn into road 12 to Pilcaya. From this point, drive 1.8 km until the detour to the dirt road that takes you to Taxco. Drive 1.5 km along this road which runs parallel to a gully. Stop 4-3 is located on a curve on the right side of the road.

39.8 **Stop 4-3. (N18°44′48″; W99°40′48″)**
Debris-Avalanche deposit 2 (DAD2)

This outcrop exhibits 5 m of DAD2. The deposit is pale-pink, heterolithologic, and composed of blocks up to 1.5 m in size. It consists of rhyolitic clasts from the Tertiary Tilzapotla Formation, olivine-basalts, and gray and red-altered dacite fragments. A complex sequence (≈10 m thick) of lahars, paleosoils, poorly developed lacustrine horizons, and distal fallout tuffs covers DAD2 (Fig. 26).

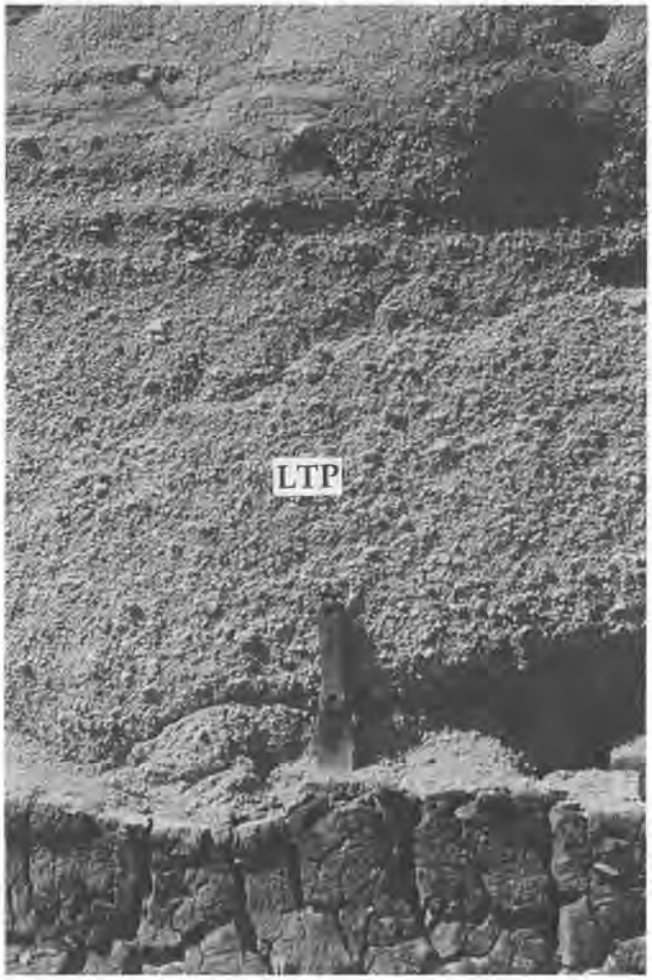

Figure 23. Lower Toluca Pumice on top of paleosoil (notice desiccation cracks). Spatula is 20 cm long.

Take the dirt road and 1.3 km ahead is stop 4-5 on the right side of the road. There, enjoy a great view to the south overlooking the distribution of debris-avalanche deposits from Nevado de Toluca.

41.1 **Stop 4-4. (N18°44′21″; W99°40′56″)**
Debris-Avalanche deposit (DAD2)
This site exhibits from the bottom to the top (1.10 m thick) a pinkish distal fallout tuff covered by a white lacustrine sequence composed of alternating beds of silty massive and laminae horizons. Laminae horizons show cross-stratification and load structures. The whole sequence is overlain by DAD2 with a flat contact. DAD2 is heterolithologic, and includes blocks of gray dacite, basalt, schist, and conglomerate fragments (Tertiary Balsas Group) embedded in an indurated sand matrix (Fig. 26).

Take the dirt road back to road 12. Drive through La Concepción and Coazusco and continue to Ixtapan de la Sal. Here, take road 55 in the direction of Toluca. Drive through Villa Guerrero and Tenancingo. At Tenancingo, take the paved road to San Nicolás. At San Nicolás, turn right into the road that leads to Malinalco, the site of Stop 4-5 (Fig. 25).

110.5 **Stop 4-5. (N18°57′08″; W99°29′05″)**
Malinalco Archaeological Site
The village of Malinalco is located at 1750 m.a.s.l. The archaeological site sits on a terrace above the base of the mountain known as Cerro de los Idolos. This hill is made out of a thick sequence of lahars (debris flows and lahar-runouts), and fluviatile and lacustrine beds that belong to the Tepoztlán Formation of Early Miocene age. Prehispanic Malinalco was originally inhabited by the Matlazincas until 1469 when it was conquered by the Aztecs under the reign of emperor Axayacatl in 1476. The beginning of the construction of Malinalco buildings (present ruins) was ordered in 1501 by emperor Ahuitzotl, and it was continued during the reign of Motecuhzoma Xocoyotzin between 1503–1515. The construction of these buildings ended with the occupation by the Spaniards in 1521. The ascent to the ruins is made through a narrow stairway located at the Santa Monica quartier. The construction of the Monastery located on the main plaza of the Malinalco village was started in 1537 by Augustine missionaries (INAH, 1969).

From Malinalco take the highway to the north heading to Joquicingo and Tenango.

141.5 At Tenango enter highway 55 north to Toluca.

197.5 In Toluca follow signs to Querétaro and exit the city to the north on highway 55. After 37 km pass Ixtlahuaca and after another 29 km arrive in Atlacomulco, where we will spend the night at Hotel Fiesta Mexicana.

