# Geology of Las Cumbres Volcanic Complex, Puebla and Veracruz states, Mexico

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**ABSTRACT**

*Las Cumbres Volcanic Complex (LCVC) is part of a nearly NE–SW aligned volcanic range formed by the Cofre de Perote extinct volcano to the north, and the active Citlaltépetl volcano to the south. This volcanic range is one of the most striking morphological features in the eastern Trans-Mexican Volcanic Belt. This geological study describes the different volcanic structures and associated deposits forming the LCVC, which was built upon Cretaceous limestones and Tertiary intrusive rocks of syenitic composition. The LCVC geological map includes ten lithostratigraphic volcanic units, some of which include members representing different eruptive periods. The LCVC history has been subdivided in four stages: The first and older stage (~600 ka) consists of thick andesitic lava flows that formed the Las Cumbres stratovolcano, with an estimated volume of 200 km$^3$. The second stage (350 – 40 ka) is represented by the collapse of the east flank of the Las Cumbres stratovolcano. This eruption completely modified the morphology of the Las Cumbres volcano and produced debris avalanche and pyroclastic deposits, as well as lava flows with a minimum volume of 50 km$^3$. The third stage (40 – 20 ka), include the rhyolitic fall deposits of the Quetzalapa pumice, the debris avalanche deposits from the small flank collapse at the Sillatepec dome, and the extrusion of the dacitic Chichihuale dome. Its estimated volume is 20 km$^3$. The fourth stage (<20 ka) was dominated by intense monogenetic activity, particularly to the north of the LCVC, with scoria cones showing a regional NE–SW orientation. According to the mineralogy and chemistry of the rocks presented in this paper, processes of assimilation and contamination might have affected the LCVC magmas.*

*Key words: volcanism, volcanic complex, Trans-Mexican Volcanic Belt, volcanic stratigraphy, Veracruz, Puebla, Mexico.*

**RESUMEN**

*El Complejo Volcánico de Las Cumbres (CVLC) es parte de la cordillera volcánica formada por el extinto volcán Cofre de Perote en el norte y el volcán activo Pico de Orizaba o Citlaltépetl en el sur. Este rasgo fisiográfico es uno de los más sobresalientes en la parte oriental de la Faja Volcánica Transmexicana y constituye el parteaguas entre el Altiplano Mexicano y la Planicie Costera del Golfo. El presente estudio geológico describe las diferentes estructuras volcánicas que constituyen el CVLC, cuyo basamento está formado por calizas del Cretácico Superior, así como por rocas terciarias de composición sienítica que intrusionan a las calizas. En el mapa geológico se representan diez unidades litoestratigráficas de origen volcánico derivadas de la actividad de los diferentes centros de emisión que conforman el CVLC. La historia eruptiva del CVLC se subdivide en cuatro etapas. La primera y más antigua (~600 ka) está constituida por potentes flujos de lava de composición andesítica que formaron el estratovolcán Las Cumbres, con un volumen total de aproximadamente 200 km$^3$. Durante la segunda etapa (350 – 40 ka) ocurrió el colapso del flanco oriental del estratovolcán Las Cumbres. Este evento* *modificó completamente la morfología del volcán y produjo depósitos de avalancha, derrames de lava y depósitos piroclásticos con un volumen mínimo de 50 km³. La tercera etapa (40 – 20 ka) incluye los depósitos riolíticos de caída de la Pómez Quetzalapa, el colapso de dimensiones moderadas del flaco norte del domo Sillatepec y la extrusión del domo dacítico Chichihuale. El volumen de magma implicado durante esta etapa se estima en 20 km³. Durante la cuarta etapa (<20 ka) predominó una intensa actividad monogenética, especialmente en la porción norte del CVLC. A escala regional los conos de escoria muestran una orientación predominante de NE–SW. De acuerdo con los análisis mineralógicos y geoquímicos presentados en este artículo se infiere que ciertos procesos de asimilación y contaminación pudieron afectar a los magmas del CVLC.*

*Palabras clave: vulcanismo, complejo volcánico, Faja Volcánica Trans-Mexicana, estratigrafía volcánica, Veracruz, Puebla, México.*

## INTRODUCTION

Las Cumbres Volcanic Complex (LCVC) includes several volcanic centers of Quaternary age, located within an area of approximately 1,000 km², between the states of Puebla and Veracruz, on the eastern edge of the Trans-Mexican Volcanic Belt (TMVB). The TMVB is a continental mostly calc-alkaline province resulting from the subduction of the oceanic Cocos and Rivera plates, under the North America plate along the Middle America Trench (Ferrari, 2000) (Figure 1, inset). The LCVC is part of a volcanic range oriented in a NNE–SSW direction that constitutes the water divide between the rivers draining to the Gulf of Mexico coastal plain, as Jamapa and Huitzilapan–Pescados, and those flowing to the Serdán-Oriental closed basin in the Mexican Alatiplano (Figure 1).

The area is limited to the north by an intensely eroded volcanic structure composed mainly by andesitic and dacitic rocks first called "North and South Caldera" by Negendank *et al*. (1985), and later "La Gloria Volcanic Complex" (LGVC) by Höskuldsson and Robin (1993). In the northern end of the volcanic range is the extinct Cofre de Perote or Nahucampatépetl compound volcano (4,200 m a.s.l.), mainly of andesitic composition. Eastward of Cofre de Perote there is a younger volcanic field conformed by several well defined vents known as Las Lajas. Southward, the LCVC is limited by the active Pico de Orizaba or Citlaltépetl (5,675 m a.s.l.) and the extinct Sierra Negra (4,500 m a.s.l.) stratovolcanoes, both composed manly by andesitic rocks (Carrasco-Núñez and Ban, 1994; Carrasco-Núñez, 2000). The LCVC is limited to the west by the lacustrine basin of Serdán–Oriental (average altitude 2,500 m a.s.l.). Within this basin several volcanic vents occur, such as large rhyolitic domes, small cinder cones, and explosion craters locally named *xalapazcos* in Nahuatl language (Ordóñez, 1905, 1906; Siebe, 1986). Farther northwest of the LCVC is located Los Humeros caldera, whose pyroclastic flow and fall deposits are widely distribuited in the region (Ferríz and Mahood, 1984).

The purposes of this study are to provide new geological and geochemical data of the LCVC and to suggest a model for its volcanic evolution. The geological map of Figure 2 shows the spatial distribution of the different identified units. Additionally two structural sections (Figure 3) show the most important stratigraphical relations in the area.

## REGIONAL GEOLOGY

The LCVC is built upon limestones and shales of Cretaceous age (INEGI, 2002; Yánez-García and García Durán, 1982). The regional trend of the rocks shows a predominant NW–SE direction which suggests approximately perpendicular compressive forces. In the Altiplano, the limestones form small ranges that emerge from the lake basin of Serdán–Oriental with a horst and graben geometry resulting from a tensional regime. To the east and southeast of the LCVC, these rocks form abrupt mountain ranges which display anticlines and synclines with NW–SE axes (Figure 1). The sedimentary basement is affected by intense faulting and fracturing with predominant NW–SE, NE–SW and E–W trends (Yánez-García and García Durán, 1982; INEGI, 2002).

Cretaceous limestones are intruded by NE–SW striking dikes composed by middle Oligocene rocks of syenitic, aplitic and granodioritic composition (Yáñez-García and Casique-Vásquez, 1980). The intrusive rocks produced marble and mineralized bodies with small concentrations of gold, silver and zinc that were quarried during the XVIII and XIX centuries at a mine located beside the explosion crater called La Preciosa (Figure 1)

La Gloria Volcanic Complex (northward of the LCVC) is conformed by the remnants of a major collapsed stratovolcano consisting of andesitic and dacitic lavas, as well as pyroclastic products that were spread out mainly eastward. This complex is part of the pre-Las Cumbres volcanic basement (Figure 1).

The rocks forming the LCVC are affected by NE–SW and E–W regional faults, which in part might still be active as indicated by evidences documented from the 1920 Jalapa earthquake (Comisiones del Instituto Geológico de México, 1922; Singh *et al*., 1984; Suter *et al*. 1996, 2002).

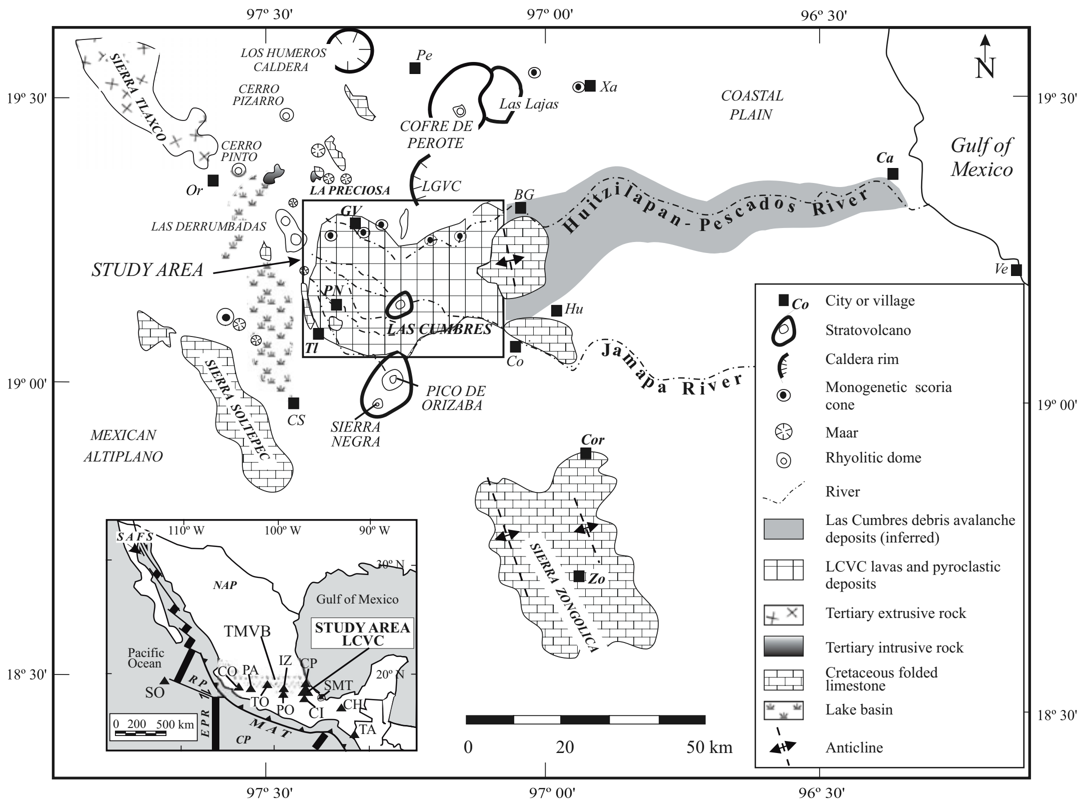


Figure 1. Regional map showing the location and the main geological features of the studied area. Inset shows the tectonic framework of Mexico. Tl: Tlachichuca, PN: Paso Nacional, GV: Guadalupe Victoria, Or: Oriental, BG: Barranca Grande, Pe: Perote, Xa: Xalapa, Ca:Cardel, Ve: Veracruz, Hu: Huatusco, Cor: Córdoba, Zo: Zongolica, Co: Coscomatepec, CS: Ciudad Serdán. LGVC: La Gloria Volcanic Complex, NAP: North American Plate, RP: Rivera Plate, CP: Cocos Plate, EPR: East Pacific Rise, MAT: Middle America Trench, SAFS: San Andreas Fault System, TMBV: Trans-Mexican Volcanic Belt, CO: Colima volcano, PA: Parícutin, TO: Nevado de Toluca, PO: Popocatépetl volcano, IZ: Iztaccíhuatl volcano, CP: Cofre de Perote, CI: Citlaltépetl volcano, SMT: San Martín Tuxtla volcano, TA: Tacaná volcano, CH: Chichón volcano, SO: Socorro. (Modified after Rodríguez *et al.*, 2002 and Hubbard, 2001).

