Journal of Volcanology and Geothermal Research 176 (2008) 241–264

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Revised stratigraphy and eruption rates of Ceboruco stratovolcano and surrounding monogenetic vents (Nayarit, Mexico) from historical documents and new radiocarbon dates

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A R T I C L E   I N F O

Article history:
Received 30 October 2007
Accepted 3 April 2008
Available online 20 April 2008

Keywords:
Ceboruco
radiocarbon
eruptive history
stratigraphy
Trans-Mexican Volcanic Belt

A B S T R A C T

More than a dozen new radiocarbon dates reconstruct the eruptive history of Ceboruco volcano. Six of these further constrain previous results for the important plinian Jala eruption, which occurred near 1060±55 yr BP. A calibrated radiocarbon age of AD 990–1020 was obtained as best overlap range for all samples. Pottery fragments found directly underneath the pumice deposit indicate that this area was inhabited by human populations that witnessed the eruption. This age therefore represents an important time marker in the prehistory of this region, because an area of >560 km2 was devastated and covered by a thickness of >50 cm of pumice and ash fallout.

After the prominent Jala eruption (VEI=6), at least seven major lava flows and several smaller domes were issued from Ceboruco's crater. Analysis of historical documents allows us to conclude that most of these eruptions took place well before the arrival of the Spanish conquerors to this area in 1528. Ceboruco's last historic eruption (1870–1872) produced a ca. 7 km long viscous dacite lava flow. Its emplacement was accompanied by block-and-ash flow activity and deposition of ash fallout. Because a repeat of such an eruption in the future would seriously endanger the nearby population and disrupt important life-lines, a detailed discussion of eyewitness accounts and other documents, including drawings and paintings is provided. Some of these materials are made available to the broader public for the first time in the present article.

Several surrounding monogenetic vents were previously dated by others using the K–Ar and the Ar–Ar methods. Because these dating methods are often not suitable for very young rocks, we also dated several Holocene monogenetic vents by the radiocarbon method. These dates together with geologic mapping allowed calculating eruption rates and recurrence intervals of different types of eruptions. Accordingly, an andesite/dacite lava flow (accompanied by block-and-ash flow activity) was erupted from Ceboruco's crater on average every 143 years during the last 1000 years. In contrast, a monogenetic eruption forming either a scoria cone or a dome has occurred in the area surrounding Ceboruco on average every 1000 years during the Holocene. During the period between AD 1000 and AD 1500 Ceboruco displayed an elevated activity experiencing a rhyodacite plinian eruption (3–4 km^3 DRE) followed by the emplacement of six andesitic/dacitic lava flows also with a total volume of 3–4 km^3.

All these figures indicate that the Ceboruco volcanic region is one of the most active areas in the entire Trans-Mexican Volcanic Belt. Consequently, production of a detailed volcanic hazard map and implementation of other preventive measures aimed at reducing potential losses in case of renewed volcanic activity should be mandatory.

1. Introduction

Ceboruco (2164 m a.s.l.), a late Quaternary andesitic to dacitic stratovolcano, is located in the Tepic-Zacoalco graben in the western part of the Trans-Mexican Volcanic Belt (TMVB) in the present State of Nayarit (Fig. 1). After Colima it is the most active volcano in the western TMVB and the only volcano in Nayarit with historically documented eruptions. The main cone and its surroundings display a young morphology with fresh lavas that cover the northern and southern flanks (Fig. 2). In addition, the volcano is crowned by multiple almost unvegetated domes and smaller pyroclastic cones located within the interior of two nested summit craters (Figs. 3–7), all of which were emplaced during the last 1000 years. At present, mild fumarolic activity (<100 °C) is observable at a few spots within the crater area. Ceboruco's last eruption occurred in 1870 and attracted the attention of contemporaneous 19th century naturalists. Caravantes (1870) and

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0377-0273/$ – see front matter
doi:10.1016/j.jvolgeores.2008.04.006

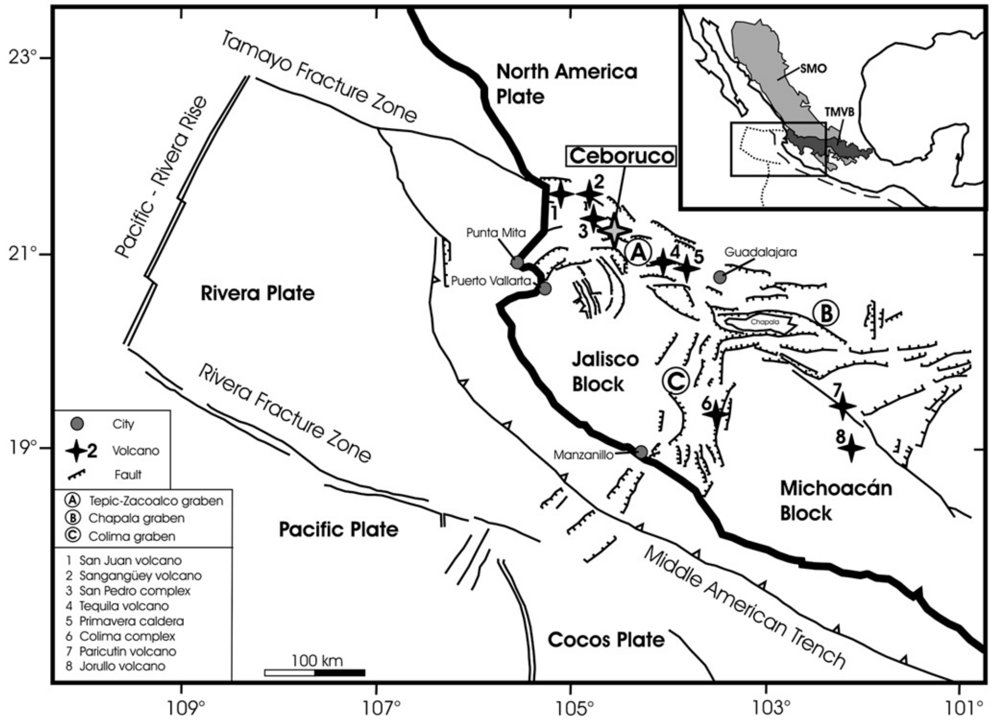

Fig. 1. Location of Ceboruco within the western TMVB and main tectonic features of western Mexico (after Núñez-Cornú et al., 2002).

Iglesias et al. (1877) described their own observations of the eruption, while Barrera (1931) reported accounts by other eyewitnesses.

In the vicinity of the volcano different types of monogenetic edifices occur and include 18 scoria cones, 8 silicic lava domes, and 2 phreato-magmatic pyroclastic cones (Figs. 3 and 4). Most of these also display a young morphology.

Previous studies include Thorpe and Francis (1975), who published the first Sr-isotope analyses of volcanic rocks in this region and included a first geologic sketch map of Ceboruco. Nelson (1980) carried out the first comprehensive geologic studies. Although he focused on petrological aspects of the volcano and flanking vents, he also presented an eruptive history, that included the first radiocarbon ages for Ceboruco's only known plinian eruption, which produced the widespread 1060±55 yr BP Jala pumice. Subsequently J. Gardner and co-workers studied the origin of this important deposit in greater detail and tried to resolve questions related to transport and deposition of pyroclastic material, magma interactions before and during the eruption, etc. (Gardner and Tait, 2000; Browne and Gardner, 2004, 2005; Chertkoff and Gardner, 2004). These authors concluded that the eruption had a magnitude of VEI=6, with a bulk tephra volume of 10.7 km^3 and a dense rock equivalent (DRE) of erupted pumice of 3–4 km^3 covering an area of 560 km^2 (Nelson, 1980) with a deposit thickness of >50 cm.

New petrologic, geochemical, isotopic, and tectonic studies in this part of the TMVB have revealed the occurrence of bimodal volcanism (Ferrari et al., 1994, 2000, 2002, 2003; Petrone et al., 2001, 2006; Frey et al., 2004) in an extensional tectonic setting. These studies have also produced a great number of radiometric ages (K–Ar and Ar–Ar) that include a few ages for monogenetic vents in the Ceboruco area. In this context it is important to note that the reported K–Ar and Ar–Ar ages <20,000 years have large errors.

The present study is aimed at filling gaps in our knowledge of Ceboruco's stratigraphy and eruptive history including a characterization of eruptive styles of surrounding monogenetic vents. Because the youngest eruptions occurred in the Late Pleistocene and Holocene, the radiocarbon method is certainly the most appropriate dating method, especially when enough datable organic material can be obtained. A total of 13 new radiocarbon ages are reported (Table 1) as a result of the present study and include 6 dates for different monogenetic eruptions, one for a reworked pumice-and-ash flow deposit from the Marquesado ash-fan, and 6 new dates for the plinian Jala eruption from Ceboruco volcano.

Ceboruco's eruptions after the plinian Jala eruption (last 1000 years) are difficult to date by the radiocarbon method due to the lack of suitable outcrops with enough datable material. For this reason, historical documents (mostly Spanish chronicles from the Colonial period) were studied in order to further evaluate the timing of these young eruptions. When possible, determination of erupted volumes of individual eruptions and eruption rates over different time periods was also attempted.

The area around the volcano was populated since at least 300 yr BC (Bell, 1971; Zepeda et al., 1993) as documented by numerous archaeological sites. At present, municipalities around Ceboruco include a total of ca. 85,000 inhabitants (INEGI census, 2005). Of these, ca. 30,000 dwell in the immediate surroundings of the volcano.