JOCOTITLÁN VOLCANO

Jocotitlán is a composite volcano with an altitude of 3,950 m that rises 1,300 m above the lacustrine, fluvial, and volcaniclastic sequences of the northern Toluca basin, 10 km south of the Acambay graben (Figs. 28 and 29). A Holocene, northeast-spreading debris-avalanche deposit (DAD), which is characterized by numerous hummocks, exists on the northern flank of the volcano (Siebe et al., 1992). A prominent, horseshoe-shaped escarpment, which opens to the northeast, is associated with this DAD. ^{14}C-

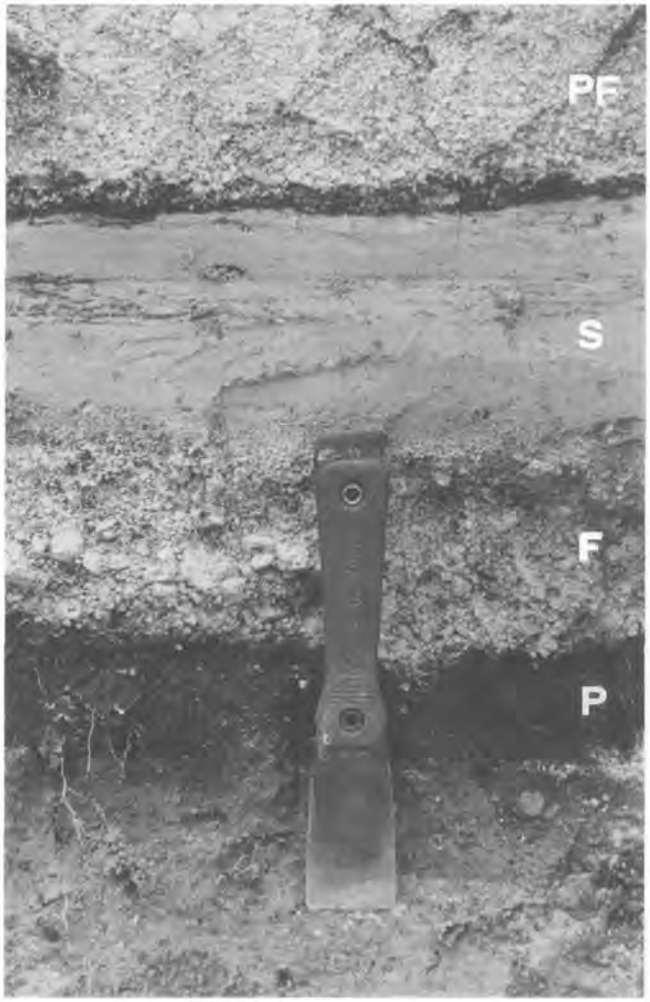

Figure 24a. Base of the White Pumice Flow deposit at stop 3-5. F = pumice fall, P = paleosoil dated at 26,275 BP, PF = base of the pyroclastic flow of Fig. 23b, S = surge.

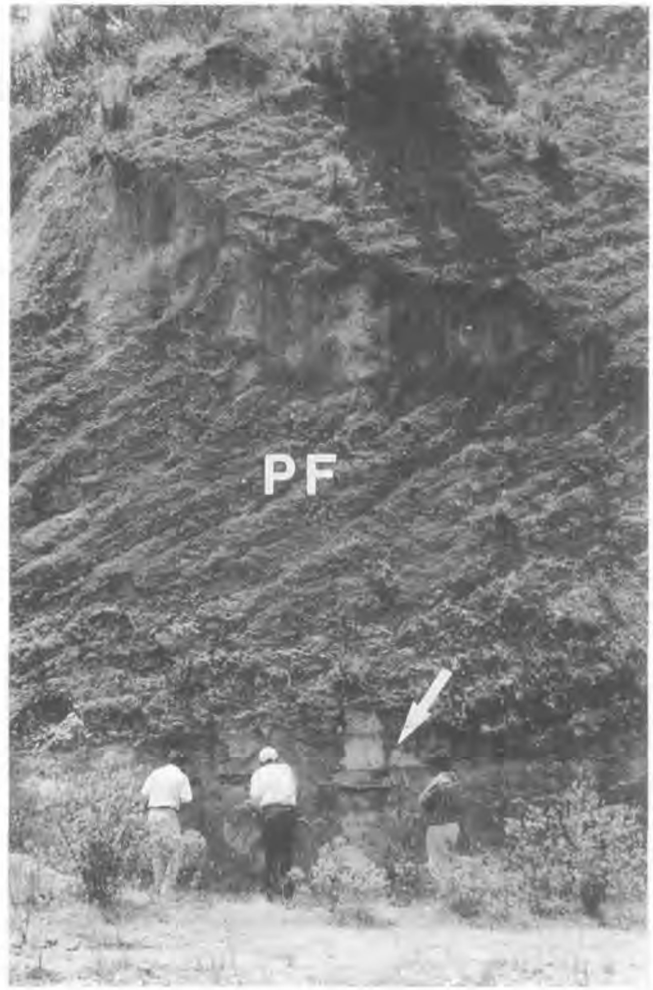

Figure 24b. Massive White Pumice Flow deposit (stop 3-5).

dating of the youngest pyroclastic deposits from the summit region of Jocotitlán volcano yielded ages ranging between 890 ± 70 and 680 ± 80 y. BP (Siebe et al., 1992). Therefore, Jocotitlán volcano should be considered potentially active and should be monitored.

The morphology of Jocotitlán is intermediate between that of a stratovolcano and a dome. The present edifice rests on an older Tertiary complex of dacite domes and andesitic scoria cones. The first constructional stage of the volcano was characterized by the emplacement of dacitic to andesitic lavas, which created an edifice with shallow dips and a concave-upward profile. It ended with a large explosive eruption which led to the deposition of an obsidian-rich, dacitic Plinian pumice-fall deposit of regional extent. At several localities, this deposit is more than 10 m thick and is commonly intercalated with pumice-rich pyroclastic surge deposits within proximal areas of the volcano. This catastrophic first stage was followed by the construction of a large dacite dome complex with a steep convex-upward profile. This second stage was accompanied by the effusion of several extensive lava flows and minor pyroclastic surge and pumice-fall activity.