## METHODOLOGY

Field work and interpretation of aerial photographs scale 1: 50,000, and satellite images (Tematic Maper, scale 1: 100,000) yielded the fundamental data for the geological map and the structural sections (Figures 2 and 3). The topographic data base was obtained from 1:50,000 scale topographic maps edited by the Instituto Nacional de Estadística Geografía e Informática (INEGI).

Mineralogical and textural analyses were carried out in 21 samples of lava and pyroclastic material with a petrographic microscope. Major and trace element analyses were obtained by XRF for ten whole rock samples at Bondar Clegg Laboratories, and for six additional samples at Laboratorio de Fluorescencia de Rayos X, Instituto de Geología, Universidad Nacional Autónoma de México.

Radiometric ages were obtained by the $^{14}C$ method in charcoal and soil samples at the University of Arizona in Tucson. The age of small charcoal samples was determined by the accelerator mass spectrometry (AMS) method. Additionally, a lava sample (CIT-9924) was dated by the $^{40}Ar/^{39}Ar$ mehtod by Steven Ownby at the University of Michigan. The location of the analyzed samples is shown in Figure 4.

Volumes of lava flows were calculated from its maximum surface distribution and average thickness. The volume of the debris avalanche deposit was calculated estimating the missing volume of the cone.

## STRATIGRAPHY OF LAS CUMBRES VOLCANIC COMPLEX

The volcanic units proposed in this study are related to the different volcanic vents that constitute the LCVC. These are one stratovolcano, domes, explosion craters and monogenetic cones. Table 1 summarizes the most important characteristics of the principal emission centers.

The definition of the different units is based on field work, mineral and chemistry composition, textural characteristics, and mode of emplacement of the volcanic products. Figure 5 shows the composite stratigraphic column of the LCVC. Relative ages are based on field stratigraphic relations and reported K/Ar radiometric dates (Höskuldsson, 1992; Höskuldsson and Robin, 1993; Carrasco-Núñez and

Ban, 1994; Carrasco-Núñez and Rose, 1995; Carrasco-Núñez, 2000). $^{14}$C radiometric dates were obtained from charcoal and soil samples (Table 2). Figures 6 and 7 show the stratigraphic relations in the east and west side, respectively, of the LCVC at the localities mentioned in Table 2. The most important mineralogical characteristics of the units described in this section are summarized in Table 3.

## Huitzilapan andesite (Qhui)

The oldest unit of the LCVC is a lava flow of basic andesitic composition, distributed to the NE of the area (Table 1). The most important outcrops are exposed along the Huitzilapan river valley between the villages of Chilchotla and Quimixtlán (Figure 2). This unit constitutes the

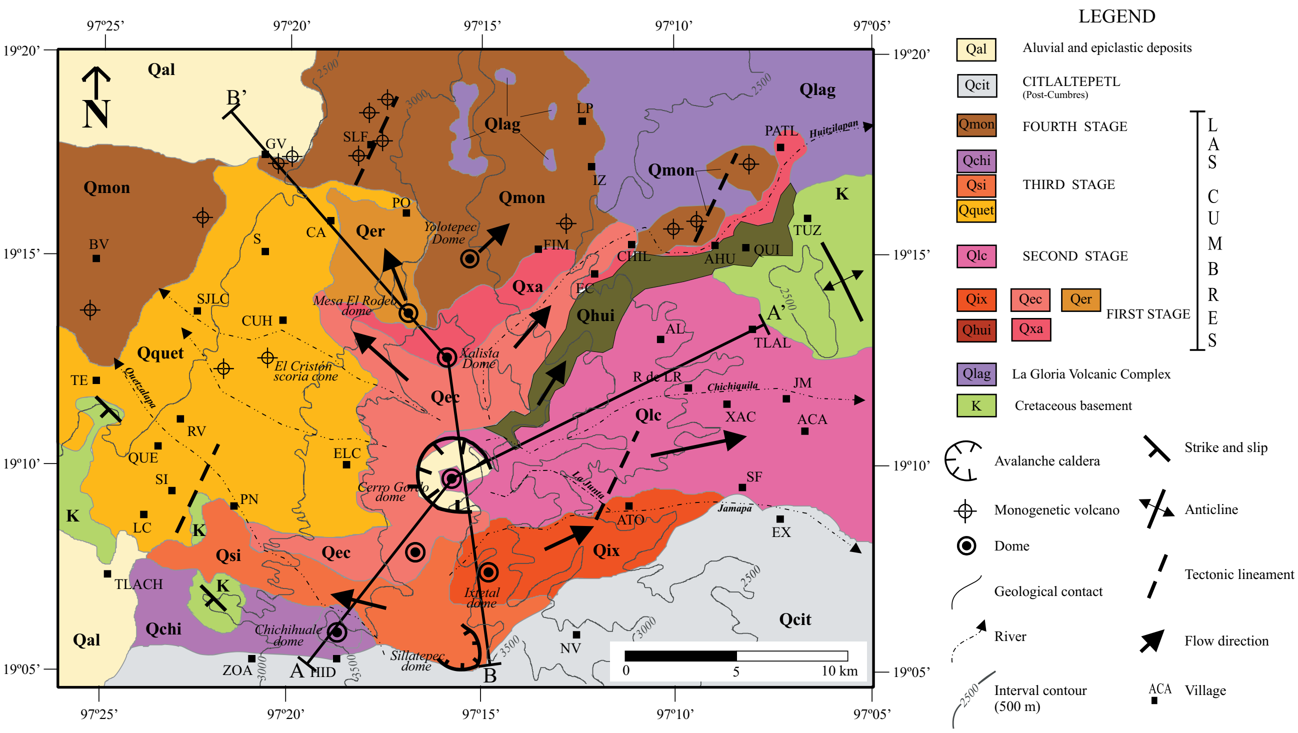


Figure 2. Geologic map of the Las Cumbres Volcanic Complex. Location of structural sections shown in Figure 3 is indicated. ACA: Acalocotla, AHU: Ahuacapan, AL: Alta Luz, ATO: Atotonilco, CA: Canoitas, CHIL: Chilchotla, CUH: Cuauhtémoc, BV: Buena Vista, ELC: El Campamento, EX: Excola, FIM: Francisco I. Madero, EC: El Cármen, GV: Guadalupe Victoria, HID: Hidalgo, IZ: Ignacio Zaragoza, JM: Jesús María, LC: Lázaro Cárdenas, LP: La Providencia, NV: Nueva Vaquería, PATL: Patlanalán, PN: Paso Nacional, PO: Pocitos, QUE: Quetzalapa, QUI: Quimixtlán, R de LR: Rincón de Los Reyes, RV: Río Valiente, S: Sabinal, SF: San Francisco, SJLC: San José La Capilla, SLF: Saltillo La Fragua, TE: Tepetitlán, TLACH: Tlachichuca, TLAL: Tlalnepantla, TUZ: Tuzihuic, XAC: Xacaxomulco, ZOA: Zoapan.

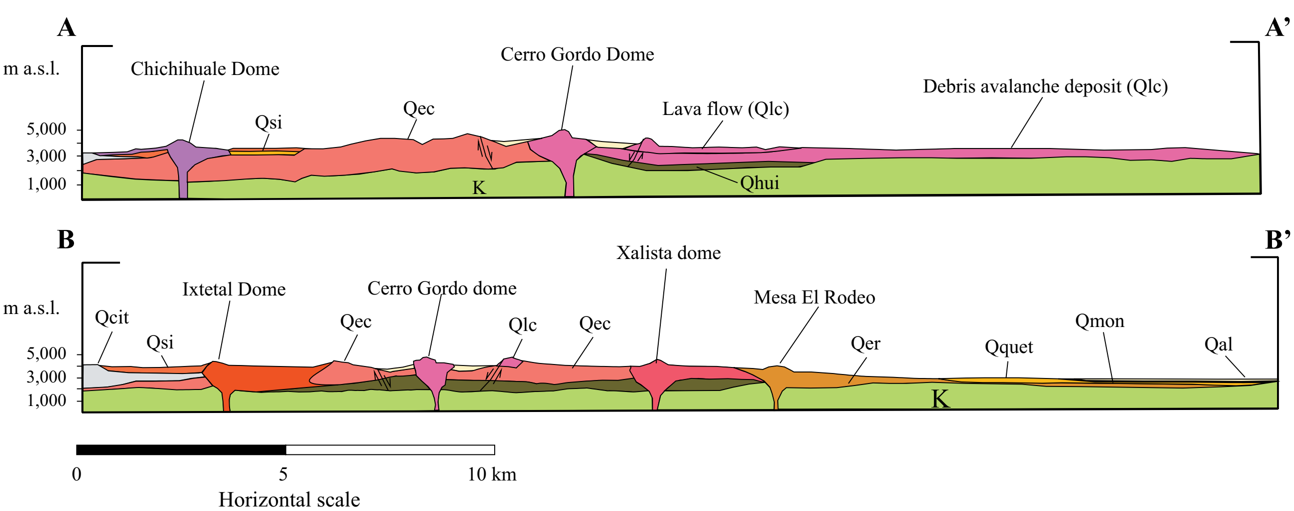


Figure 3. Structural sections from Las Cumbres Volcanic Complex. Colors of the volcanic units are the same as in Figure 2.

northeast flank of the oldest Las Cumbres volcano and, at Patlanalán section (Figure 6), it covers discordantly the La Gloria lavas and the Cretaceous limestones.

The lava flows present pseudostratification dipping towards the NE and, along the Huitzilapan valley, are profoundly furrowed by fluvial erosion. It is difficult to determine the covering area because most of this unit is covered by younger deposits, but an estimate of 100 $km^2$ is inferred. An average maximum thickness of 100 m and a volume of 10 $km^3$ is estimated for this unit. The texture of the rock is inequigranular porphyritic with abundant plagioclase phenocrysts and minor olivine and pyroxene being classified as an olivine andesite.