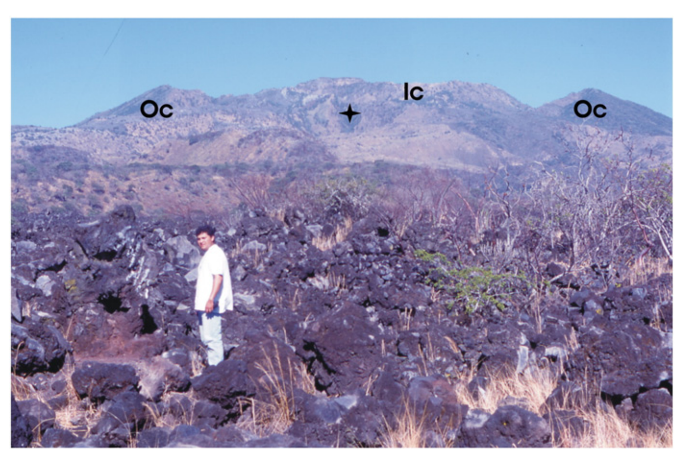

Fig. 2. Ceboruco volcano from the SW. In the foreground is the ca. 500–600 year old El Ceboruco lava flow, which originated from a small crater marked with a star. Oc indicates the outer and Ic the inner crater rim. Photo taken Feb. 19, 2003 by C. Siebe.

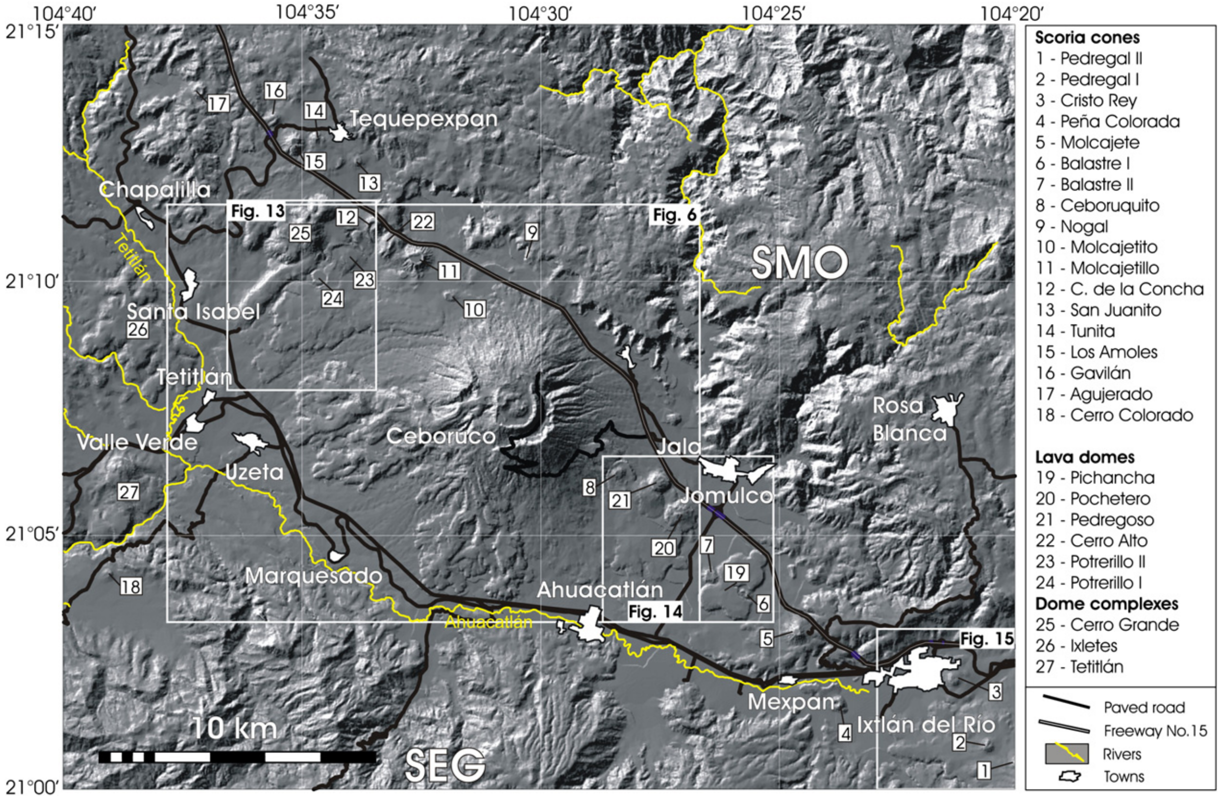

Fig. 3. Shaded relief map of Ceboruco stratovolcano and distribution of monogenetic vents. Most vents occur along a narrow NW–SE oriented, 5 km wide stripe paralleling the Ceboruco half-graben. SMO = volcanics of the Sierra Madre Occidental overlain by the Jala ignimbrites and rhyolites, together forming the NE graben shoulder. SEG = Sierra El Guamúchil volcanics above Jalisco Block granite basement forming the SW graben shoulder. Insets are areas covered in more detail in Figs. 6, 13–15.

A well-constrained stratigraphy and eruptive history of Ceboruco volcano and surrounding monogenetic vents will serve as a base for future hazard assessments in this area. The present study represents a contribution toward this important goal.

2. Geologic and tectonic setting

The study area is characterized by three large-scale geologic domains of regional importance, which are the Sierra Madre Occidental (SMO) to the NE, the Jalisco Block (JB) to the SW, and the western part of the Trans-Mexican-Volcanic Belt (TMVB), which separates the SMO from the JB (Fig. 3). The SMO is a ~1000 m-thick volcanic plateau, which consists of Tertiary ignimbrites and rhyolites, built during several stages of volcanic activity, with major tectonic displacements that occurred during the so called "ignimbrite flare up" between 38 and 18 Ma ago (Fig. 1) (e.g. McDowell et al., 1990; Aguirre-Díaz and Labarthe-Hernández, 2003). In the Ceboruco area, younger SMO ignimbrites (~20 Ma) (Ferrari et al., 2000) occur in restricted outcrops near Mexpan (Figs. 3 and 4). Elsewhere, they are covered by younger silicic (Jala rhyolites and ignimbrites) and basaltic–andesitic sequences (Ixtlán and Buenavista basalt and andesite) that range in age between 4.7 and 3.8 Ma (Ferrari et al., 2000, 2003) (Fig. 4).

To the SW of the depression occupied by Ceboruco volcano is the Sierra El Guamúchil (SEG) topographic high, which is part of the Jalisco Block and consists mainly of rhyolites and ignimbrites, and minor dacites and andesites, some of which were dated at 65 Ma (Ferrari et al., 2003) (Fig. 4). At the foot of the SEG, ignimbrites belonging to the younger Jala ignimbrite and rhyolite sequences crop out to the north of the depression. The Jalisco Block consists of volcanic and sedimentary sequences intruded by late Cretaceous plutons, collectively labeled the Puerto Vallarta Batholith (e.g. Schaaf et al., 1995). Best outcrops of the batholith can be found at the Pacific coast near Puerto Vallarta and Punta Mita (Fig. 1). These plutonic rocks presumably also underlie the study area, since granitoid xenoliths were found in scoria deposits from monogenetic cones (e.g. Balastre II scoria cone, Fig. 3).

It is widely accepted that the Tepic-Zacoalco graben, separating the SMO from the JB, is an extensional structure that is part of a larger system of grabens, half-grabens, and faults (e.g. Luhr et al., 1985; Nieto-Obregón et al., 1992; Allan, 1986; Ferrari et al., 1994, 2000, 2003; Rosas-Elguera et al., 1996) (Fig. 1). The origin and extent of this extensional structure to the N of the JB has been debated recently. Basically, two different ideas have been postulated. The first ascribes the extensional structures to rift systems marking the beginning of a future separation of the Jalisco Block from mainland Mexico (similar to the separation of the Baja California peninsula) as postulated by several authors (e.g. Luhr et al., 1985; Allan, 1986; Nieto-Obregón et al., 1992). This model implies cessation of subduction of the Rivera plate (e.g. Luhr et al., 1985, Allan, 1986). The other model explains the observed structures as the result of an upper-plate response to accumulated tectonic stress, resulting from oblique subduction of the Rivera plate in reaction to a change in motion of the adjacent Pacific and Cocos plates (Ferrari et al., 1994; DeMets and Traylen, 2000) as well as to a lower convergence rate and a steeper subduction angle (Rosas-Elguera et al., 1996).

According to DeMets and Stein (1990), the Rivera plate is subducting at a rate of 2 cm/yr near Manzanillo (Fig. 1). The slow subduction rate of a relatively young and hot oceanic lithosphere results in low seismicity, complicating the determination of the Wadati–Benioff zone beneath western Mexico (Pardo and Suárez, 1993).

The Ceboruco asymmetric graben is part of a large-scale depression, the so called Tepic-Zacoalco graben, which has a NW–SE orientation and forms together with the N–S oriented Colima graben and the E–W Chapala graben a triple junction near Guadalajara (Fig. 1). The NE boundary of the Ceboruco half-graben is marked by a normal fault, with a fault scarp cut into the sequence of Jala rhyolites and ignimbrites (Ferrari et al., 2002). Another fault, more or less parallel to the northern boundary of the graben,