A major Quaternary collapse of its northeastern flanks abruptly ended this second constructional stage. A breached crater with a 90° sector opened to the northeast and the collapsed products formed a major rockfall DAD (Fig. 29). The avalanche covers an area of 80 km^2, has a maximum runout distance L of 12 km, and a maximum height of drop H of 1,300 m which corresponds to an H/L ratio of 0.11. Its estimated volume is 2.8 km^3. The extent of the deposit is farthest in the east where it was least impeded by topographic barriers. The surface morphology is characterized by 250 hummocks of varying shape and size, and a series of parallel transverse ridges separated by closed

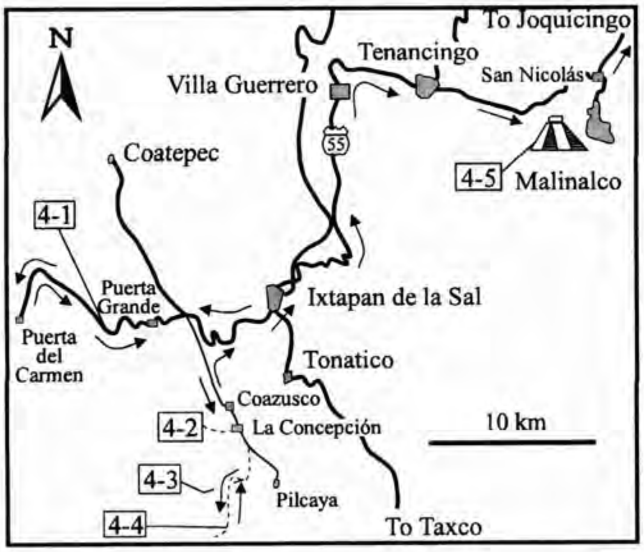

Figure 25. Map showing the field trip stops to be visited during the fourth day.

depressions. These features are typical for many DADs (e.g. Glicken, 1986; Crandell et al., 1984). However, the large topographic dimensions of the Jocotitlán deposit (conical hills up to 195 m in height, elongated ridges 205 m in height and 2.7 km in length, and a pronounced terminal scarp up to 50 m in height) distinguish this deposit from most others of this type.

The deposit is extremely heterogeneous with respect to clast size (5 cm pebbles to megaclasts several decameters in size) with the majority of the clasts between 1 and 5 meters. Sand-size and finer material is also present, but constitutes only a small fraction of the total volume.

Another remarkable feature related to this catastrophic event is the intense deformation of the underlying volcaniclastic and lacustrine sediments by faulting and folding that occurred during and after deposition of the DAD. The debris-avalanche bulldozed these soft sediments where they formed preexisting topographic highs. In addition, these sediments were faulted and bent due to differential loading where they lie directly below the DAD.

Flank failure may have been triggered by a major earthquake in the Acambay graben, 10 km north of Jocotitlán

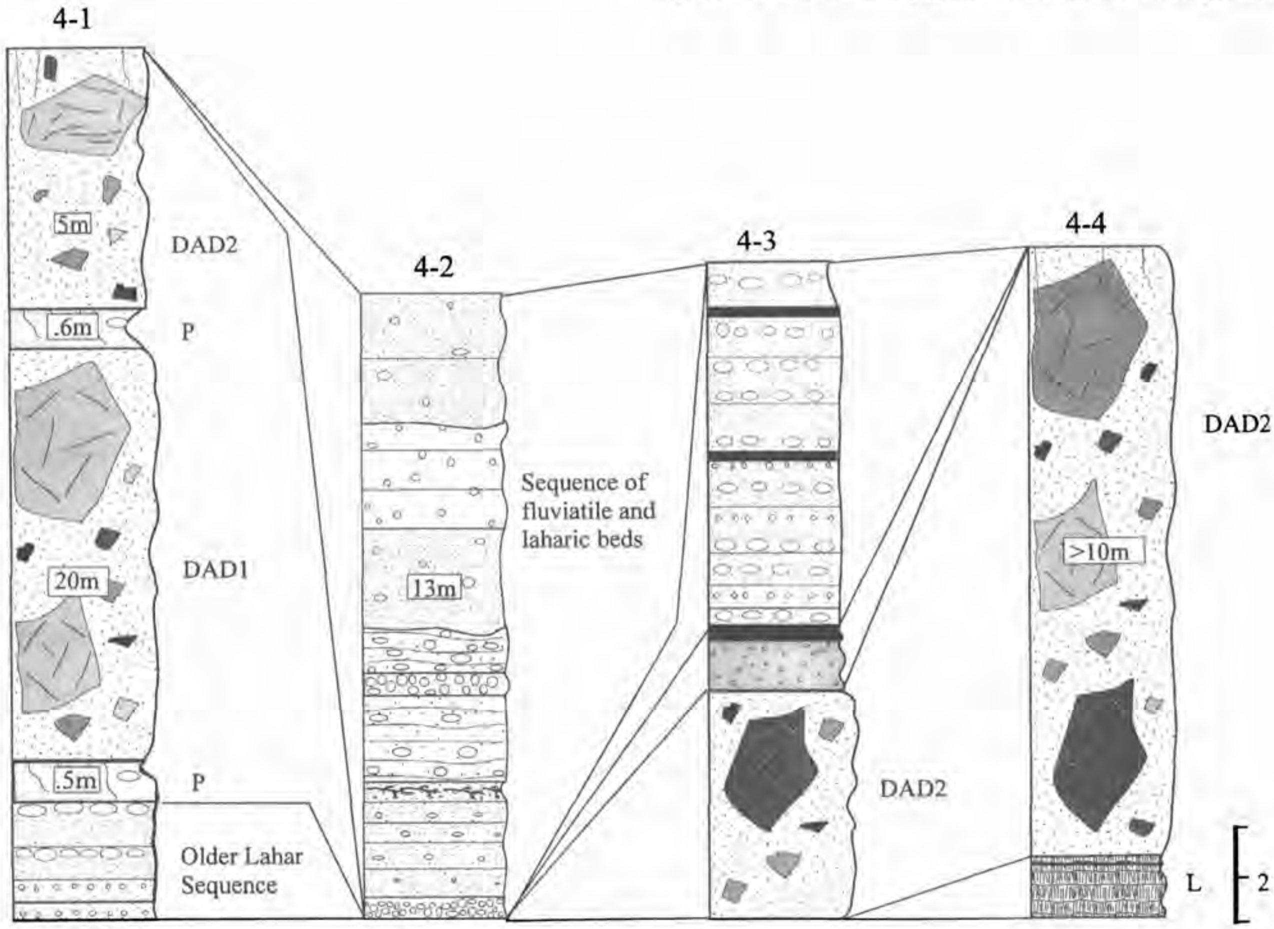

Figure 26. Stratigraphic columns of exposures to be visited during Day 4.