## Xalista andesite (Qxa)

This formation includes the volcanic products emitted by the Xalista dome (Table 1). The base of this unit is formed by massive andesitic lava flows mainly distributed to the NE. The average thickness is estimated in 50 m and the covering area is approximately 80 $km^2$. The volume of the Xalista deposits is estimated in 4 $km^3$. The base of the Xalista andesite is formed by lava flows whose most distal outcrops are found near the village of Francisco I. Madero (Figure 2). The texture of the rock is porphyritic with hornblende and plagioclase phenocrysts. The summit of the Xalista dome is formed by dikes and sills of cryptocrystalline rhyolites with a glassy matrix of fluidal aspect with presence of quartz phenocrysts and small amounts of sanidine. A highly vitiric, charcoal-rich pyroclastic ash-flow deposit, distributed mainly to the NE along the Huitzilapan valley, was dated at 44,470 ± 1,710 years B.P., which is considered a minimum age for the deposit because is almost at the limit of the $^{14}C$ method. This deposit is covered by younger scoria fall layers from proximal monogenetic volcanoes (Qmon) at Patlanalán section (Figure 6).

## El Campamento andesite (Qec)

From base to top, the El Campamento andesite is formed by a partially welded pyroclastic flow deposit 3 to 5 m in thickness with elongated and oriented clasts of basaltic-andesitic composition, embedded in a sandy matrix. The mineral composition of the clasts includes olivine and pyroxene. These deposits are distributed to the SW and form terrace-like deposits along the Quetzalapa River (Figure 2). The upper member is formed by andesitic lava flows with hornblende and plagioclase phenocrysts and minor olivine and pyroxene in the matrix. This is the most voluminous and widely distributed lava flow produced by the Las Cumbres volcano (Figure 2). In the vicinity of El Campamento village on the west flank, the 100 m thick lavas are profoundly furrowed by gorges with U-shaped morphology typical of glacial erosion. The El Campamento andesite formed the final conic structure of the ancient Las Cumbres volcano, previous to its partial collapse.

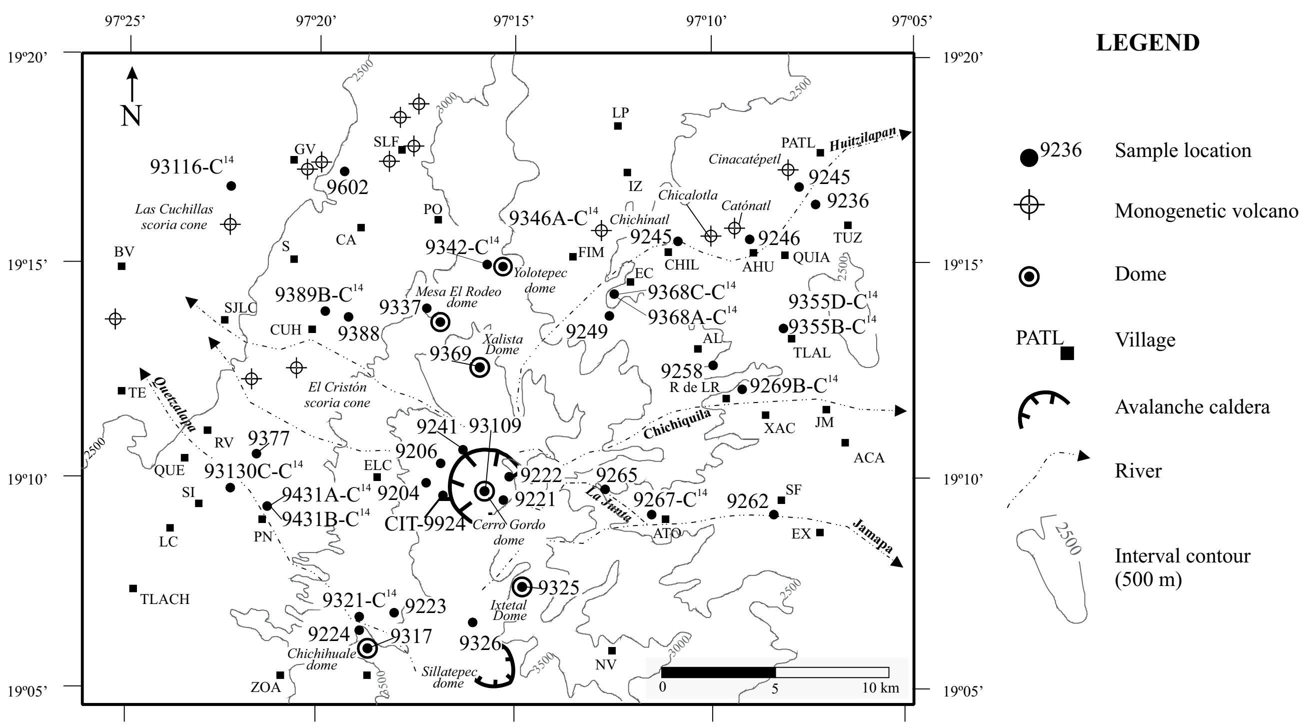


Figure 4. Map showing the location of samples included in Tables 2, 3, and 4. Villages names as in Figure 2.

Table 1. Principal characteristics of the volcanic vents at the LCVC.

| Name | Type | Morphology | Observations |
|---|---|---|---|
| **Yolotepec**<br>< 6 ka | Exogenous rhyolitic dome | Small circular structure with a plane summit, located 10 km N of the LCV.<br>Highest point 3,160 m a.s.l.<br>V ~<1 km$^3$ | Formed by rhyolitic pyroclastic flow, surge and fall deposits. One of the several monogenetic vents distributed in the north of the LCVC. |
| **Chichihuale**<br>< 23 ka | Exogenous dacitic dome | Located 9 km SW of the LCV. The dome has nearly vertical walls to the south and steep slopes to the north side. Highest point 3,680 m a.s.l. V~1 km$^3$. | Block and ash-flow deposits from Chichihuale are discordantly covering the Quetzalpa pumice deposits and the Sillatepec pyroclastic deposits. |
| **Cerro Gordo**<br>> 40 ka | Dacitic plug dome | Located in the centre of Las Cumbres crater. Vertical walls in the south and less pronounced slopes in the north. Highest point 3,940 m a.s.l. V ~2 km$^3$. | Considered as the final event of the Las Cumbres volcano. |
| **El Cristón** | Monogenetic parasitic basaltic cone | Located 6 km NW of the LCV. Eroded lava cone. Highest point 2,780 m a.s.l.<br>V ~2 km$^3$. | Mostly buried by younger pyroclastic fall and flow deposits like the Quetzalapa pumice. |
| **Sillatepec** | Andesitic dome | Located 7 km SW of the LCV. Horseshoe shaped crater open to the west. Highest point 4,060 m a.s.l.<br>V ~7 km$^3$ | The older activity, contemporaneous with the LCV, consisted on the emission of massive andesitic lava flows. During the younger activity occurred the collapse of the west flank, associated with subplinian volcanic activity (~20 ka). |
| **Ixtetal**<br>350 ka<br>(Höskuldsson, 1992) | Dacitic-rhyolitic exogenous dome | Steep summit walls. Small collapse to the NE. Highest point 3,780 m a.s.l. V ~10 km$^3$. Quarried during the pre-Colombian epoch. | Dacites and rhyolites at the base and outer zones of the dome. Obsidian intrusions at the summit and pyroclastic flow deposits to the NE. |
| **El Rodeo**<br>< 600 ka | Rhyolitic exogenous dome. | Located 8 km NW of the LCV. Flat summit dome. Highest point 3,300 ma.s.l.<br>V ~5 km$^3$. | Highly vitiric rhyolite with obsidian intrusions on the summit. Restricted ash-flow deposits to the north. |
| **Xalista**<br>< 600 ka | Dacitic-rhyolitic exogenous dome | Located 5 km north of the LCV. Small collapse to the NE. Highest point 3,860 m a.s.l.<br>V ~6 km$^3$ | Dacitic lava flows at the base and obsidian intrusions at the summit. Obsidian rich ash-flow deposits along the Huitzilapan valley. |
| **Las Cumbres volcano (LCV)**<br>< 600 ka | Andesitic effusive stratovolcano. | 4 km diameter circular crater. Rim mean altitudes 3,850 m a.s.l. (west), and 3,500 m a.s.l. (east). V ~200 km$^3$. | Collapse of the east flank partially destroyed the edifice, opening a horse-shaped crater, closed later by a fissural lava flow directed to the east. |

This unit is part of the eroded rim around the central crater of the Las Cumbres volcano (Figure 2) and has an estimated volume of 150 km$^3$. A sample of this andesite (CIT-9924), collected at the western rim of Las Cumbres, was dated by the Ar/Ar method yielding an age of 0.365 ± 0.015 Ma (M. Sheridan, written communication). In the most distal outcrops, toward the lower western flanks, this unit is covered discordantly by younger pyroclastic flow and fall deposits at section Cuauhtémoc (Figure 7).

## El Rodeo rhyolite (Qer)

The deposits issued by the El Rodeo dome (Table 1) have a restricted distribution (Figure 2). This unit consists mainly of massive, cryptocrystalline viscous rhyolitic lava with abundant opaque black obsidian. The estimated volume of magma associated to the El Rodeo dome is 5 km$^3$.

Block-and ash-flow deposits related with the final stages of activity cover the northern flanks of El Rodeo. These deposits have an average thickness of 2m and consist of angular to subrounded rhyolite blocks with obsidian clasts in a sandy matrix. The stratigraphic relations observed in the field suggest that the El Rodeo dome may be contemporaneous with the emplacement of the El Campamento andesite.

## Ixtetal rhyolite (Qix)

This unit consists of a light beige colored rhyolite, aphanitic in texture with few phenocrysts of amphibole, quartz and sanidine, which contains dikes and sills of cryptocrystalline rhyolite and dark brown, translucent obsidian with low water content. Ignimbrite-like deposits associated with the emplacement of this dome can be observed in the Jamapa valley, near the village of Atotonilco (Figure 2). The deposits are composed of obsidian and rhyolite fragments contained in a vitric matrix with an average thickness of 10 m. The volume is estimated to be 10 km$^3$.

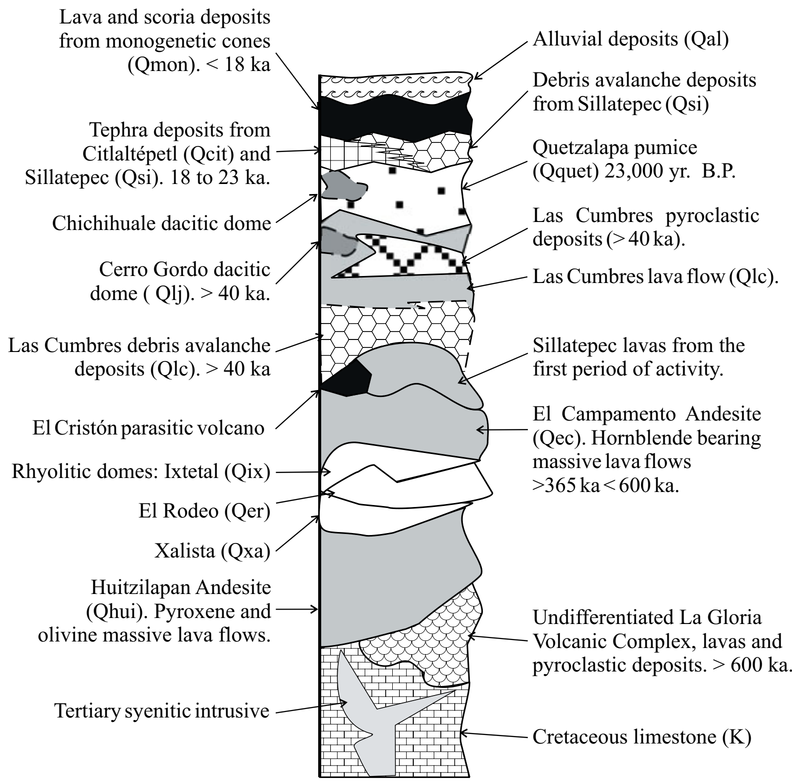


Figure 5. Composite stratigraphic column of Las Cumbres Volcanic Complex.