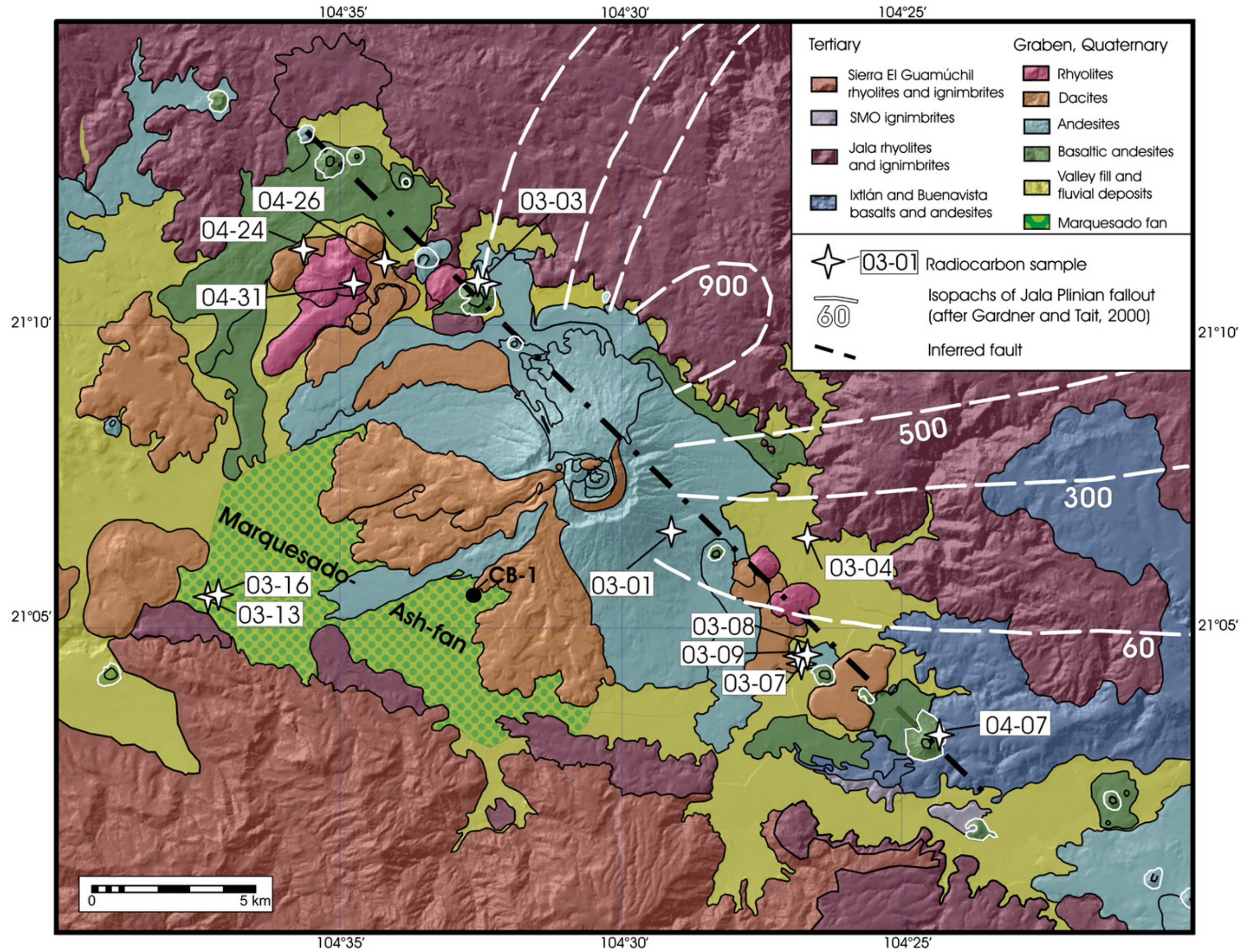

Fig. 4. Geologic sketch map of the study area and location of radiocarbon sampling sites. Isopachs of Jala plinian pumice fallout (in cm) are also shown (after Gardner and Tait, 2000).

is only evidenced by the alignment of scoria cones and lava domes in the area. The SW boundary of the Ceboruco depression is marked by the successive elevation of the SEG, without showing clear evidence for another fault (half-graben or asymmetric graben).

The first extension-related volcanic activity in the region is evidenced by a succession of andesitic and basaltic lava flows immediately overlying rocks of the Jalisco Block (geothermal exploration well CB-1 drilled by the Comisión Federal de Electricidad, ca. 3 km S of Ceboruco's crater, e.g. Venegas, 1995) dated at 8 Ma (Ferrari et al., 2003), which also correlates with plateau-forming lavas of the same age in other parts of the Tepic-Zacoalco graben (e.g. near Tepic). A second phase of extension-related volcanism occurred in the late Pliocene with the Ixtlán and Buenavista basalt and andesite series dated at 3.8 Ma (Ferrari et al., 2000, 2003). The activity of the modern Ceboruco graben probably initiated in the early Pliocene or before, because the Jala Ignimbrites and rhyolites (4.8 to 4.2 Ma) are cut by the fault marking the NE boundary of the graben. The undeformed Ixtlán and Buenavista volcanic series cover this same fault and were dated at 3.8 Ma (Fig. 4).

3. Radiocarbon dating

In this work we present 13 new radiocarbon ages (Table 1) obtained on charcoal samples from pyroclastic deposits and underlying paleosols. When dating underlying paleosols, only the uppermost 2 cm were sampled in order to obtain the best possible maximum age for the overlying volcanic deposit. All samples were analyzed by the conventional method at the Laboratory of Isotope Geochemistry, University of Arizona, Tucson. Calibrated ages were computed using the program CALIB developed by Stuiver and Reimer (1986) (Table 1).

We tried to obtain additional dates for the previously dated plinian Jala pumice fallout. This high-magnitude (VEI 6) eruption (Gardner and Tait, 2000; Browne and Gardner, 2004, 2005, Chertkoff and Gardner, 2004) had devastating effects on the environment and local populations and a more precise determination of its age was desirable. In addition, this deposit represents an excellent marker horizon that was particularly useful in identifying Ceboruco's youngest lava flows. The 1870, El Norte, Ceboruco, Coapan I and Coapan II, Cajón, and Copales lava flows (Figs. 4 and 6) are all younger than the Jala pumice.

Although we focused primarily on undated monogenetic volcanoes, we also attempted to date events previously dated by K–Ar (Petrone et al., 2001; Ferrari et al., 2003) and Ar–Ar (Frey et al., 2004), but with large uncertainties. Frequently, difficulties in finding suitable materials for radiocarbon dating within pyroclastic deposits required the use of underlying paleosols to obtain a maximum age for the deposits. In other cases (e.g. Ceboruco lava flows) when there was insufficient time between eruptions for formation of a mature paleosol and vegetation, the age was constrained indirectly by stratigraphic and morphologic means.

4. The plinian Jala eruption

The eruptive sequence of the plinian Jala eruption was described in detail by Gardner and Tait (2000), who also determined a volume

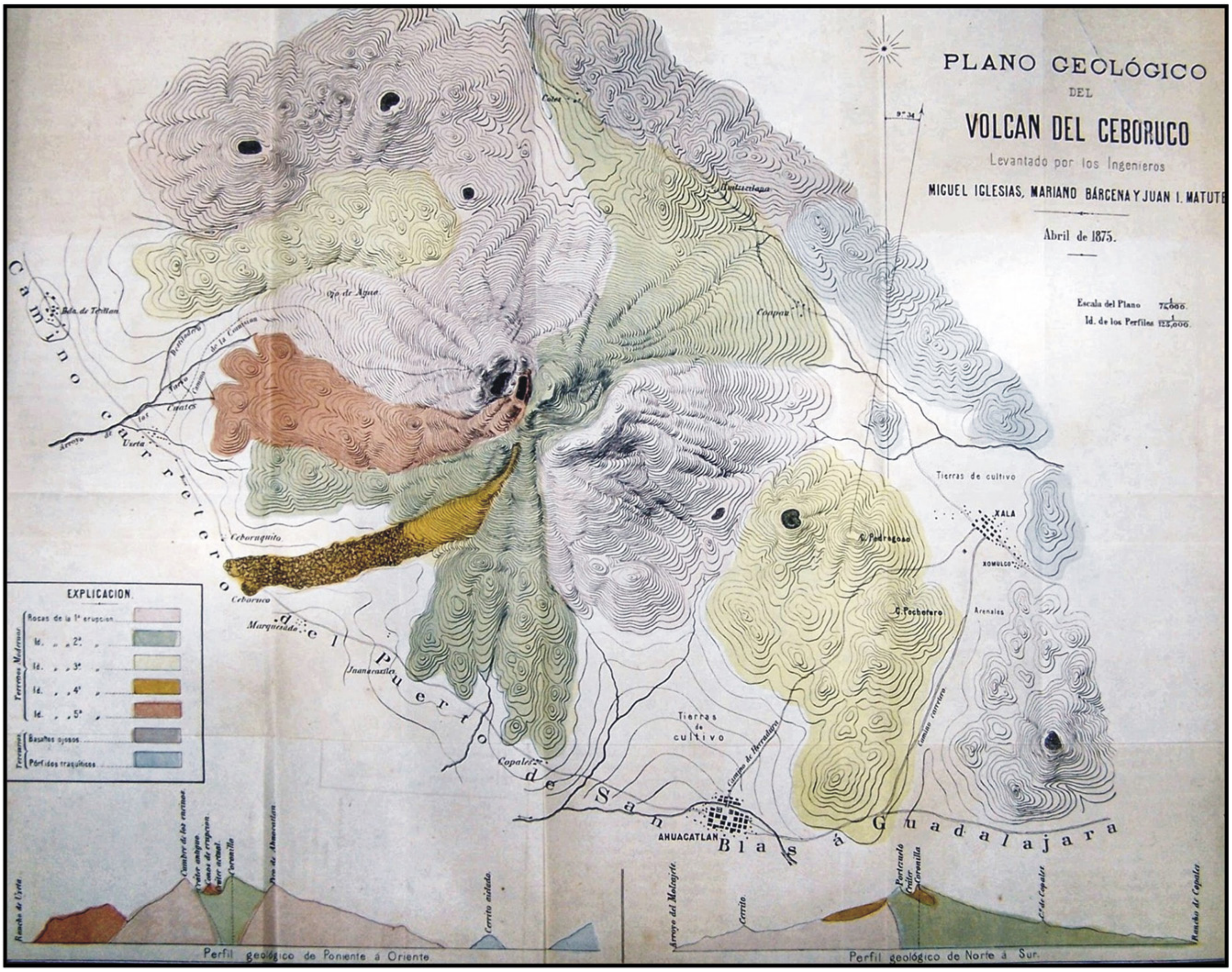

Fig. 5. Geologic map and cross-section of Ceboruco volcano produced by the scientific commission ordered to investigate the erupting volcano in 1875 (Iglesias et al., 1877). The 1870–75 lava flow is shown in red, while the Ceboruco lava flow, which erupted between AD 1005 and 1528 is shown in yellow.

of 3–4 km^3 (DRE) for the magma involved. Correlation of the northern and southern deposits of the plinian eruption was established by Browne and Gardner (2004) after a tentative correlation by Nelson (1980). Eruption processes and mechanisms of resulting crater-formation were discussed recently by Chertkoff and Gardner (2004) and Browne and Gardner (2004, 2005). With six new dates for the only known plinian deposits of Ceboruco, we further constrain the age of this important eruption.