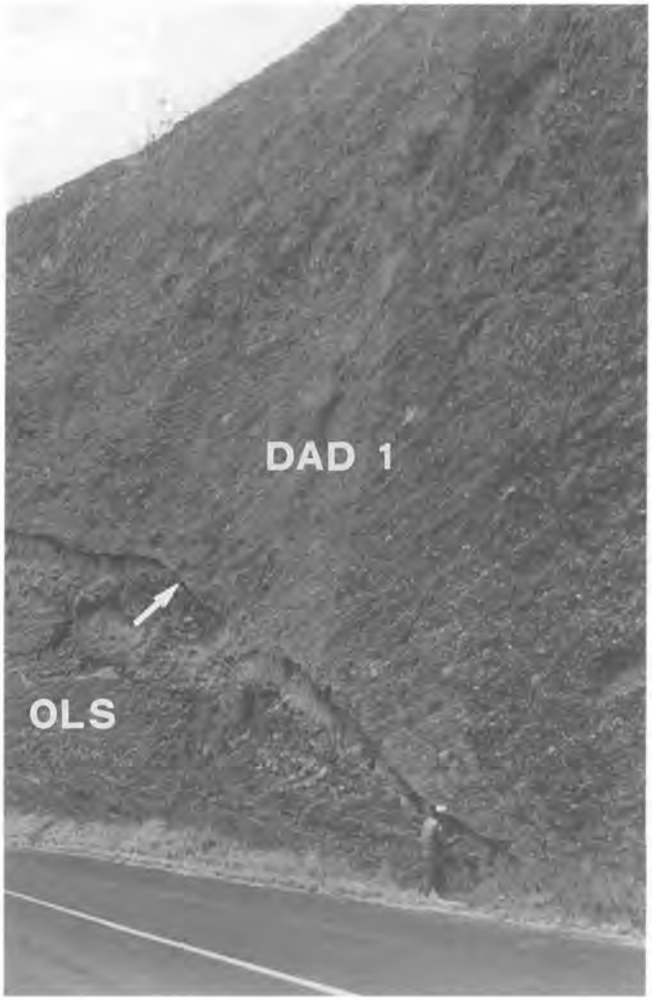

Figure 27a. Old lahar sequence (OLS) and the debris avalanche deposit (DAD1) at outcrop 4-1. Arrow points to the lower contact of DAD1.

Figure 27b. Debris-avalanche deposits DAD1 and DAD2 at outcrop 4-1. Lower arrow shows a tree cast within DAD1. Upper arrow depicts the flat contact between the deposits. Exposure is 21 m. thick.

volcano. Explosive activity contemporaneous with flank failure is recorded by pumice and obsidian-rich pyroclastic surge deposits and pumice fall-out layers emplaced directly above and between large boulders of the DAD. Organic substance from these deposits related to the debris-avalanche deposit yielded a ^{14}C-age of 9690 ± 85 y. BP (Siebe et al., 1992).

Following the formation of the breached crater and the emplacement of the DAD and its associated pyroclastic units, a stage of repeated dome growth slowly infilled the crater, partly obliterating its outline. Field evidence suggests a long period of repose between this latter dome activity and the most recent explosive event, dated at 680 ± 80 yr. BP. This recent event produced thick hydromagmatic rim breccias, obsidian and pumice-rich dacitic (SiO_2 = 63–64%) block-and-ash flow deposits and pyroclastic surge deposits which were confined to steep ravines west and south of the present summit.

Petrological and geochemical data indicate that Jocotitlán has erupted very homogeneous products throughout its history. Almost all rocks are two-pyroxene andesites and dacites with SiO_2 contents ranging between 59 and 69%. The most common mineral assemblage consists of plagioclase, hypersthene, augite, and titanomagnetite set in a microcrystalline to glassy groundmass. The extreme homogeneity of these rocks is confirmed by consistent trace-element abundances.

Rare earth element (REE) patterns show no europium anomaly and only slight enrichment in heavy REE. These data suggest a chemically stable source for the magma and

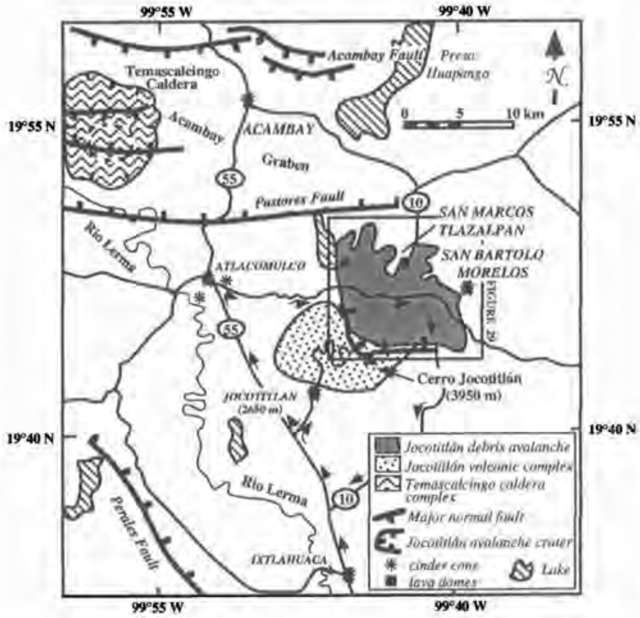

Figure 28. Geological setting of the Jocotitlán volcanic complex, State of Mexico. Box shows location of Fig. 29, arrows indicate field trip route (after Siebe et al., 1992).

eruptions from the same level within a long-lived magma chamber

Day 5. Saturday, October 31 (morning).