The stratigraphic relations observed in the field suggest that the Ixtetal rhyolite may be contemporaneous with the El Campamento andesite, because the andesitic lava flows were constrained by the Ixtetal dome. For this unit, a K/Ar date of 0.35 ± 0.06 Ma was reported by Höskuldsson (1992).

## El Cristón basalt (Qcr)

Deposits belonging to this unit cannot be mapped because they are covered by fall deposits of the Quetzalapa pumice (Figure 2). Massive basaltic lavas can be observed only on the walls of the adjacent gorges. The rocks are aphanitic with microphenocrysts of olivine and plagioclase. The age of the El Cristón lavas is uncertain, but since they rest discordantly over the El Campamento andesite and are cover by the Quetzalapa pumice deposits, should be younger than 300 ka and older than 25 ka.

## Las Cumbres formation (Qlc)

This unit includes the deposits formed after the partial collapse of the east flank of the Las Cumbres volcano (Table 1). It groups a sequence of debris avalanche, lava flows, pyroclastic fall and flow deposits and the Cerro Gordo dacitic dome (Table 1). The latter is located in the centre of the Las Cumbres crater (Figure 8).

The base of this unit consists of a heterolithologic debris avalanche deposit produced by the partial collapse of the east flank of the Las Cumbres volcano. In the proximal zones near the Atotonilco village, it contains boulder-sized clasts with jigsaw-fractures. The avalanche deposit has an estimated thickness of 150 m and covers discordantly the Huitzilapan and El Campamento andesite lavas. Hubbard (2001) estimated a volume for the missing part of the Las Cumbres volcano in >8.1 x $10^{10}$ $m^3$ (~80 $km^3$) which is probably overestimated. On the basis of its surface distribution, a volume of 40 $km^3$ for the Las Cumbres debris avalanche deposit is considered more realistic. Distal facies of this member can be observed along the course of Los Pescados River, farther out of the study area (Scuderi *et al*., 2001).

To the E and NE of the Las Cumbres volcano, the avalanche deposits are cover by pyroclastic fall and flow deposits with paleosoil beds. In the proximal areas, a lava flow covers the avalanche deposits. The lavas are phorphyritc andesites with inequigranular texture; the predominant mafic minerals are pyroxenes and in minor quantities olivine and biotite. Some outcrops located near to the source show incipient sericitic alteration. The pyroclastic flow and fall deposits and the lava flows constitute the upper members of this unit, an estimate of the volume of magma implicated is 40 $km^3$, which makes a total volume for the Las Cumbres formation of 80 $km^3$.

The most complete proximal outcrops of the unit are exposed along the La Junta and Chichiquila gorges and in

Table 2. $^{14}C$ dates for the Las Cumbres Volcanic Complex.

| Sample number | Locality | Unit | Material | Laboratory number | Age years B.P. | $\delta^{13}C_{PDB}$ ‰ | Author |
|---|---|---|---|---|---|---|---|
| CUM-93116 | Las Cuchillas | Qmon | Charcoal | A-7582 | 1,965 ± 85 | -22.4 | This study |
| CUM9346A | Chichinatl | Qmon | Charcoal | A-7431 | 3,140 ± 67 | -24.2 | This study |
| CUM-9321C | Chichihuale | Qmon | Charcoal | A-7428 | 4,990 ± 55 | -24.6 | This study |
| CUM-9342 | Yolotepec | Qmon | Charcoal | A-7430 | 5,860 ± 60 | -24.6 | This study |
| CUM-9267 | Atotonilco | Qcit | Charcoal | A-6875 | 12,800 ±315 | -25.4 | This study |
| CUM-9368C | El Carmen | Qsi | Paleosoil | A-7424 | 18,170 ± 190 | -24.4 | This study |
| CUM-93130C | Paso Nacional | Qsi | Soil | A-7584 | 18,335 +255/-245 | -24.2 | Rodríguez *et al.* (2002) |
| CUM-9355B | Tlalnepantla | Qsi | Paleosoil | A-7425 | 18,550 ± 130 | -24.4 | This study |
| CUM-9431B | Paso Nacional | Qsi | Charcoal | AA-15029 | 19,455 ± 180 | -24.6 | Rodríguez *et al.* (2002) |
| CUM-9431A | Paso Nacional | Qquet | Charcoal | AA-15028 | 20,680 ± 235 | -24.5 | Rodríguez *et al.* (2002) |
| CUM-9389B | Cuauhtémoc | Qquet | Charcoal | A-7581 | 22,935 +1,505/- 1,265 | -29.5 | Rodríguez *et al.* (2002) |
| CUM-9269B | R. de los Reyes | Qlc | | A-6877 | 37,580 +13,500/-4,780 | -24.8 | This study |
| CUM-9355D | Tlalnepantla | Qlc | Charcoal | A-7427 | 39,720 ± 1,685 | -25.9 | This study |
| CUM-9368A | El Carmen | Qlc | Charcoal | A-7423 | 40,020 ± 3,115 | -26.5 | This study |
| CUM9350* | Patlanalán | Qxa | Charcoal | n.a | 44, 470 ± 1,710 | n.a. | This study |

* Kevin Scott, written communication. This date is considered as a minimum age because it is in the limit of the $^{14}C$ method.

the vicinity of the village of Tlalnepantla, E and NE of the Las Cumbres volcano respectively (Figure 2).

The younger member of this unit is the Cerro Gordo dacitic dome, in the central part of the Las Cumbres crater (Figure 8). The mineralogical assemblage of the Cerro Gordo dacite includes phenocrysts of quartz, biotite, amphiboles and xenocrysts of olivine with reaction borders (Figure 9).

The $^{14}C$ ages obtained from soil and charcoal samples (Table 2) collected in the eastern pyroclastic sequences (Figure 6), are older than 40,000 yr. B.P., which is considered to be a minimum age for the Las Cumbres debris avalanche deposits.

## Sillatepec andesite (Qsi)

This unit is related to the Sillatepec dome activity and consists of andesitic lava flows, debris avalanche deposits and pyroclastic flow and fall deposits. The lower member of this unit consists of massive andesitic lava flows with an average thickness of 100 m, which constitute the former Sillatepec volcano. The lavas are light gray, porphyritic andesites with 2 to 3 mm-sized hornblende phenocrysts. The lava flows were clearly constrained by the topography and cover discordantly the El Campamento andesite and the Ixtetal rhyolite (Figure 2). This first stage of the Sillatepec dome was mainly effusive.

Avalanche deposits from Sillatepec are distributed along the valley of the Quetzalapa river; these are covered by hornblende bearing pyroclastic fall and flow deposits that constitute the younger members of this unit. The estimated maximum volume for the debris avalanche deposit is 0.5 $km^3$, considering a similar missing volume at Sillatepec dome.

Two radiocarbon dates were obtained from charcoal found inside the pyroclastic flow deposits at the Paso Nacional village (Figures 4 and 7), yielding ages of 19,455 ± 180 and 18,335 ± 255 yr. B.P., which are related to the last eruptive period of Sillatepec.

## Quetzalapa pumice (Qquet)

Different outcrops of this unit can be found on the west flank of the LCVC and in the lacustrine basin of Serdán–Oriental. The unit consists of a thick sequence of pumice fall deposits of rhyolitic composition, which are well sorted, clast supported with reverse grading at the base, and have a medium to high accessory lithics content. The Quetzalapa pumice fall deposit is clearly distinguishable because of the abundance of biotite macrophenocrysts embedded in a highly vesicular glassy matrix. The maximum average thickness of the deposit in the proximal areas is about 15m. A detailed description of this deposit was made by Rodriguez *et al.* (2002).

An average date of 23,000 years B.P. for the Quetzalapa pumice fall deposits (Rodríguez *et al*., 2002) seems to be in accordance with the erosional contact relations of this unit with the Sillatepec debris avalanche deposits along the Quetzalapa valley.

## Chichihuale dacite (Qchi)

This unit was produced by the activity of the Chichihuale dome and consists of viscous dacitic lava and block and ash-flow deposits at the base. The lava consists of an inequigranular porphyritic dacite with plagioclase, quartz, biotite and clinopyroxene phenocrysts embedded in a matrix of aligned quartz and plagioclase microphenocrysts. Block and ash-flow deposits associated with the emplacement of the dome crop out along the gorges on the west flank, where they cover discordantly the Quetzalapa pumice fall deposits at section Chichihuale (Figure 7). The distal facies of the flow deposits from Chichihuale are fine ash-flow deposits, that near the village of Tlachichuca (Figure 2) wedge over the slope of the Cretaceous limestones.

A $^{14}C$ date of 4,990 ± 55 yr. B.P was obtained from a charcoal sample found in pyroclastic deposits overlying the Chichihuale block and ash-flow deposits (Table 2 and Figure 7). This field relation suggests that the Chichihuale dacite is younger than 23,000 years B.P. and older than 5 ka.