The three radiocarbon ages published by Nelson (1980) include two dates obtained on charcoal samples from underneath the plinian Jala pumice fallout and one date obtained on a charcoal sample from an associated pyroclastic flow deposit, that occurs within the upper series of the Marquesado block-and-ash fan (see also Table 1). Our two charcoal fragments found directly underneath the Jala pumice fallout at localities where the Jala pumice lies on products of the Molcajetillo scoria cone (Fig. 3) yielded ages of 1055±85 and 1060±55 yr BP respectively. These ages are very similar to those determined (1010±200 and 1030±200 yr BP) by Nelson (1980). The other four samples dating the plinian Jala eruption were obtained at different outcrops from the uppermost 2 cm of paleosols directly below the Jala pumice fallout. Paleosols on the eastern and northern slopes of Ceboruco yielded older ages (1200±35, 1280+85/−80, 1540±85 yr BP) (Fig. 4, Table 1), while a paleosol at an outcrop on the western slope of Ceboruco near the Cerro Grande dome complex yielded an age of 960±90 yr BP (Fig. 4, Table 1).

While the plinian fallout was mainly distributed to the NE, most of the associated pyroclastic flows were deposited to the SW of the volcano. Nelson (1980) dated a piece of charcoal found within a pyroclastic flow deposit of the Marquesado block-and-ash fan at 1500±300 yr BP. The discrepancy of ca. 500 years between this age and the ca. 1000 yr BP ages still lacks a satisfactory explanation.

We also determined an age of 1905±85 yr BP for a lahar sequence in the valley between Uzeta and Las Glorias (Fig. 4) by sampling the uppermost part of a mature paleosol directly underneath the lahar sequence. The lahar deposits contain rounded pumice clasts, which are visually and geochemically identical to Jala pumices. The Jala pumice fallout deposited on Ceboruco's southern slope has been almost completely eroded due to its small thickness in this area and occurs only as remnants in the form of rounded pumice clasts in small-volume lahar deposits, and mixed with soil on the surface of agricultural fields on the lower southern and south-western slopes, as well as in fluvial deposits in valleys on the eastern slope of Ceboruco. Because of the stratigraphic relationship and the geochemical fingerprints of the fallout and pyroclastic flow-and-surge deposits on the northern and southern sides of the volcano (Browne and Gardner, 2005) it is assumed that despite of the older ages for the deposits on the southern side, they were produced by the same eruption. Maybe, pyroclastic flows and lahars picked up older wood during transport prior to their final emplacement.

Calibrated AD ages were calculated using the program CALIB (Stuiver and Reimer, 1986) for all existing radiocarbon ages dating this most important eruption of Ceboruco, including the three previously existing ages from Nelson (1980) and the six new ages obtained during

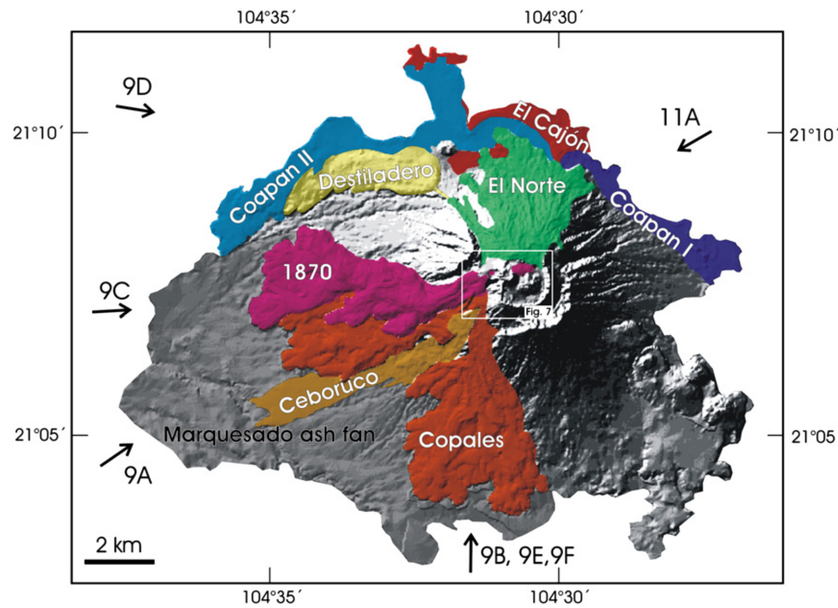

Fig. 6. Shaded relief model of Ceboruco showing lava flows erupted shortly before (Destiladero) and after the plinian Jala eruption (Copales, Cajón, Coapan I, Coapan II, El Norte, Ceboruco, and 1870–75; from oldest to youngest). Inset is area covered in detail in Fig. 7. Arrows indicate view directions of pictures shown in Figs. 9A–F and 11A.

this study (Table 1). The best AD age was obtained by graphically comparing all statistically determined calibrated age ranges (1σ). The overlapping area is the most probable AD age, which in this case is AD 990–1020. Accordingly, the best conventional radiocarbon age stems from sample 03-03-2, which yielded an age of 1060±55 yr BP, and corresponds to AD 945–1022. Although all available conventional ages were graphically plotted, the outlying ages were disregarded and only 5 of the 10 ages were considered. These are: 960±90, 1055±85, and 1060±55 yr BP (this study) and 1010±200 and 1030±200 yr BP (Nelson, 1980).

5. Historically documented eruptions

The 1060±55 yr BP (AD 1005) plinian Jala pumice is an excellent marker horizon. Stratigraphic relations indicate that after its emplacement at least seven major lava flows (Fig. 6) were issued from the crater area and flowed down Ceboruco's flanks. In addition, several smaller lava domes and cones were emplaced within the summit crater (Figs. 7 and 8). These young eruptions are difficult to radiocarbon date due to the lack of outcrops displaying lower contacts of its products. Furthermore, short time periods between eruptions did not allow for soil development and recovery of vegetation, and hence formation of datable materials. Therefore, a review of historical documents was undertaken.

5.1. Ceboruco's activity between the ca. AD 1005 (plinian Jala eruption) and AD 1870

Archaeological evidence indicates that the fertile valleys around Ceboruco volcano were populated since at least 200 to 300 BC (Bell, 1971; Zepeda et al., 1993). In western Mexico a great variety of tribes co-existed and no predominant culture like the Aztec in central Mexico developed. This cultural diversity was also reflected in the variety of different languages spoken in this area (Razo-Zaragoza, 1988).

Ceboruco's name until the time of the Spanish conquest was “Tonan” (Pérez-Verdía, 1951) which in Nahuatl means “a light, brilliant like the sun” (López-González, 2002). Later, the Spanish conquerors renamed the volcano to “Ceboruco”, which was a term applied not only to this specific volcano, but also more generally to rugged terrain (such as Aa-lava flows) that is difficult to cross (e.g. Razo-Zaragoza, 1988; López-Portillo y Weber, 1980). The word “ceboruco” was used in the Canary Islands and has the same meaning as the Spanish word “vericueto”, which means “rugged terrain with obstacles difficult to traverse” (López-Portillo y Weber, 1980; Razo-Zaragoza, 1988).

After the Spanish conquest in 1521, several early chroniclers (mostly clergymen and soldiers) such as Fray Antonio Tello, Antonio de Ciudad Real, Lázaro De Arregui, and Everardo Peña-Navarro documented important historical events that occurred since the first arrival of the conquerors in western Mexico. This region was named Nueva Galicia and included the present states of Nayarit, Jalisco, Colima, Aguascalientes, and parts of Sinaloa, Zacatecas, and San Luis Potosí.

Unlike volcanoes with long periods of dormancy in the TMVB such as Nevado de Toluca or La Malinche (e.g. Arce et al., 2003; Castro-Govea and Siebe, 2007), Ceboruco was clearly recognized as a volcano and not just a mountain in all early Spanish maps (Gutiérrez-Contreras, 1979; Orendain, 1961) and historical documents, as well as in the memories of the native people.

Although historical documents referring to Ceboruco at the time before the Spanish conquest (AD 1521) do not exist, various legends about the volcano and its eruptions had persisted. These legends were passed orally from one generation to the other and were eventually written down by Spanish chroniclers. Unfortunately, they lack any reference to exact dates.

One legend narrated by inhabitants of Ahuacatlán and Jala (Fig. 3) in the year 1820, describes the volcano as having a perfect shape and being very high, until “due to earthquakes it sank in half of it” (Banda, 1871). Maybe this legend refers to the Jala eruption or the “collapse” of the Dos Equis dome, which had formed after the Jala eruption in the center of the plinian crater.

Another legend repeatedly mentioned by different chroniclers (e.g. de Mota y Escobar, 1966; Tello, 1968; de Ciudad Real, 1976) refers to villages at the foot of Ceboruco destroyed and buried by lava “because its inhabitants had sinned”. De Arregui, who published the “Description of Nueva Galicia” in 1621, refers to a “tradition of the Indians” and mentions details of an eruption including “noise” that was so strong that people living close to the volcano were left deaf and that villages near the volcano's flanks were abandoned.