Pre-Columbian pyroclastic deposits and Holocene debris-avalanche deposit at Jocotitlán volcano (3950 m.a.s.l.)

During the morning of the fourth day, we will drive to the summit of Jocotitlán volcano and inspect young pyroclastic deposits, which were produced in Pre-Columbian time ca. 700 to 900 years ago. In the afternoon we will focus on a 10 000 year old debris-avalanche and associated deposits which extend to the north of Jocotitlán volcano (Figs. 28 and 29). Some of the outcrops related to the debris-avalanche deposit were visited during a 1991 field-trip of the Geological Society of America and previously described in Suter et al., (1991).

Road Log

km

00.0 Take highway 55 from Atlacomulco and drive south in direction of Toluca (Fig. 28).

16.0 Exit highway 55 and drive 4.4 km northeast to the town of Jocotitlán (2650 m). At the main square, take the street to the north, which leads to an unpaved road to the summit of the volcano.

After a driving time of ca. 40 minutes and at an altitude of 3470 m we will reach outcrop 5-1 on the left side of the road.

32.0 **Stop 5-1. (N19°44′52″; W99°46′24″)**
Exposed is an excellent sequence produced by Jocotitlán's most recent eruption (Figs. 30 and 31). Brown sandy surge deposits are intercalated with pumiceous block-and-ash flow deposits, as well as a conspicuous layer of orange-colored airfall pumice. The pumiceous flow deposits contain charcoal, which was dated and yielded radiocarbon ages ranging between A.D. 850 ± 70 and A.D. 1270 ± 80.

Continue for another 30 minutes and reach Estación Microondas close to the main summit at 3950 m (stop 5-2).

39.5 **Stop 5-2. (N19°44′18″; W99°45′28″)**
From the summit, an excellent view of the area covered by the debris-avalanche towards the north can be obtained (Fig. 29).

79.0 Return to Atlacomulco.

Day 5 Saturday, January 31 (afternoon).

Debris-avalanche deposit at Jocotitlán

Take the highway from Atlacomulco to the east, in direction to Villa del Carbón (Fig. 28). About 10 km east of Atlacomulco, at Acutzilapán, the road reaches the debris-avalanche deposit (DAD) from where it passes on its surface for approximately 15 km. Here is stop 5-3.

km

90.0 **Stop 5-3. (N19°47′54″; W99°45′37″)**
This site is located 1 km north of Acutzilapán (Fig. 29). It provides a good view of Jocotitlán volcano and the hummocky topography of the DAD. In addition, the limits of the breached crater, which is now partly filled by a dome complex, can be recognized (Fig. 32).

Site 5-4 is located at a road cut 3 km east of Acutzilapán (Fig. 29).

93.5 **Stop 5-4. (N19°46′56″; W99°43′55″)**
This is one of the best outcrops exposing the internal structure of the DAD which consists predominantly of a very poorly sorted, clast-supported mixture of angular to subangular clasts of almost exclusively dark porphyritic lava (60–67% SiO_2) with plagioclase, hypersthene, and augite phenocrysts. Jigsaw-fit of clasts from blocks of the former edifice can be commonly refitted across fracture planes. Jigsaw-fit structure is a diagnostic feature of DADs (Shreve, 1968; Glicken, 1986).