**Monogenetic products (Qmon)**

This unit consists of monogenetic scoria cones distributed over the north part of the LCVC near the villages of Guadalupe Victoria, Saltillo La Fragua and Chilchotla (Figure 2). The lava flows are mainly olivine-bearing basalts with aligned microphenocrysts of plagioclase and iron ox-

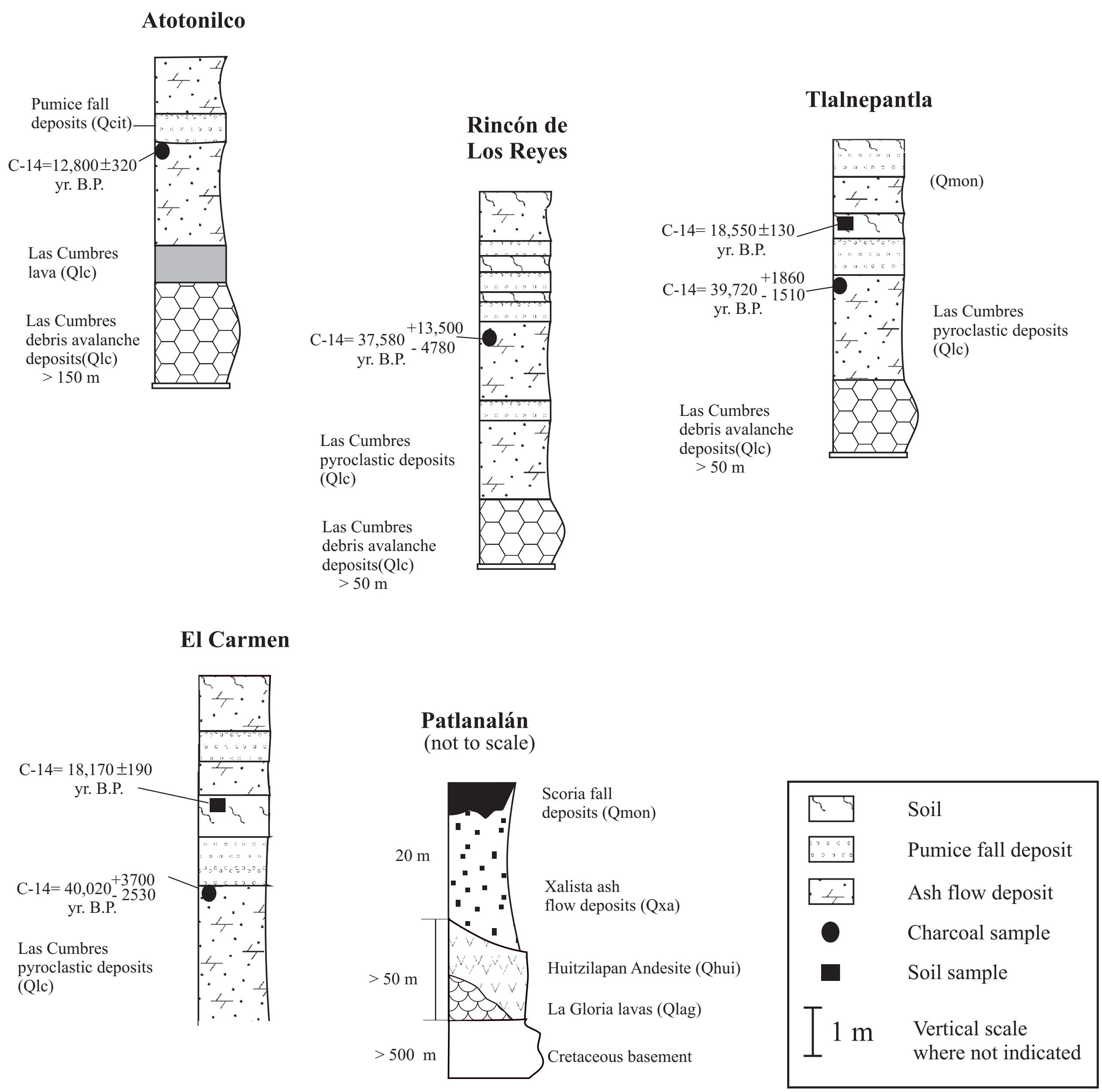


Figure 6. Stratigraphic relations in the east side of Las Cumbres Volcanic Complex.

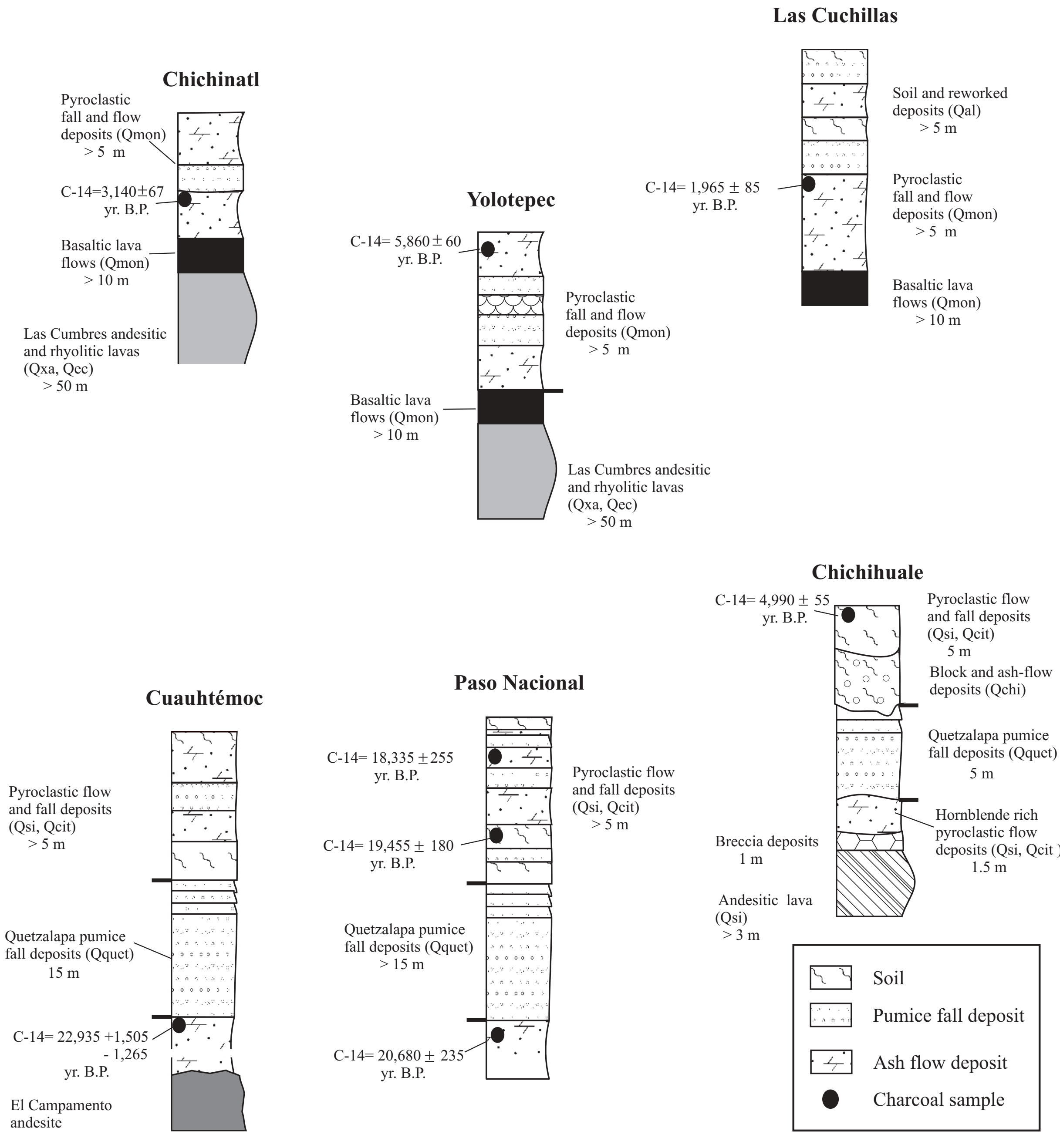


Figure 7. Stratigraphic relations in the west side of Las Cumbres Volcanic Complex.

ides in the matrix. Most of the scoria cones are subalkaline in composition (Negendank *et al*., 1985). The associated pyroclastic deposits cover discordantly the Quetzalapa pumice fall deposits. Three charcoal samples obtained from the Yolotepec tuff cone and the Chichinatl and Las Cuchillas scoria cones, yielded ages of 5,680 ± 60, 3,140 ± 67 and 1,965 ± 85 yr. B.P. (Figures 4 and 7). The charcoal is included in soils and pyroclastic flow deposits related to the activity of the tuff and scoria cones. They represent minimum ages for this unit, but they agree with the low erosion degree of the monogenetic cones.

## Citlaltépetl products (Qcit)

This unit groups the volcanic deposits produced by the activity at Citlaltépetl volcano. Detailed studies of these deposits and the different eruptive stages of Pico de Orizaba

Table 3. Petrographic analysis for selected lavas and pyroclastic materials from the LCVC. Abbreviations: qz: quartz, pl: plagioclase, fsp: feldspar, opx: orthopyroxene, cpx: clinopyroxene, am: amphibol, bt: biotite, ol: olivine, ox: oxide, gl: glass.

| **Unit** | **Locality** | **Sample nr.** | **Rock** | **Phenocysts** | | | | | | | | | **Matrix** | **Texture** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | qz | pl | fsp | opx | cpx | am | bt | ol | ox | | |
| Qmon | Cinacatépetl | CUM-9245 | Basaltic andesite | | 1 | | | 5 | <1 | | 2 | <1 | pl+ox = 90 | Porphyritic Inequigranular. Trachytic matrix. |
| Qmon | Catonatl | CUM-9246 | Olivine basalt | | 5 | | 2 | 1 | | | 5 | 10 | pl+ox = 77 | Porphyritic Inequigranular. Trachytic matrix. |
| Qmon | Chilchotla | CUM-9247 | Olivine basalt | | 1 | | 2 | | | | 10 | 3 | pl = 84 | Porphyritic Inequigranular. Trachytic matrix. |
| Qchi | Chichihuale | CUM-9224 | Dacite | 5 | 20 | | 1 | 2 | | 5 | | | pl+qz = 67 | Porphyritic Inequigranular. Trachytic matrix. |
| Qchi | Chichihuale | CUM-9317 | Dacite | 3 | 20 | | 1 | 2 | | 3 | | | pl+qz = 71 | Porphyritic Inequigranular. Trachytic matrix. |
| Qquet | Quetzalapa | CUM-9377 | Rhyolitic pumice | 5 | | 5 | | | | 3 | | <1 | gl = 86 | Clastic, vesicular |
| Qquet | Cuauhtémoc | CUM-9388 | Rhyolitic pumice | 3 | | 5 | | | | 2 | | <1 | gl = 89 | Clastic, vesicular |
| Qlc | Cerro Gordo | CUM-9221 | Dacite | 3 | 20 | | 1 | 1 | 3 | 4 | 3 | 3 | pl+gl = 62 | Glomeroporphyritic |
| Qlc | Cerro Gordo | CUM-93109 | Dacite | 3 | 15 | | 1 | 1 | 5 | 5 | 3 | 2 | pl+gl = 65 | Porphyritic, seriate Trachytic matrix. |
| Qlc | Las Cumbres | CUM-9222 | Andesite | | 40 | | 1 | <1 | | | | 3 | pl+px+gl=55 | Porphyritic equigranular. |
| Qlc | La Junta | CUM-9265 | Andesite | | 30 | | 2 | 1 | <1 | | | 2 | pl+ox+gl=65 | Porphyritic equigranular. Trachytic matrix. |
| Qsi | Sillatepec | CUM-9223 | Andesite | | 40 | | 1 | 2 | | | 1 | 1 | pl+ox+gl=55 | Porphyritic Inequigranular. |
| Qsi | Sillatepec | CUM-9326 | Andesite | | 15 | | 1 | 3 | 1 | | | <1 | pl+gl = 79 | Porphyritic Inequigranular. Trachytic matrix. |
| Qix | Ixtetal | CUM-9325 | Rhyolite | 10 | | 2 | | | 1 | 1 | | <1 | gl+qz = 85 | Microcrystalline, fluidal. |
| Qec | El Campamento | CUM-9204 | Andesite | <1 | 40 | | <1 | <1 | 3 | <1 | | 2 | gl+pl = 51 | Porphyritic. Cryptocrystalline fluidal matrix |
| Qec | El Campamento | CUM-9206 | Andesite | <1 | 50 | | | 1 | 3 | 1 | 1 | 3 | gl+pl = 40 | Glomeroporphyritic. Trachytic matrix |
| Qer | El Rodeo | CUM-9337 | Rhyolite | 25 | | 2 | | | | | | | gl = 73 | Cryptocrystalline, fluidal matrix |
| Qxa | Xalista | CUM-9369 | Rhyolite | 20 | | 1 | | | | | | | gl = 79 | Cryptocrystalline |
| Qhui | Patlanalán | CUM-9236 | Basaltic andesite | | 25 | | 2 | 1 | 5 | | 1 | 1 | pl+gl = 65 | Porphyritic. Trachytic matrix. |
| Qhui | El Cármen | CUM-9249 | Basaltic andesite | | 20 | | 2 | 2 | 1 | | 2 | 1 | pl+gl = 72 | Porphyritic Inequigranular. Trachytic matrix. |
| Qhui | Alta Luz | CUM-9258 | Basaltic andesite | | 15 | | 1 | 1 | 2 | | 2 | 2 | pl+px+gl=77 | Porphyritic Inequigranular. Trachytic matrix. |

have been carried out by Robin and Cantagrel (1982), Robin *et al*. (1983), Höskuldsson (1992), Höskuldsson and Robin (1993), Siebe *et al.* (1993), Carrasco-Nuñez (1993), Carrasco-Núñez and Ban (1994), Carrasco-Núñez and Rose (1995), and Carrasco-Núñez (2000).