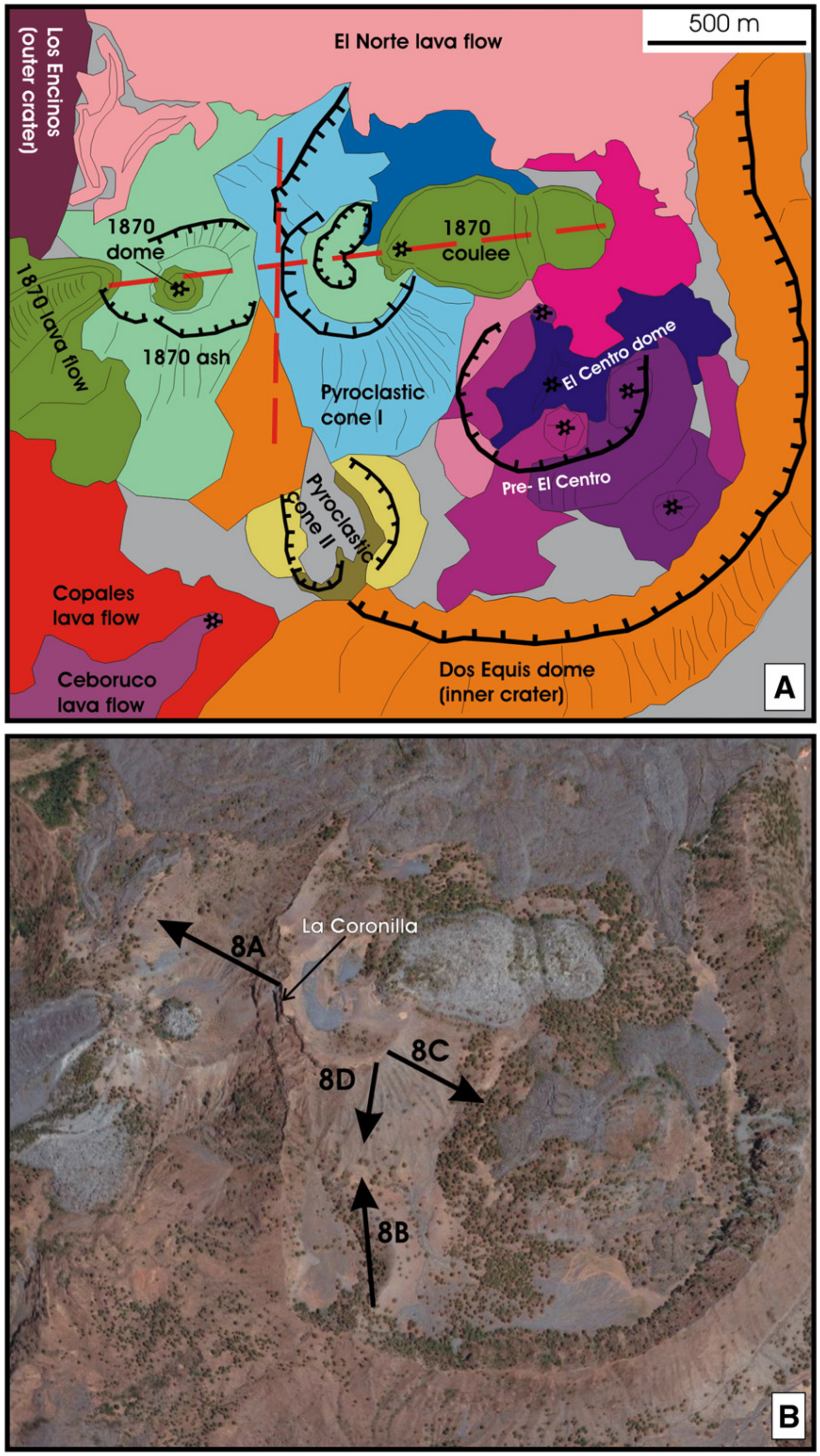

Fig. 7. Geologic map (A) and satellite image (B) of Ceboruco's summit area. Red dashed lines indicate inferred faults. Arrows in (B) indicate viewpoints of photographs shown in Fig. 8. The highest point of the actual edifice of Ceboruco "La Coronilla" is also shown.

Antonio Tello from the Franciscan order of friars wrote his chronicles in the year 1653 and also mentions this legend. Accordingly, villages at the flanks of the volcano were destroyed and their inhabitants killed by "fire and rocks" that were "thrown out" by the volcano.

Antonio de Ciudad Real who functioned as secretary to the General Commissary of the Franciscan order, Alonso Ponce de León, inspected the Franciscan provinces in New Spain from 1584 to 1589. He also visited Nayarit and mentions the same "tradition" told by natives, who preserved that legend from their "grandfathers", describing the "astonishingly black" lava flow (probably El Ceboruco lava flow, Figs. 2, 5, and 6), which had covered an ancient village.

Furthermore, the Spanish Alonso Ponce de León who traveled from village to village was shown parts of the destroyed villages on the northern side of Ceboruco while proceeding from Jala to Tequepexpan (Fig. 3) (de Ciudad Real, 1976). Interestingly, a legend narrated to him by people living on the southern side of the volcano

Table 1
Radiocarbon dates for Ceboruco and surrounding monogenetic volcanoes

Age (yr BP) Conventional	Age (AD) Calibrated (1σ*)	$\delta^{13}C$	Laboratory number	Sample number	Latitude	Longitude	Altitude (asl)	Dated material and locality
1. Jala Plinian eruption (cal AD)								
960±90	996–1168	−18.8	A-13530	04-24	21°11′12.6″	104°35′49.4″	1229 m	Paleosol underneath Jala pumice, W of Cerro Grande.
1055±85	884–1045 1096–1119 1141–1147	−24.4	A-12900	03-03	21°10′42.2″	104°32′37.4″	1375 m	Charcoal in paleosol, below Jala pumice, on top of Molcajetillo scoria cone.
1010±200**	783–787 821–842 860–1219	–	W-3490					Charcoal below Jala pumice, SE flanks of Ceboruco.
1030±200**	782–789 810–848 855–1189 1197–1207	–	W-3493					Charcoal below Jala pumice, SE flanks of Ceboruco.
1060±55	898–920 945–1022 945–1023	−23.2	A-12902	03-03_2	21°10′42.2″	104°32′37.4″	1375 m	Charcoal in paleosol below Jala pumice, on top of Molcajetillo scoria cone.
1200±35	779–874	−23.0	A-12899	03-01	21°06′37.2″	104°28′48.9″	1444 m	Charcoal in paleosol below Jala pumice, E-flank of Ceboruco.
1280+85/−80	658–783 788–815 843–859	−16.2	A-12903	03-07	21°04′33.5″	104°26′51.0″	1040 m	Paleosol below Jala pumice, paved road to Jala.
1500±300**	229–871							Charcoal from lower unit of Marquesado ash-fan, near Marquesado village.
1540±85	429–594	−16.1	A-12901	03-04	21°06′27.1″	104°26′57.0″	1100 m	Paleosol below Jala pumice, Jala soccer field.
1905±85	19–220	−13.7	A-12906	03-13	21°05′27.1″	104°37′15.8″	750 m	Paleosol between upper and lower pyroclastic sequence, E of Tetitlán lava dome.
2. Monogenetic vents (cal BC)								
2345±40	504–494 BC 489–461 BC 451–440 BC 418–381 BC	−24.1	A-13527	04-26a	21°11′09.0″	104°34′07.0″	1337 m	Charcoal from pyroclastic flow deposit of Potrerillo tuff ring, N of Potrerillo dome.
2355±110	747–888 BC 665–644 BC 589–580 BC 555–356 BC 286–234 BC	−14.8	A-12905	03-09	21°04′33.5″	104°26′51.0″	1040 m	Paleosol between Pochetero and BC Pedregoso sequence, paved road BC to Jala.
2430+50/−45	734–690 BC 662–650 BC 545–407 BC	−26.3	A-13528	04-31	21°10′27.8″	104°34′49.6″	1233 m	Charcoal from pyroclastic flow deposit from Potrerillo on flank of Cerro Grande.
3550±110	2031–1744 BC	−14.3	A-12904	03-08	21°04′33.5″	104°26′51.0″	1040 m	Paleosol between Pedregoso fallout and Balastre lava flow, paved road to Jala.
9220+170/−165	8702–8674 BC 8651–8274 BC	−23.3	A-13529	04-07	21°03′05.8″	104°24′22.1″	1208 m	Paleosol below Molcajete scoria fallout, Molcajete scoria cone.
21,075+680/−625	24,031–22,756	−12.5	A-12907	03-13_2	21°05′27.1″	104°37′15.8″	750 m	Paleosol between lower pyroclastic sequence and river conglomerate, E of Tetitlán.

* 1σ=square root of (sample std. dev. ^2+curve std. dev. ^2, where ^2=quantity squared). 1σ=68.3 (% area enclosed).
** Radiocarbon dates from Nelson (1980). Underlined calibrated ages are the statistically most probable dates for the 1σ range.

also mentions a village buried underneath the Ceboruco lava flow, while a similar legend told by people living on the northern side of Ceboruco refers to the El Norte or Coapan lava flows (Fig. 6).

The eruption (or eruptions?) that produced these two lava flows (El Ceboruco lava flow to the S and El Norte or Coapan lava flows to the N), must have occurred well before the arrival of the Spanish in the 1520's, because accounts of their first journeys into this region (e.g. de Arregui, 1946; de Ciudad Real, 1976) always mention the Ceboruco lava flow on the volcano's SW flank (Fig. 2). This flow represented an important obstacle that had to be surpassed when traveling on the "camino real" (royal road) to Compostela (first capital of Nueva Galicia) or to the port of San Blas at the Pacific coast (de Arregui, 1946; de Ciudad Real, 1976). Because these two lava flows are stratigraphically the youngest and were already emplaced by 1528, no other larger lava flow could have been produced between 1528 and 1870. During this time period eruptions were limited to the emission of small domes in the summit area. In conclusion, Ceboruco must have been very active during the first 500 years after the plinian Jala eruption. During this time six lava flows and several smaller domes were emplaced before the arrival of the Spaniards in 1528.