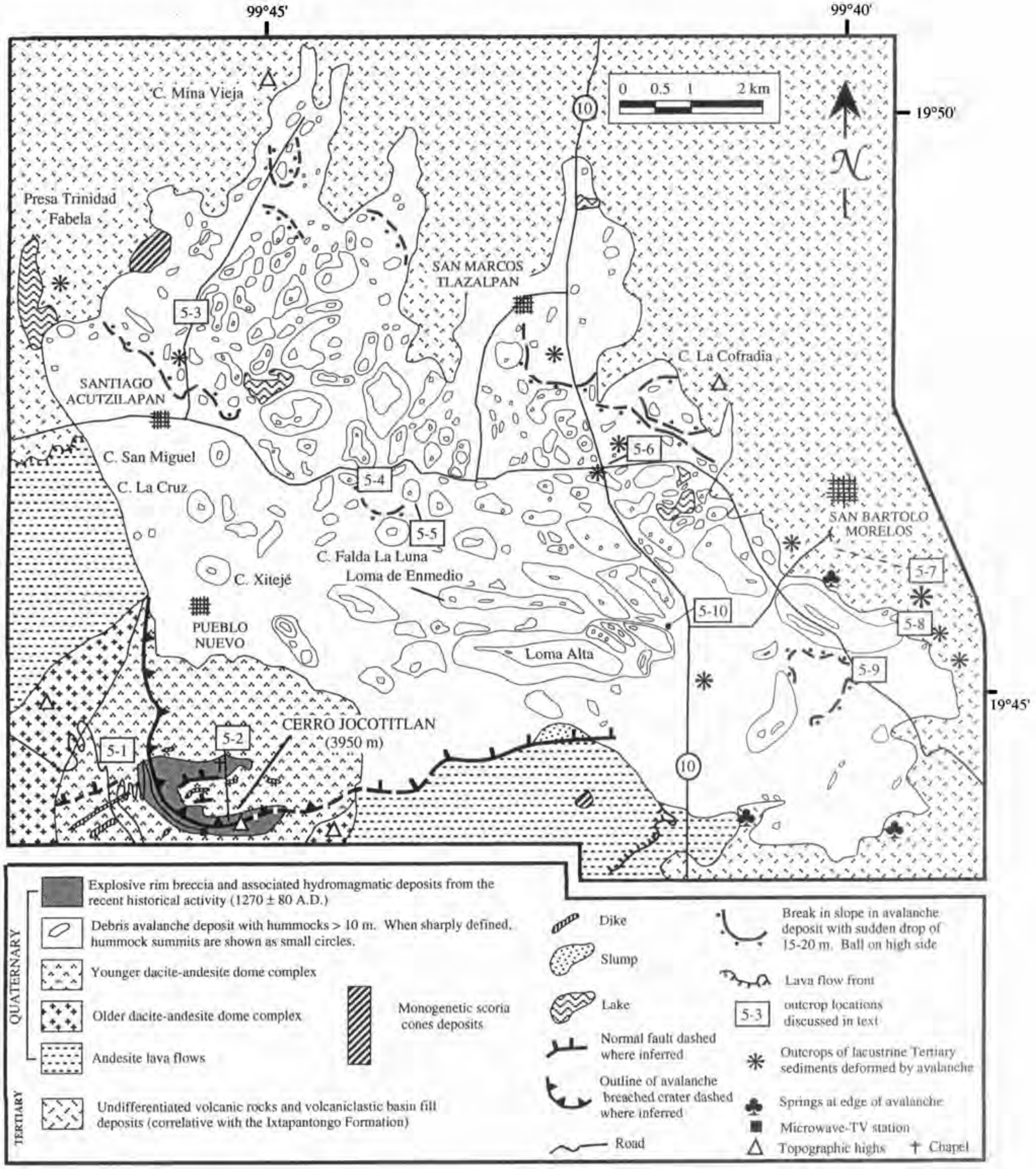

Figure 29. Map of Jocotitlán volcano and debris avalanche deposit (after Siebe et al., 1992).

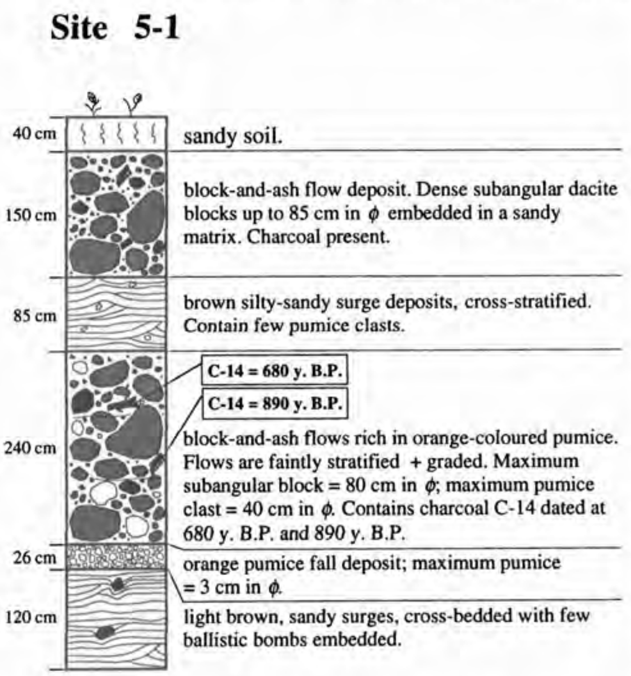

Figure 30. Stratigraphic column of outcrop at site 5-1 to be visited during Day 5. The outcrop is located on the southern upper slopes of Jocotitlán volcano, where the youngest pyroclastic deposits are best displayed (see also Fig. 31).

*Figure 31. Sequence of deposits at site 5-1 produced in Pre-Columbian time from which charcoal was obtained for radiometric dating. Charcoal bearing block-and-ash flow deposit **B**, pumice fall **P**, and surge deposits **S**, are best displayed at this location (see also Fig. 30).*

Site 5-5 provides a good view of a conical hummock located 300 m to the southeast of Site 5-4.

93.8 **Stop 5-5.**
The conical hills, in general, consist of huge piles of large clasts and blocks (1 to 10 m in diameter) apparently cored by megablocks (10 to 20 m in diameter). No feature of this DAD is more striking and invites more speculation than the remarkable conicity of its hummocks. Their steep slopes are caused by the accumulation of angular coarse material at the angle of repose surrounding the core. Therefore, the conical shape of the large hummocks is regarded as a primary transportation feature rather than the result of erosion. Farther away from the source, the hills become smaller and less conical, due to continuous fragmentation and longer travel distance.

Site 5-6 (Fig. 29) is located at the junction with Highway 10 to Ixtlahuaca to the south and Jilotepec to the north.

97.0 **Stop 5-6. (N19°47′07″; W99°42′08″)**
At this site a small window exposes pre-avalanche volcaniclastic, fluvial, and lacustrine deposits. They consist mostly of a sequence of finely to coarsely laminated layers of water-laid material of volcanic origin, such as pumice, obsidian, and lava clasts. The rocks have been tilted and faulted due to differential loading during and after deposition of the debris-avalanche. The amount of deformation suggests a tectonic origin; however, it was the friability, porosity, and water content of these deposits that made them especially susceptible to load deformation from the avalanche deposit (Fig. 33).

Continue east, past the junction with Highway 10, until the next intersection, where you turn left to San Bartolo Morelos. Turn right after approximately 1.5 km and drive 2 km on an unpaved road towards the quarried hills to the east.

Figure 32. Jocotitlán volcano as seen from Site 5-3 looking south. In the foreground are the conical hummocks Cerro San Miguel, Cerro La Cruz, and Cerro Xitejé.

105.0 **Stop 5-7. (N19°46′22″; W99°39′30″)**

This outcrop (Fig. 29) is located in one of these sand quarries where several splendid outcrops of intensively folded and faulted fluvial and lacustrine deposits can be observed (Fig. 34). Originally horizontally water-laid, light-colored, coarse pumice-rich layers alternate with dark-gray, sand-sized ash layers that are now folded and faulted in a chaotic pattern. The soft and friable sedimentary layers are older than the DAD. They acted as a topographic high which was impacted and shortened horizontally by the DAD causing intensive folding and faulting. The intensity of deformation of the soft lacustrine sediments at several localities indicates that the mass of the debris-avalanche moved coherently and was capable of transmitting a substantial part of its momentum to a sedimentary pile several decameters thick. The lacustrine sediments below and in front of the propagating debris-avalanche were deformed by thrusting and folding. Gravitational loading most likely caused subsequent normal faults which cross-cut the thrust planes. Differential deformation of coarse pumice-rich layers and dark fine ash layers was related to their different water content and grain size.