**Alluvial and epiclastic deposits (Qal)**

This unit is mainly distributed on the western side of the LCVC and consists of the valley infill lacustrine sediments in the Serdán–Oriental basin. The thickness of this

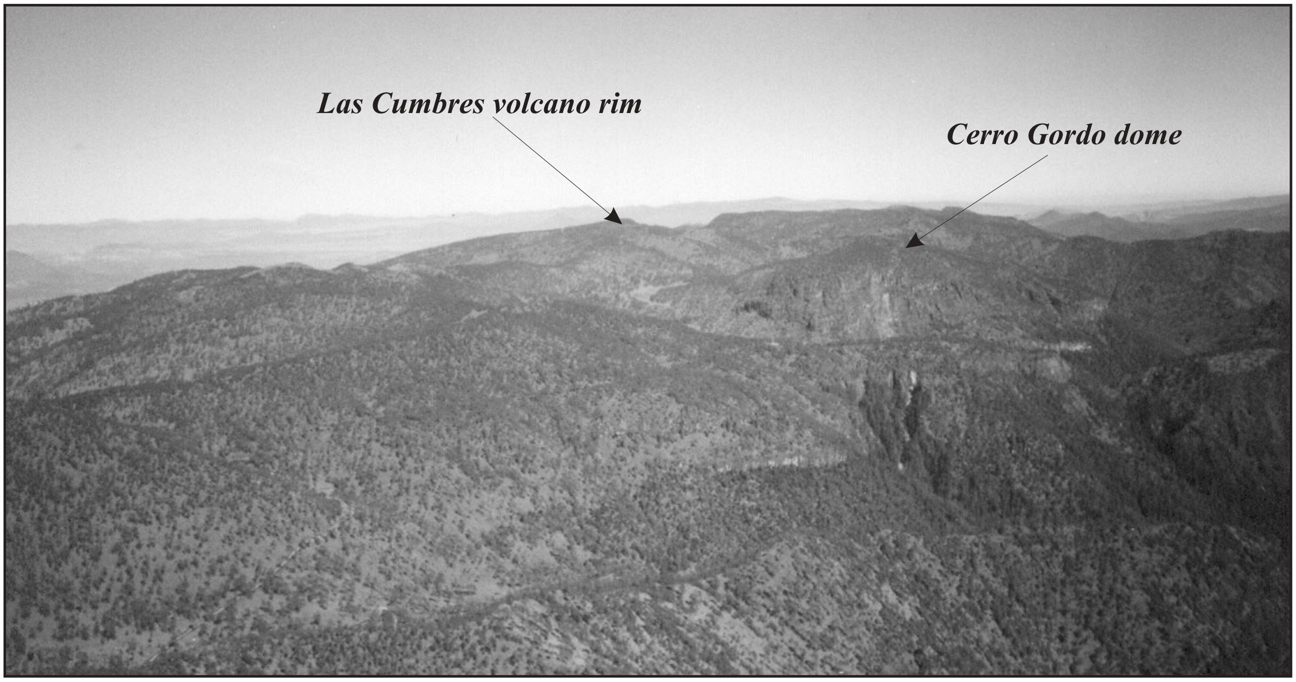


Figure 8. Photograph showing the south side of Las Cumbres volcano with the Cerro Gordo dome inside the rim.

deposit is highly variable and may be as thick as 20m. The source for this reworked material is the pyroclastic fall and flow deposits from the LCVC and Citlaltépetl volcano.

## WHOLE-ROCK CHEMICAL COMPOSITION

Twenty two chemical analysis of major and trace elements in samples from the LCVC are listed in Table 4. The table includes analysis reported by other authors in adjacent volcanic centers such as Pico de Orizaba (Carrasco-Núñez, 1993), Las Derrumbadas, Cerro Pinto, and Cofre de Perote (Negendank *et al*., 1985; Siebe and Verma, 1988).

The volcanic rocks show a medium to high potassium content in the Le Maitre (1989) classification (Figure 10). Most of the lavas and tephras have a calcalkaline affinity, although some basaltic scoria cones show a tendency to slightly alkaline compositions. The silica content of the lavas varies between 59 and 64 %, while in the pumice and obsidian samples varies between 69 and 76 % (Figure 10).

In Harker diagrmas (Figure 11), the samples show two linear trends with different slopes in the variation of elements such as $TiO_2$, $Fe_2O_3$, MgO, CaO, $Al_2O_3$ and MnO. This might be reflecting the presence of mafic phenocrysts such as olivine and pyroxene in older lavas from Las Cumbres volcano, while more evolved products such as rhyolites and dacites are characterized by the presence of biotite phenocrysts and small amounts of quartz.

In a MORB-normalized multielement digram (Figure 12), the LCVC samples show enrichment in large ion lithophile (LIL) elements such as K, Rb and Ba. This behavior is similar to other volcanic centers where the influence of crustal rocks in the chemical characteristics of the magma has been documented, as for example in the Nevado de Solimana in Peru (Vatin-Pérignon *et al.*, 1992) and the Los Encinos Volcanic Field in central Mexico (Luhr *et al*., 1995). At Los Encinos, Ba was not considered as an indicator of crustal contamination by the authors; however it is known that enrichment of this element might indicate an important influence of crustal rocks in the chemical characteristics of the magma (Lightfoot *et al*., 1991, Hildreth and Moorbath, 1988).

The lavas and tephras from the LCVC show a bimodal

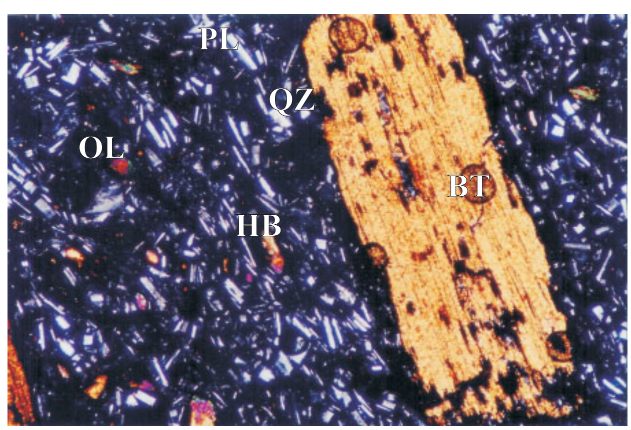


Figure 9. Microphotograph of a sample from the Cerro Gordo dacitic dome. OL: Olivine, PL: Plagioclase, QZ: Quartz, BT: Biotite, HB: Hornblende.

character that is persistent through its volcanic history. The older stages produced mainly low-silica andesites, rich in mafic minerals (Huitzilapan andesite) as well as rhyolitic domes rich in silica (Xalista, El Rodeo and Ixtetal). The intermediate stages produced more siliceous andesitic-dacitic rocks with lower content of mafic minerals (*i.e.*, the El Campamento and the La Junta andesites, and the Cerro Gordo dacite.). The younger stages are characterized by the emission of rhyolitic pyroclastic deposits (*i.e.*, Quetzalapa pumice), as well as basaltic lavas and pyroclastic deposits from monogenetic cones.

## EVOLUTION OF THE LCVC

The geological evolution of the LCVC has been divided in four different stages, which are represented in Figure 13.

First stage. Several dates have been reported for the volcanoes forming the Cofre de Perote–Citlaltépetl volcanic chain. Cantagrel and Robin (1979) reported a K/Ar age of 1.57 ± 0.05 Ma for lavas from the Cofre de Perote volcano, Höskuldsson (1992) obtained K/Ar dates between 0.9 and 0.35 Ma for some dacitic and rhyolitic domes near

Table 4. Whole rock major and selected trace elements of samples from the LCVC and surrounding volcanic centers. Major element oxide in wt. %.

| **Sample nr.** | **NT5 (**)** | **NH33 (**)** | **9342 (1)** | **9602 (2)** | **9245 (2)** | **9326 (1)** | **NH25 (**)** | **9317 (1)** | **EO33 (*)** | **9431C (1)** | **9369 (1)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | LD | CP | Qmon | Qmon | Qmon | Qsi | Qcit | Qchi | Qchi | Qquet | Qxa |
| Locality | L.D. | C. Pinto | Yolotepec | G.V. | Cinacatépetl | Sillatepec | Citlaltépetl | Chichihuale | Chichihuale | P. Nacional | Xalista |
| $SiO_2$ | 71.60 | 73.90 | 72.67 | 49.53 | 53.70 | 61.57 | 61.50 | 63.39 | 63.80 | 71.39 | 74.97 |
| $TiO_2$ | 0.15 | 0.03 | 0.21 | 1.70 | 0.91 | 0.58 | 0.68 | 0.60 | 0.58 | 0.16 | 0.11 |
| $Al_2O_3$ | 15.70 | 14.00 | 14.83 | 14.29 | 15.68 | 16.33 | 18.10 | 17.00 | 18.19 | 13.77 | 14.50 |
| $Fe_2O_3$ tot. | 2.63 | 0.77 | 0.91 | 9.14 | 9.14 | 4.49 | 5.55 | 4.75 | 4.55 | 1.15 | 0.76 |
| MnO | 0.04 | 0.14 | 0.38 | 0.77 | 0.14 | 0.08 | 0.08 | 0.08 | 0.09 | 0.07 | 0.06 |
| MgO | 0.28 | 0.09 | 0.19 | 8.13 | 4.32 | 2.07 | 2.30 | 2.08 | 1.74 | 0.32 | 0.15 |
| CaO | 1.81 | 0.49 | 1.29 | 8.09 | 6.77 | 4.54 | 5.19 | 4.82 | 4.84 | 1.08 | 0.78 |
| $Na_2O$ | 4.62 | 4.47 | 4.80 | 4.10 | 2.80 | 4.04 | 4.60 | 4.26 | 4.03 | 4.00 | 4.59 |
| $K_2O$ | 3.44 | 4.09 | 3.60 | 1.50 | 1.98 | 2.24 | 1.92 | 2.16 | 2.06 | 3.43 | 3.45 |
| $P_2O_5$ | 0.08 | 0.04 | 0.01 | 0.17 | 0.00 | 0.17 | 0.19 | 0.18 | 0.00 | 0.02 | <0.03 |
| LOI | 0.15 | 2.03 | 1.05 | 3.19 | 2.16 | 4.12 | 0.51 | 0.57 | | 4.52 | 0.25 |
| Total | 100.20 | 100.00 | 99.94 | 100.60 | 100.45 | 100.23 | 99.90 | 99.89 | 100.14 | 99.91 | 99.65 |
| ppm | | | | | | | | | | | |
| Ba | 898 | <50 | | | 536 | 765 | 693 | 815 | | 1099 | 1116 |
| Rb | 100 | 192 | | | nd | 54 | 32 | 56 | | 78 | 86 |
| Sr | 275 | 22 | | | 963 | 506 | 567 | 775 | | 174 | 155 |
| Zr | 150 | 67 | | | 151 | 207 | 149 | 190 | | 119 | 92 |
| Y | 9 | 24 | | | 23 | 20 | 20 | 13 | | 20 | 20 |