Furthermore, descriptions of the chronicler Lázaro de Arregui published in 1621, mention the surrounding valleys covered with black ash (de Arregui, 1946). This implies that at least some of the eruptions before the 16th century were not only effusive, but also accompanied by explosive activity. This observation is important for assessing past eruption styles, which might have been similar to the 1870 eruption (see Section 5.2).

In addition to the legends and general landscape descriptions provided by various chroniclers, Ceboruco was also specifically mentioned to be active in the years 1542 and 1567. An "eruption" in the year 1542 is mentioned by two chroniclers (Mota-Padilla, 1973; Peña-Navarro, 1946, 1956) who refer to the journey of Antonio de Mendoza (at the time the first Viceroy of New Spain), who was being accompanied by Cristóbal de Oñate (Governor of Nueva Galicia). Together they passed by the volcano during that year (Peña-Navarro, 1946, 1956; Tello, 1968; Pérez-Verdía, 1951). Unfortunately, first-hand documents providing further information and details of this eruption were not found during this study but might be buried in historical archives.

Another date mentioned in connection with Ceboruco by at least two chroniclers and later picked up by historians, are the important

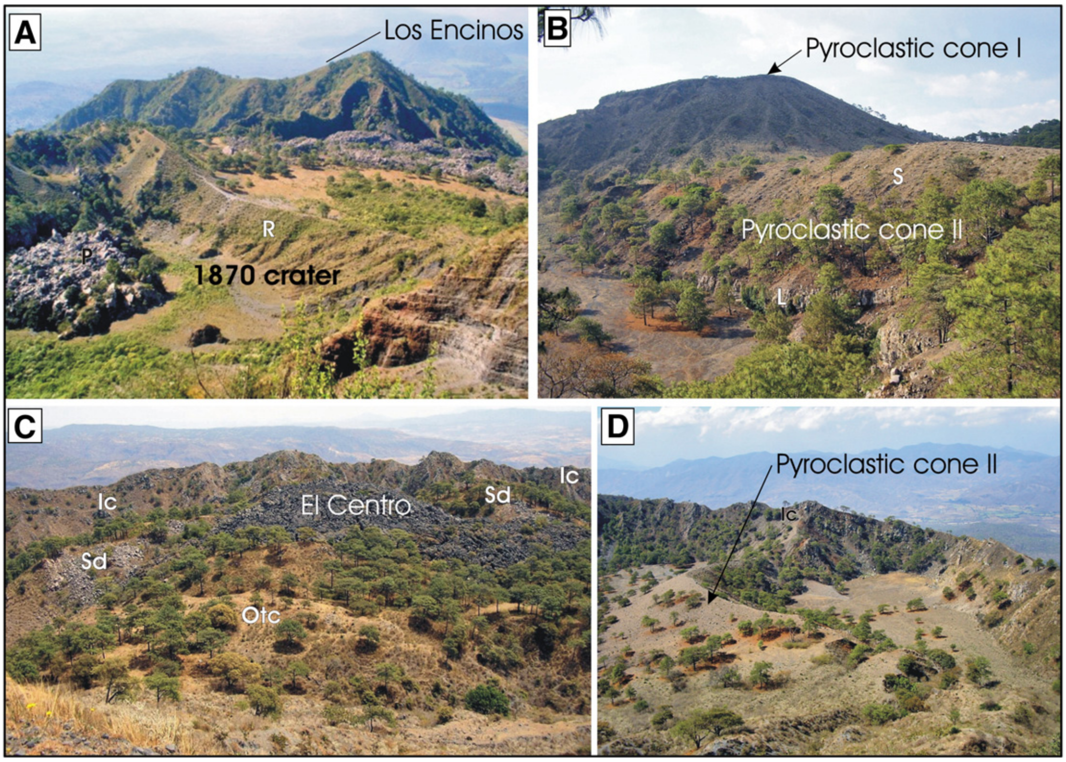

Fig. 8. Photos of Ceboruco's summit area. (A) Shows in the background the only remnant of the NW outer crater rim named "Los Encinos". From this topographic high, members of the 1875 expedition made most of their observations. In the foreground is the 1870 crater including the small plug dome (P) and associated pyroclastic ring (R). (B) Shows pyroclastic cone I (see also Fig. 7). This cone represents the highest elevation of Ceboruco's entire edifice today. In the foreground pyroclastic cone II with a lava flow (L) at the base and overlying pyroclastic sequence (S) is shown. Pyroclastic cone II is one the most recent features inside the inner crater of Ceboruco. (C) Shows the dark gray El Centro dome surrounded by remnants of an older tuff cone (Otc) in the foreground, several smaller domes (Sd) of a light grey color. El Centro might be contemporaneous with El Norte lava flow. (D) Shows pyroclastic cone II as seen from the top of pyroclastic cone I. In the background of photos (C) and (D) parts of the inner crater (Ic) are shown. These are the only remnants of the former Dos Equis dome.

earthquakes that occurred in 1566 (de Ciudad Real, 1976) and 1567 (Tello, 1968; Peña-Navarro, 1946, 1956; Pérez-Verdía, 1951; Banda, 1871). In 1567 at least two high-magnitude earthquakes occurred, one on July 15 and the other on December 30 (Tello, 1968). They were felt in the entire Jalisco province, affecting numerous villages, where houses and churches collapsed and many human lives were lost (Tello, 1968; city mayor of Ameca, cited in Banda, 1871). Furthermore, the opening of fractures and movements so strong that the natives could not stand upright were described (city mayor of Ameca, cited in Banda, 1871). The Ameca river was blocked by a landslide in the area between Ahuacatlán and Ameca forming a lake that later drained suddenly flooding the valleys with "sulfur-smelling" waters. The above chroniclers describing these devastating events state that an eruption of Ceboruco had generated the earthquake. We could not find any evidence further substantiating this statement. Maybe, at this time a small eruption was taking place in the summit area and coincided with subduction-related earthquakes. Two decades later, in 1585, a brook holding "warm sulfur-smelling water" is described to have originated from the foot of the volcano (de Ciudad Real, 1976) and around the year 1600 minor fumarolic activity is mentioned (de Mota y Escobar, 1966).

Finally, in one of the poems written during the last decade of the 16th century by Bernardo de Balbuena, who worked first as a clergyman in Guadalajara until 1592 and later as a priest in San Pedro Lagunillas (a little village not far from Compostela), Ceboruco is mentioned as "the great volcano of Jala, terrible monster of the world and its wonders, the most alive that now with its visible red light, serves as a torch to what I am writing" (de Balbuena, 1627). From this verse it can be deduced that incandescent lava (probably a small dome) was being produced at Ceboruco's summit crater at that time.

5.2. The 1870–1875 eruption

Ceboruco's single well-documented historic eruption started on February 23, 1870 and lasted for at least 5 years until 1875, when still small ash-laden eruptive columns were rising at intervals of 10 min and slow lava movement was noted (García, 1875; Iglesias et al., 1877). During this time period a 7.7 km long dacitic lava flow was emitted from the crater and emplaced along the Los Cuates Barranca draining the W slope of the volcano (Figs. 5 and 6). In 1872 the lava flow had stopped moving laterally, but inflation was causing a slow but continuous increase in height of the emplaced lava masses (Iglesias et al., 1877). During the first decades of the 20th century fumaroles were still observed along the lava flow and within the crater area (Barrera, 1931).

Siebert and Simkin (2002) classified the 1870 eruption with a Volcanic Explosivity Index (VEI; Newhall and Self, 1982) of 3. Because a repeat of a similar eruption might occur in the future, reconstruction of the eruptive phases and their exact timing from eyewitness accounts was undertaken as part of the present study. This reconstruction might serve as a guideline to help anticipate the possible course of eruptive events in case of Ceboruco's reactivation.

During the course of the 1870–75 eruption two main expeditions led by Caravantes (1870) and Iglesias et al. (1877) visited Ceboruco and provided direct accounts of different time periods of the ongoing eruption. Apart from their own observations they obtained information from inhabitants of nearby villages such as Ahuacatlán and Jala (see also Barrera, 1931; Banda, 1871). Additional information based on the writings of Caravantes (1870) and other reports was published in Germany by Kunhardt (1870) and Fuchs (1871). A summary of the reported phenomena and their timing is presented in Table 2.

Table 2
Chronology of volcanic phenomena observed by eyewitnesses of Ceboruco's last eruption (1870 to 1875)