106.0 **Stop 5-8.**

The marginal scarp of the DAD is well exposed at Site 5-8 (Fig. 29). At this locality, the stratigraphic relationship between the distal margin of the DAD and the underlying lacustrine deposits is best shown. The marginal scarp is up to 50 m high with slope angles up to 30° (Fig. 35). The steepness of the marginal scarp indicates that the moving mass became suddenly rigid implying flowage at high shear stress as described by Hsü (1975) and Davies (1982). The occurrence of small hummocks as well as large blocks embedded in the lacustrine sediments beyond the marginal scarp indicate that the avalanche was "spraying out" at its front during emplacement. Deceleration of the main avalanche body was evidently sudden, but some blocks on top, which were bouncing more freely, continued moving further due to inertia, and impacted and disrupted the lake deposits beyond the marginal scarp.

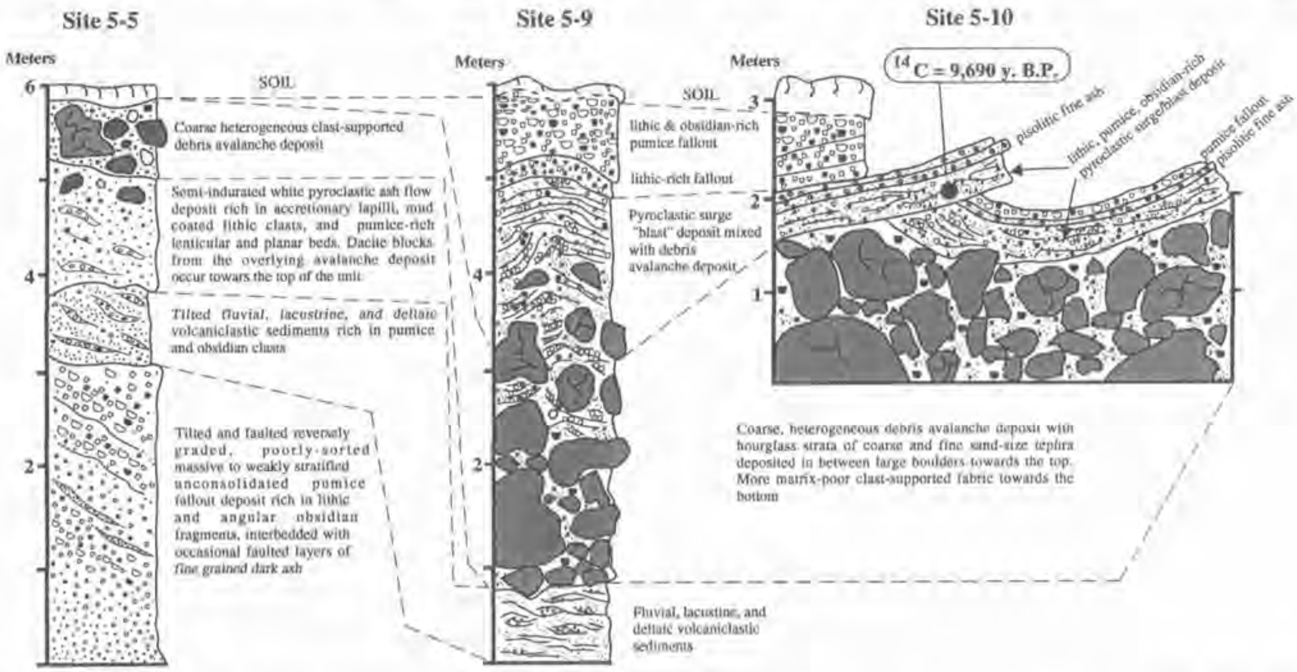

Figure 33. Stratigraphic columns and correlation of older pyroclastic units below and contemporaneous surge deposits above the debris avalanche deposit at Sites 5-5, 5-9, and 5-10. (After Siebe et al., 1992).

111.0 **Stop 5-9. (N19°46′03″; W99°39′48″)**

Site 5-9 (Fig. 29) shows a stratigraphic section of pyroclastic deposits associated with the emplacement of the DAD at a roadcut 1.0 km southwest of Site 5-8. Scarce outcrops of pyroclastic deposits with a maximum thickness of 3 m occur directly above the DAD in the marginal areas of the eastern sector of the DAD (Fig. 33). In the lower part of the pyroclastic unit, the alternating coarse-grained pumice-rich layers and fine-grained lithic layers are characterized by an hour-glass stratification which resulted from their deposition between large blocks of dacitic lavas protruding from the irregular surface of the DAD (Fig. 33). The field characteristics of this entire unit are compatible with an emplacement by a pyroclastic surge above the bouldery surface of the DAD, most probably by turbulent tephra-ladden clouds moving down valleys away from the volcano. Although the lower pyroclastic surge unit has few textural similarities with the May 18, 1980 Mt. St. Helens "blast" deposit (Hoblitt et al., 1981; Waitt, 1981), we believe that the entire sequence, including the pumice fall unit, represents the products of explosive activity that was contemporaneous with or that shortly followed the emplacement of the DAD.

From site 5-9 drive to the junction with highway 10. Drive 200 m north, park the car and walk 5 minutes to site 5-10 at the base of elongated ridge Loma Alta (Fig. 29).

116.0 **Stop 5-10. (N19°45′46″; W99°41′31″)**

This exposure also shows a stratigraphic section of pyroclastic deposits associated with the emplacement of the DAD. Ash and surge layers on top of the DAD form a laminated sequence characterized by dune structures and U-shaped channels that can be correlated with the deposits at site 5-9 (Fig. 33).

232.0 From site 5-10 return to highway 10 and drive southwards. After 23 km reach highway 55 and turn left in the direction of Toluca. Drive to Toluca (43 km) and from here continue to Mexico City (50 km).