| **Sample nr.** | **9325 (1)** | **9337 (1)** | **93109 (1)** | **9222 (1)** | **9262 (2)** | **9241 (2)** | **9204 (1)** | **9249 (2)** | **9221 (2)** | **C1SP (**)** | **NT24 (**)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | Qix | Qer | Qlc | Qlc | Qlc | Qec | Qec | Qhui | Qhui | Qlg | |
| Locality | Ixtetal | El Rodeo | C.Gordo | Cumbres | SF | Cumbres | Cumbres | Cármen | Cumbres | LG | COP |
| $SiO_2$ | 75.90 | 75.76 | 62.60 | 62.18 | 61.68 | 61.42 | 63.15 | 62.01 | 57.83 | 59.90 | 62.10 |
| $TiO_2$ | 0.08 | 0.10 | 0.62 | 0.65 | 0.63 | 0.46 | 0.52 | 0.66 | 0.90 | 0.78 | 0.92 |
| $Al_2O_3$ | 13.85 | 14.02 | 16.29 | 16.18 | 15.97 | 16.42 | 16.85 | 16.22 | 16.17 | 17.40 | 16.60 |
| $Fe_2O_3$ tot. | 0.54 | 0.66 | 4.91 | 8.42 | 8.41 | 8.18 | 6.47 | 8.74 | 10.68 | 6.55 | 5.61 |
| MnO | 0.07 | 0.06 | 0.09 | 0.17 | 0.14 | 0.14 | 0.11 | 0.13 | 0.18 | 0.11 | 0.08 |
| MgO | 0.10 | 0.11 | 3.72 | 1.81 | 2.30 | 2.00 | 0.71 | 1.68 | 2.17 | 3.64 | 3.15 |
| CaO | 0.39 | 0.47 | 4.48 | 4.98 | 4.60 | 5.18 | 4.28 | 4.18 | 6.07 | 6.75 | 5.38 |
| $Na_2O$ | 4.37 | 4.55 | 3.64 | 3.00 | 2.81 | 2.82 | 3.30 | 2.90 | 3.10 | 3.46 | 3.89 |
| $K_2O$ | 4.28 | 3.90 | 2.24 | 2.40 | 3.31 | 2.82 | 2.60 | 3.10 | 2.00 | 1.37 | 2.68 |
| $P_2O_5$ | <0.03 | 0.05 | 0.15 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.22 | 0.23 |
| LOI | 0.34 | 0.29 | 1.40 | 0.91 | 0.41 | 0.86 | 1.51 | 0.71 | 0.41 | 0.24 | 0.36 |
| Total | 99.95 | 99.98 | 100.14 | 100.70 | 100.26 | 100.32 | 99.50 | 100.33 | 99.51 | 99.80 | 100.40 |
| ppm | | | | | | | | | | | |
| Ba | 764 | 973 | 754 | 530 | 564 | 454 | 470 | 564 | | 556 | 611 |
| Rb | 113 | 99 | 37 | 66 | 61 | 54 | 50 | 60 | | 27 | 74 |
| Sr | 29 | 68 | 551 | 1052 | 922 | 1132 | 1021 | 1093 | | 676 | 454 |
| Zr | 65 | 80 | 157 | 159 | 158 | 153 | 147 | 173 | | 107 | 209 |
| Y | 24 | 23 | 16 | 13 | 13 | 20 | 19 | 15 | | 24 | 22 |

Note: *: Carrasco-Núñez (1993); **: Negendank *et al.* (1985); LD: Las Derrumbadas; CP: Cerro Pinto; G.V. : Guadalupe Victoria; SF: San Francisco; LG: La Gloria; COP: Cofre de Perote; 1: This study at Bondar Clegg Laboratories; 2: This study at Instituto de Geología, UNAM. LOI: Lost on ignition.

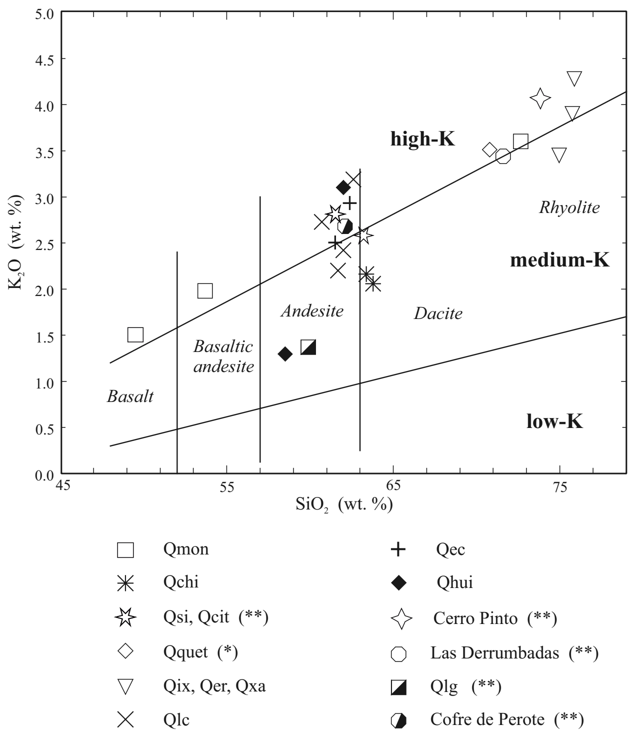


Figure 10. Si-K classification diagram for samples from the LCVC and surrounding volcanic centers (modified after Le Maitre, 1989). In the diagram are also included data from (*): Rodríguez *et al.* (2002) and (**): Negendank *et al.* (1985).

Citlaltépetl, Carrasco-Núñez (1993) suggested a maximum age of 0.6 Ma for the beginning of volcanic activity in the Citlaltépetl volcano. These dates suggest a N–S regional migration of the volcanic activity, however, there are several exceptions to this tendency.

The LCVC lavas show an evolution from low silica olivine-bearing andesites, to high silica pyroxene-hornblende bearing andesites. During this time, andesitic-rhyolitic domes, such as Xalista, Ixtetal and El Rodeo (Figures 2 and 13), were also emplaced.

Second stage. It began with the partial collapse of the eastern flank of Las Cumbres volcano. As a consequence, a horseshoe shaped structure was opened to the east, which afterwards was closed by a fissural lava flow that partially covered the debris avalanche deposits (Qlc). During this stage, the parasite cone El Cristón was emplaced on the west flank of Las Cumbres volcano. This stage ended with the emplacement of the Cerro Gordo dacitic dome inside the crater of the Las Cumbres volcano. The $^{40}Ar/^{39}Ar$ date of 0.365 ± 0.015 Ma obtained from the lava rim at Las Cumbres volcano, and the $^{14}C$ dates older than 40 ka obtained from soils and charcoal samples, constrain the age of the Las Cumbres volcano collapse.

Third stage. Three different and relevant eruptions occurred during the third stage of activity. The first one was the subplinian eruption that produced the rhyolitic Quetzalapa pumice, the second one was the partial collapse of the Sillatepec dome, and the last one the extrusion of the Chichihuale dacitic dome. According to the $^{14}C$ ages obtained for this period, the third stage occurred between 30 and 5 ka B.P.

Fourth stage. The last stage was characterized by the emplacement of at least 15 monogenetic cones located in the northern part of the LCVC, most of them of basaltic composition with the exception of the Yolotepec which is a rhyolitic tuff cone. The maximum age of the monogenetic volcanism at the LCVC is constrained by the last Sillatepec activity (18,500 years B.P). Some $^{14}C$ dates in charcoal from the Yolotepec dome area yield ages between 3,140 ±70, 4,990 ± 55 and 5,680 ± 60 y. B.P related to the last manifestations of monogenetic volcanism.

## DISCUSSION

The regional pre-Cumbres basement consists of calcareous sedimentary rocks of Cretaceous age, affected by syenitic dikes and sills. Syenites average chemical composition show intermediate contents of silica and high contents of potassium (Clark, 1989). Chemical analyses from the LCVC indicate a medium to high potassium content in most of the lavas, especially those of rhyolitic composition (Figure 10). The Harker diagrams (Figure 11) show a linear trend with two different slopes, especially in the elements MgO, $Fe_2O_3$ and $TiO_2$. Potassium and calcium show mostly a linear behavior. This suggests the influence of contamination and crustal assimilation processes between the basal rocks (rich in Ca and K) and the LCVC magmas.

The magmatic evolution model proposed for the LCVC stipulates the existence of a primary magmatic chamber of basaltic-andesitic composition. Olivine phenocrysts contained in the oldest andesite lava flows is an indication of the existence of this kind of magmas. Pre-existing rock was assimilated at the upper zones of the magmatic chamber, modifying the composition of the original magma into a magma rich in silica, potassium and calcium. These processes might occur along the first, second and third stages of the LCVC. High contents of LIL trace elements in lava samples from Las Cumbres such as K, Rb and Ba suggests a crustal contamination influence. The relations between LIL trace elements and crustal contamination processes have been fully discussed by several authors in other volcanic areas (*i.e.*, Hildreth and Moorbath 1988; De Paolo, 1981) and is not the focus of this paper.

Volcanism during the third stage of activity of the LCVC is probable related to the existence of different magma reservoirs of andesitic, dacitic and rhyolitic composition, whose best examples are the Sillatepec and Chichihuale domes, and an evolved small magma chamber composed of a high potassium rhyolitic magma, represented by the Quetzalapa pumice deposits (Rodriguez *et al.* 2002).

Basaltic monogenetic activity during the fourth stage at the LCVC, is mainly related to a deep fracture system oriented NE–SW. The 1920 earthquake along a fault zone oriented in this same direction suggests the existence of neotectonic activity in the area (Comisiones del Instituto Geológico de México, 1922; Siebe *et al*., 1993; Suter *et al*., 1996, 2002; Scott *et al*. 2001). Intersections of these fractures with other fault and fracture systems might form the volcanic conduits (Siebe *et al*., 1993).

## CONCLUSIONS

The LCVC is conformed by a stratovolcano (Las Cumbres), several rhyolitic and dacitic domes, and a small monogenetic field formed by scoria and tuff cones of basaltic and rhyolitic composition.