Date	Type of activity	Reference
Year 1870		
February 15	Noise, low-magnitude earthquakes.	Banda (1871)
February 16	Noise, earthquakes.	Iglesias et al. (1877)
February 18	Noise, stronger earthquakes, “white” vapor emanating near La Coronilla.	Iglesias et al. (1877)
February 21	Fumarolic activity (“white vapor”)	Caravantes (1870), Kunhardt (1870)
	After 2 low-magnitude earthquakes, explosion with emission of vapor and ash, then “fire-column”.	Fuchs (1871)
February 23	Eruptive column, strong noise, low-magnitude earthquakes, vapor and ash emissions from crater and dispersion to the NE; during the night “fire” and different eruptive columns at various locations, first lava appears, ash explosions, up to a distance of 6 leguas (1 legua = 5,572.7 m), “boiling sand” flowing down Los Cuates barranca “like water” as the eruption started “with force”.	Caravantes (1870), Iglesias et al. (1877), Banda (1871), Kunhardt (1870), eyewitness, in Caravantes (1870)
February 27	Earlier observed accumulation of lava on S side of the crater starts flowing down Los Cuates barranca (first to the S, later to the SW).	Iglesias et al. (1877)
End of February	Not one single ash column but “various”, along fractures in Los Cuates barranca, lava also emerging from these fractures.	Iglesias et al. (1877)
March 6	Noise similar to “ocean waves during a storm”, “whistles like a locomotive”, thick columns of black “vapor”, “fire” in the crater during night.	Caravantes 1870
March 7	Excursion of Caravantes with local people to Los Cuates barranca: examination of deposits left by block-and-ash flow of February 23 (still 74 °C hot), lava had advanced from the crater to upper reaches of Los Cuates barranca (thickness 80 m), ash columns and sulfur smell close to lava flow, in the crater 2 to 3 columns (being active alternating or simultaneously), lava advances 5–6 m/day.	Caravantes (1870)
March 15	Advancing lava flow changes color from gray to black.	Caravantes (1870)
Middle of March	Eruption still ongoing: “every eruption goes along with the strong expulsion of gases with sounds of thunderstorms; rocks are thrown out vertically; very viscous lava is flowing along barranca where it forms a wall; high white columns which bear ash.	Fuchs (1871)
June 24	Ceboruco is active without cessation, ash falls with such density that people in Marquesado village (S of Ceboruco) can hardly see.	“Civilización de Guadalajara” (newspaper), cited in Fuchs (1871)
Year 1871	Large areas covered with ash, up to 40–50 cm thickness.	Banda (1871)
Year 1872	The lava flow stops advancing along Los Cuates barranca after a little more than 2 years, reaching a final distance of 7520 m from the crater.	Iglesias et al. (1877)
Year 1875		
February 11	Strong earthquake felt in Guadalajara, San Cristóbal destroyed. Subsequently an official committee is ordered to investigate Ceboruco.	García (1875)
March 20 to March 28	Subterranean “explosions”, small columns every 10 minutes, sometimes laden with ash that reaches up to 15 km (Ixtlán del Río) from the crater, changing the shape of central part of lava flow due to persisting internal movement. “new part of lava flow, with blocks falling down from ridges, are red in color during the night”.	Iglesias et al. (1877)
	Continuous eruption for 5 years, with strongest activity until 1882, finally ceases.	
After 1885	Fumarolic activity.	

Furthermore, we are including illustrations and paintings drawn by eyewitnesses. These important and interesting documents are presented here for the first time to a broader readership (Fig. 9).

First signs of reactivation include reports of subterranean noise and seismic activity noticed in the years 1783 and 1832. Those in 1832 were felt strong enough to cause fear among the inhabitants of Jala, who left their homes for a few days (Iglesias et al., 1877).

The exact timing of clear signs of reactivation differs between authors, but occurred between February 15 and 21, 1870. Precursors of the eruption included noise, seismic activity, and white vapor emanating from the summit area. All authors coincide in that the eruption started on February 23 with the rise of columns of vapor and ash that were accompanied by strong noise and weak earthquakes. During the night people noticed “fire” coming out of the crater at 4 or 5 different locations. Also, at the beginning of the major eruptive phase on February 23 “boiling sand, moving like water” descended the Los Cuates barranca. Decades later and after reading descriptions of the 1902 eruption of Mt. Pelée in Martinique, Waitz (1920) recognized that Caravantes' descriptions at Ceboruco closely resembled those of “nuée ardentes” observed at Mt. Pelée (Lacroix, 1904). Caravantes (1870) also described fresh pyroclastic deposits (block-and-ash flow deposits) emplaced in the Los Cuates barranca that he observed during an ascent to Ceboruco's crater on March 7, 1870. Apparently, these block-and-ash flows had been detaching from the advancing lava flow front shortly before his climb. Furthermore, while hiking uphill along the Los Cuates barranca, Caravantes noticed three sites near the summit issuing eruptive columns of vapor and ash, either in an alternating manner or simultaneously. He also described the lava flow advancing along the Los Cuates barranca, whose front had a height of 80 m. All these observations by Caravantes were published only a few months later and illustrated with a lithography by the famous landscape-painter José Maria Velasco (Fig. 9A) who had also joined this expedition (Trabulse, 1992).

Banda (1871) mentions observations by Caravantes and Fuentes, who participated in the first expedition of 1870, in addition to accounts by people from nearby villages who had climbed the erupting volcano. He described the advancing lava flow and the extension of ash fallout, which according to him covered the terrain up to a distance of 15 “leguas” (1 legua = 5572.7 m) with a thickness of 40 to 50 cm. Furthermore, Banda (1871) published two paintings depicting the ongoing eruption and advancing lava flow. These paintings were produced during the year 1870 by an unidentified artist (Fig. 9B and C).

Strong seismic activity was felt in Guadalajara and the rest of Jalisco state during the first months of 1875. The strongest earthquake occurred on February 11 (García, 1875; Palacio, 1877) and destroyed the village San Cristóbal to the NE of Guadalajara. The almost daily occurring earthquakes were described to have a “vertical pushing direction” each lasting from a few seconds to almost a minute. Whether these earthquakes were directly related to Ceboruco's activity is far from clear and doubtful. Nonetheless, a few weeks after the strong earthquake of February 11, the local government sent

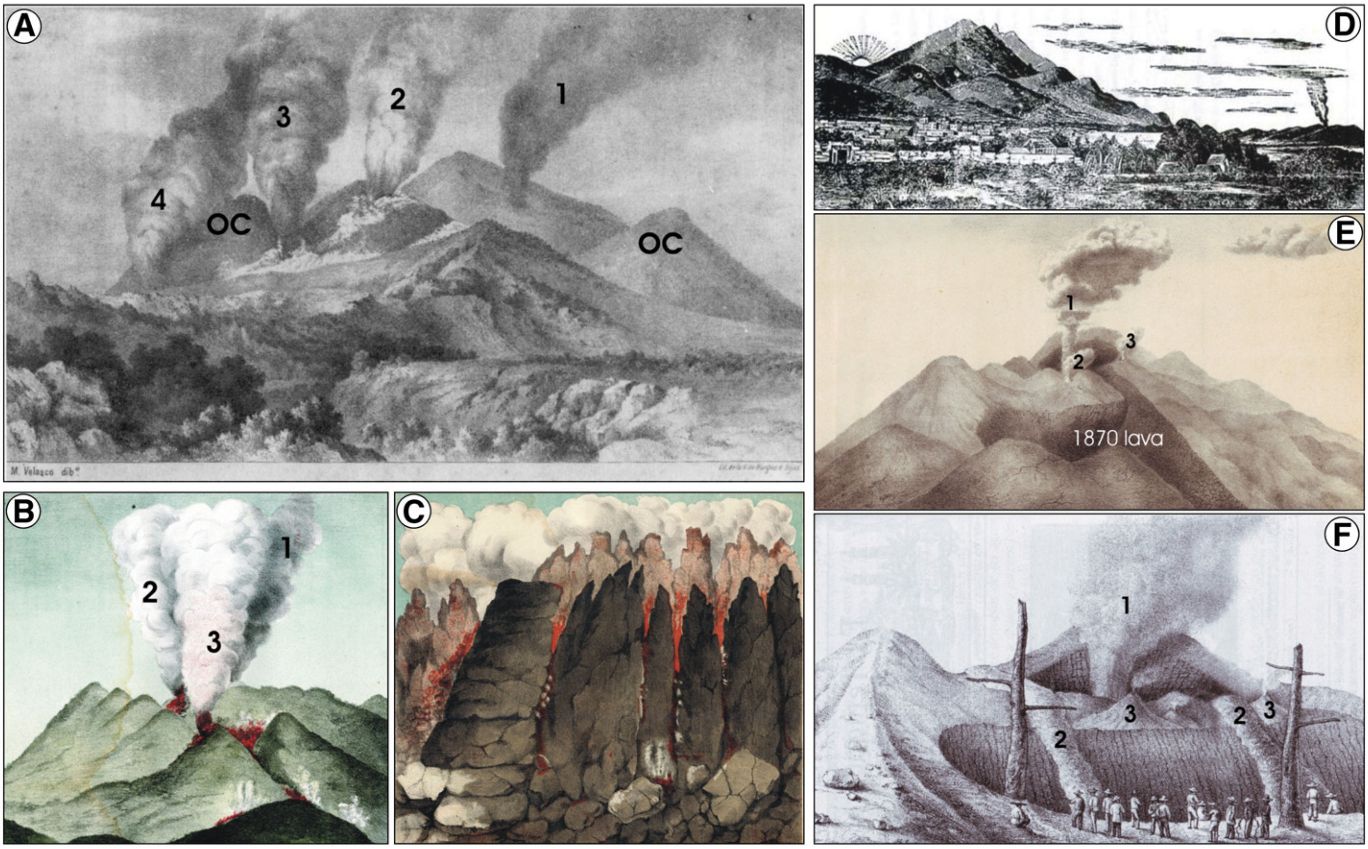

Fig. 9. (A) Lithography by José María Velasco of the erupting Ceboruco volcano as seen from the south in 1870 (Caravantes, 1870). The lithography shows the main eruptive column emanating from the 1870 crater (2), as well as columns (3 and 4) generated by the advancing lava flow along the Los Cuates barranca. The origin of column (1) is unclear and might be caused by forest fires or associated with the emplacement of the 1870 coulée located to the NE of the 1870 crater (see Fig. 7). OC indicates the outer crater rim. Lithographies (B) and (C) were created by an unidentified artist and published in Banda (1871). B shows Ceboruco from the village of Uzeta, which was threatened by the advancing lavas (Numbers 1 to 3 as in Fig. 9A). C seems to depict either a spiny dome in the crater or the margins of the advancing lava flow. For more than a decade Ceboruco was present in local newspapers such as "Lirismo" or "Lucifer". A lithography by C. Deave (D) shows a panoramic view from Tepic in the year 1875. The sun is rising behind Sangangüey volcano while the erupting Ceboruco can be seen in the background with a column of ash rising from its summit. This lithography was published in the local newspaper "Lirismo" in 1920. In 1875 several engineers climbed Ceboruco's W-flank to observe the ongoing eruption. (E) This lithography depicts a view from Los Encinos (see Figs. 7 and 8), a location on the western rim of the outer crater on the W-side of Ceboruco. The 1870 crater with an ash-laden eruptive column (1) and fumaroles (2 and 3) emanating from heaps of pyroclastic material composing the W rims of the 1870 crater are also shown. The highest point of the volcano (La Coronilla) is in the background. (F) Is a lithography based on drawings by members of the scientific expedition on March 20, 1875 (Iglesias et al., 1877). It shows a view from Los Encinos toward the SE. An ash plume (1) is rising from the 1870 crater from which lava flows (2) emanated in previous years. Fumaroles emanating from heaps of pyroclastic material (3) located on the crater rim are also depicted. A crowd of 16 people can be seen in the foreground. These are mostly curious peasants from Uzeta and Ahuacatlán that joined the expedition to the crater.

again a detachment of engineers (Iglesias, Bárcena, Matute, etc.) with the order to provide a detailed report of Ceboruco's activity.