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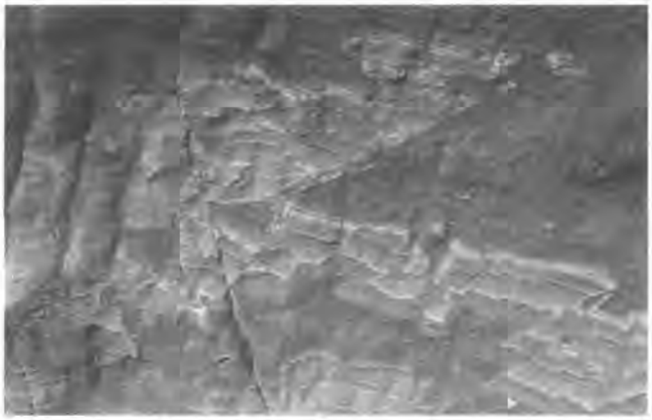

Figure 34. Strongly folded and faulted lacustrine deposits at Site 5-7. Arrow points at Swiss Army knife for scale.

Figure 35. View of terminal scarp (ca. 50 m thick, upper right corner) of the debris-avalanche deposit about 12 km from the source at location 5-8. Towards the upper left is a small erratic hummock (vegetated by trees) that went beyond the main margin of the avalanche. The hummock consists of very large boulders and lies on top of deformed fluvio-lacustrine deposits. Arrow points at person for scale.

support. Satellite imagery was provided by M. Abrams from the Jet Propulsion Laboratory, NASA. Digital topography was provided by F. Aceves. A short course on pyroclastic rocks organized by Ing. Labarte as well as the 1997 IAVCEI field trip to the volcano were a significant platform to discuss several aspects of stratigraphy with a large group of experimented volcanologists. C-14 dates presented in this guide were carried out by Chris Eastoe and A. Long at the University of Arizona in Tucson. Chemical analyses of the younger Toluca products were performed at LTD Laboratories, Ontario, Canada. This study was financed by the Consejo Nacional de Ciencia y Tecnología (CONACYT 0179P-T9506) and DGAPA, UNAM (IN107196) grants.

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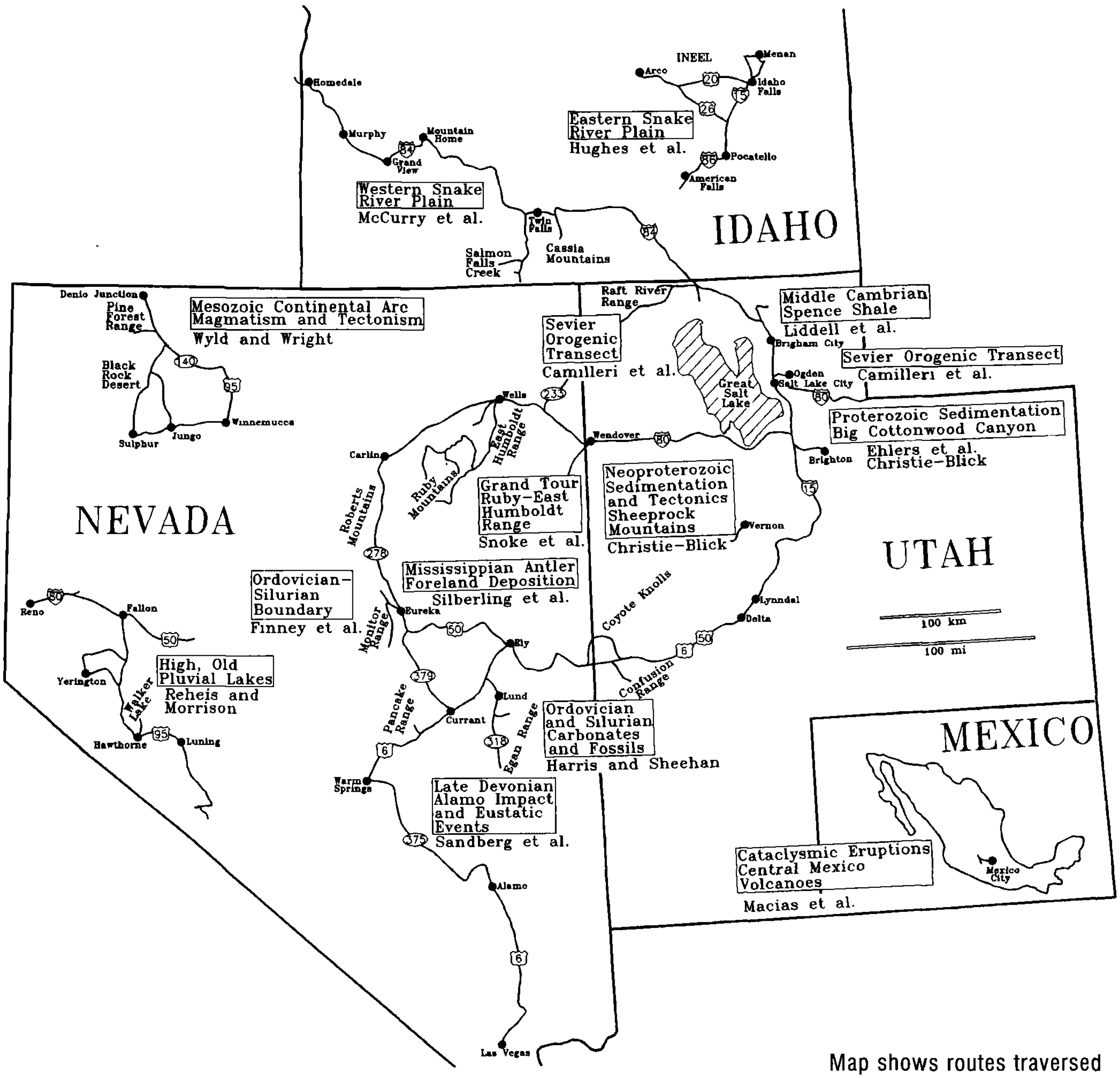
PART ONE

PROTEROZOIC TO RECENT STRATIGRAPHY, TECTONICS AND VOLCANOLOGY: UTAH, NEVADA, SOUTHERN IDAHO AND CENTRAL MEXICO



Map shows routes traversed by field trips in this volume.