Ten lithostratigraphic units were mapped which represent four different volcanic stages of the formation of the LCVC. The most voluminous volcanic deposit consists largely of andesitic lava flows and debris avalanche deposits from the Las Cumbres volcano. Rhyolitic, dacitic and even andesitic dome activity produced less voluminous lava flows and pyroclastic flow and fall deposits. The closing phase of these domes was the intrusion of obsidian in dikes and sills. Finally, monogenetic activity produced basaltic scoria cones and rhyolitic tuff cones.

Geochemical and mineralogical data suggest a primary magmatic chamber of basaltic composition during the opening stages of the LCVC. Processes of crustal contamination, assimilation and differentiation, produced

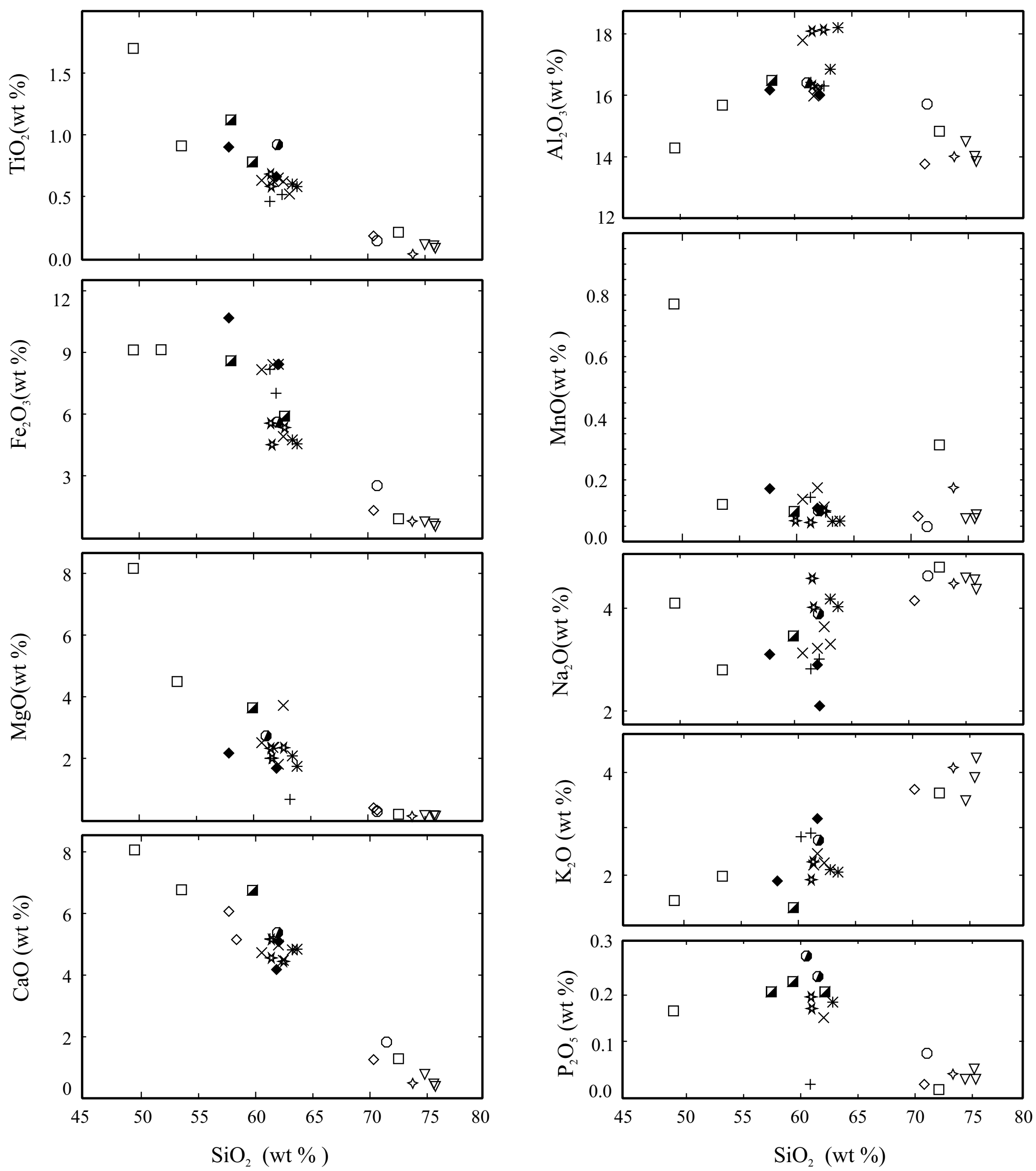


Figure 11. Harker diagrams for samples from the LCVC and surrounding volcanic centers. Key symbols as in Figure 9.

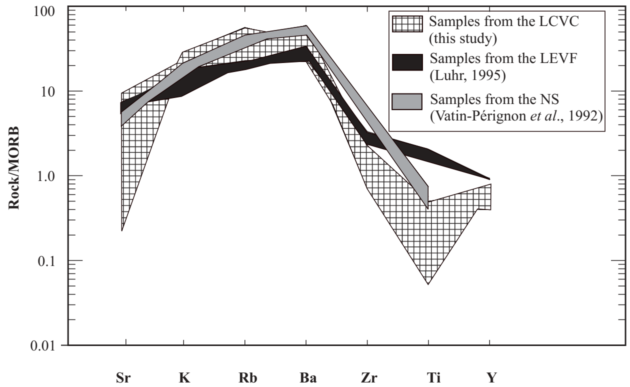


Figure 12. MORB-normalised multielement diagram for selected samples of the LCVC. Data of Los Encinos volcanic field (LEVF) of central Mexico and Nevado de Solimana (NS) in Peru are showed for comparison.

successive andesitic and rhyolitic magmas. Enrichment an LILE such as K, Rb and Ba is related to the assimilation of pre-Las Cumbres continental crust in an andesitic magma chamber.

The Middle to Late Pleistocene geological history of the LCVC has been divided in four periods. The first one is related to the production of about 200 km$^3$ of andesitic lava emitted by the Las Cumbres stratovolcano, as well as the extrusion of andesitic-rhyolitic domes with obsidian (Xalista, El Rodeo, Ixtetal) and other andesitic and basaltic lavas from adjacent vents (Sillatepec, El Cristón).

The second stage is characterized by the emplacement of a huge debris avalanche deposit derived from the partial collapse of the eastern flank of the Las Cumbres stratovolcano. Successive andesitic lava flows and the extrusion of

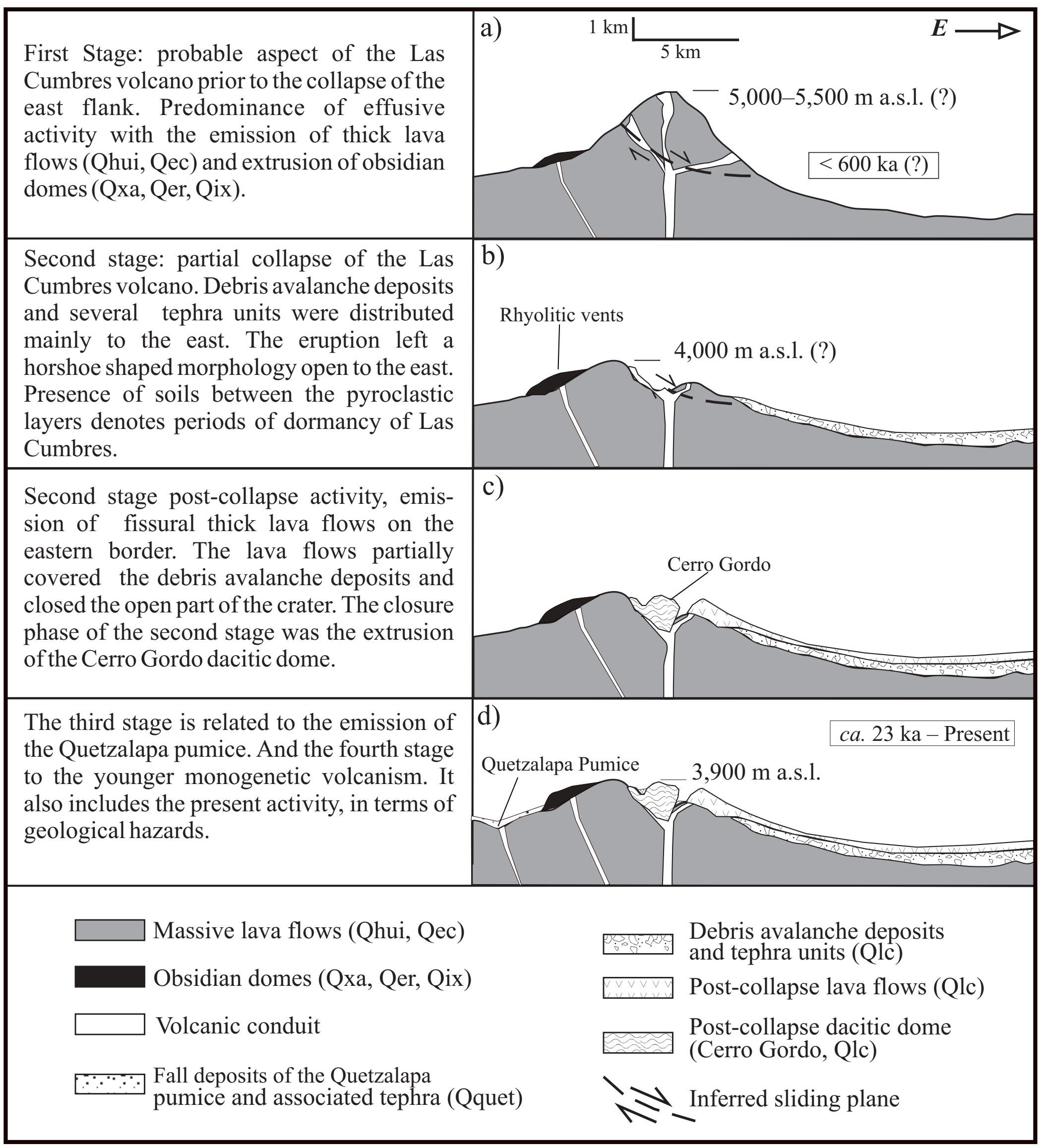


Figure 13. Representation of the first, second and third stages of Las Cumbres Volcanic Complex.

a dacitic dome ended this second period of activity. The estimated volume of volcanic material produced during this stage is 80 $km^3$.

During the third period, a rhyolitic plinian eruption produced the Quetzalapa pumice fall deposit. The final volcanic events of the third stage are the partial collapse of the west flank of the Sillatepec dome, and the extrusion of the dacitic Chichihuale dome. The total volume of material implicated in this stage is estimated in 20 $km^3$.

The fourth and last period is related to the monogenetic activity. Ash and scoria cones of basaltic composition, as well as small eruptive centers of rhyolitic character (Yolotepec dome) constitute the younger eruptive manifestations of the LCVC. Most of the scoria cones are roughly aligned in a NE–SW direction which coincides with the orientation of the younger fracture and fault systems in the region.

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