On this occasion the engineers stayed for about two weeks in the area and produced a geologic sketch map (Fig. 5), photographic documentation that served as a basis for lithographies (Fig. 9E and F), and a description of the still ongoing eruption. An excursion to the outer crater rim was undertaken in which not only the investigators from Guadalajara but also local villagers participated. The group hiked around the newly emplaced lava flow and climbed to Los Encinos, a point at the W outer crater rim (Figs. 7 and 8A). From here they could see the SW rim of the 1870 crater and parts of the new lava flow, but were not able to look deep inside the new crater nor observe the small 1870 plug dome nor the 1870 coulée (Figs. 7A, 8A, and 9F). The lithographies presented in Fig. 9 are probably based on observations and photographs taken during the 1875 excursion and were published by Iglesias et al. (1877). They show the new crater area (Fig. 9E) and a view of Ceboruco crater area from Los Encinos (Fig. 9F). Several participants of this expedition published accounts of this memorable field trip (e.g. Iglesias, 1875; García, 1875; Bárcena, 1875).

By the time of the arrival of the engineers, gas-and-ash laden eruptive columns were still rising in intervals of 10 min. New lava injection caused vertical inflation of the lava flow, but no lateral movement. Ash fallout was found as far as Ixtlán del Río, a town located at a distance of 15 km to the SE from the crater (Fig. 3).

Iglesias et al. (1877) as well as Barrera (1931) report eyewitness descriptions of the emerging lava, which first bulged up the terrain close to the crater and at various other localities within the upper part of Los Cuates barranca, before breaking through the surface as "glowing blocks", which then would "fall down on either side of the ridges". According to these descriptions the lava emerged along various fractures on the upper SW flank as well as in the crater area of Ceboruco.

After 5 years of continuous eruption, skin and breathing-tract diseases affecting people in nearby villages were reported. Furthermore, cattle and wild animals suffered mortal teeth abrasion from chewing plants powdered by fine ash. Crops were affected partly negatively (Ahuacatlán) but also positively (Jala).

In 1894 Ordóñez (1896, 1897) visited the volcano and found a granite xenolith (enclave) near Ceboruco's summit (Rubinovich and Lozano, 1998). In that year (19 years after the cessation of the eruption) two major fumaroles were still active within the 1870 crater area with temperatures of 96 °C. Additional fumaroles were visible along the 1870–72 lava flow (Ordóñez, 1896).

Since 1877 Ceboruco has remained in a fumarolic stage. This activity has continuously diminished over the course of time but persists until the present day. Temperatures of the fumaroles at the summit area were determined to vary between 84 °C (outer crater) and 92 °C (inner crater) in 1994 (Venegas, 1995).

6. Post-Jala (AD 990–1020) eruptive activity and volumes of lava flows

Neither radiocarbon ages nor any detailed historical records exist for Ceboruco's activity for the time between the Jala eruption in AD 990–1020 (1060±55 yr BP) and the most recent historic eruption of 1870–1875. Nonetheless, a reconstruction of its eruptive history for this time span based on field observations, satellite imagery, aerial photography, and sparse historical documents was attempted. In addition, volumes of products (mostly lava flows) erupted during this period were estimated.

Volumes of lava flows were estimated using ArcView Geographic Information System (GIS) and Integrated Land and Water Information System (ILWIS) computer software in conjunction with field observations (Table 3). First, the outlines of lava flows were traced with the aid of ILWIS in order to obtain the best possible approximation of the original emplacement area. The volume of each lava flow was calculated by multiplying the surface area (determined with the aid of ArcViewGis) with the average thickness of each lava flow (determined by a method combining field observations with estimates obtained with the help of a digital elevation model) (Table 3).

Shortly before the plinian Jala eruption, a compositional change from the uniformly andesitic lava flows to more evolved magmas occurred when the trachy-dacitic Destiladero lava flow (Fig. 6, Table 3) was emplaced on Ceboruco's NW flank. The Destiladero lava flow has a volume of 0.42 km^3 and is covered by Jala pumice.

After the cataclysmic plinian Jala eruption that formed the outer crater and ejected a volume of 3–4 km^3 (DRE) (Gardner and Tait, 2000) with an estimated VEI of 6, a total of 7 lava flows (including the 1870–75 lava flow) were emitted from the crater area. In addition, various smaller domes and cones were emplaced within this crater (Figs. 6, 7, 8, and 10A).

Although Frey et al. (2004) proposed the existence of 9 post-Jala lava flows, we conclude that a total of only 7 lava flows were produced after the plinian Jala eruption (Fig. 6). They are easy to identify because they are not covered by Jala pumice. Since Frey et al. (2004) did not specify exactly which lava flows were erupted after the Jala eruption, a discussion of discrepancies is not possible at this moment.

The post-Jala lava flows include (from oldest to youngest) the Copales, Cajón, Coapan I, Coapan II, El Norte, Ceboruco, and 1870–75 lava flows (Fig. 6). Copales and the 1870 lava flows are dacitic, whereas the others are andesitic in composition.

Within the outer crater (Jala) the Dos Equis dome formed (Nelson, 1980) before it was drained by the closely associated trachy-dacitic Copales lava flow. Lateral drainage of the Dos Equis dome led to its deflation (by subsidence), subsequent collapse, and the formation of Ceboruco's inner crater (Nelson, 1980). Today, remnants of the Dos Equis dome form the walls of the inner crater (Figs. 7 and 8). Younger lava flows to the N and SW have completely buried other remnants of the Dos Equis dome. The exact timing of deflation of the Dos Equis dome and subsequent emplacement of the Copales flow (Nelson, 1980) down the southern flanks of the volcano is not known. The legend of the "high mountain with the perfect shape" mentioned earlier and preserved for a long time by the native people of the surrounding villages might have its origin either in this event or in the earlier plinian Jala eruption.

Due to its large area (26.39 km^2) and its considerable thickness the dacitic Copales lava flow has with 2.1 km^3 by far the greatest volume (Table 3). Although the Copales is partly overlain by younger flows, it is possible to calculate its volume because its original flow margins are traceable underneath the younger lavas with the aid of digital elevation models.

Four andesitic lava flows (Cajón, Coapan I, Coapan II, and El Norte) cover the northern flank of Ceboruco and adjacent areas at the foot of the volcano (Fig. 6). Because each subsequently emplaced lava flow partly covers the preceding older flows, their respective volumes were estimated by tracing their original emplacement area and not by considering only their present exposure area (Table 3). The andesitic Cajón lava flow (0.07 km^3) is overlain by the trachy-andesitic Coapan II lava flow (0.31 km^3). The Coapan I lava flow (0.08 km^3) was certainly emplaced more or less contemporaneously with the Coapan II from which it can be distinguished by its basaltic trachy-andesite composition (Fig. 6, Table 3). The vents of these three lava flows lie buried underneath the more recent El Norte lava flow (0.36 km^3) on the upper flanks near the outer crater rim.

El Ceboruco (Fig. 2) is the second youngest lava flow, has a volume of 0.16 km^3, and was emplaced on the SW flanks between the two lobes of the Copales flow (Figs. 5 and 6). The vent of this unvegetated, dark grey andesite is located below the outer crater rim on the upper SW flanks of Ceboruco (Fig. 2).

Historical evidence (see earlier discussion) indicates that the two morphologically young flows El Norte and Ceboruco were emplaced before AD 1528. This implies that 6 lava flows with a total volume of ca. 3 km^3 (Table 3) were emplaced within the first 500 years following the Jala eruption (Fig. 10A). By the arrival of the Spaniards, indigenous people would not remember witnessing any eruption, but only legends preserved from their ancestors. Therefore, the El Ceboruco lava flow (Fig. 6) must have been emplaced at least several decades before AD 1528 (Fig. 10A).

With the exception of minor summit eruptions (see below) that formed smaller domes and pyroclastic cones within Ceboruco's inner crater, the volcano remained in a state of relative quiescence until its more serious reactivation in 1870 (see Section 5) when the 1870 lava flow was emplaced. The 1870 eruption was preceded by phreato-

Table 3
Geologic and morphometric parameters characterizing Ceboruco's lava flows emplaced shortly before (Destiladero) and after (Copales, Cajón, Coapan I, Coapan II, El Norte, Ceboruco, and 1870–75; from oldest to youngest) the AD 990–1020 plinian Jala eruption

Lava flow	Rock type	SiO_2 (wt.%)*	Area (km^2)	Thickness (m)	Maximum length (km)	Aspect ratio (L/T)	Volume (km^3)
Destiladero	Trachy-dacite	63.56	6.97	60	7.54	125.7	0.42
Copales	Trachy-dacite	65.09	26.39	80	7.03	87.9	2.11
El Cajón	Trachy-andesite	61.04	7.07	10	5.00	500	0.07
Coapan I	Basaltic-andesite	56.90	4.04	20	6.80	340	0.08
Coapan II	Trachy-andesite	61.10	10.46	30	12.40	413.3	0.31
El Norte	Trachy-andesite	61.70	9.08	40	4.20	105	0.36
Ceboruco	Trachy-andesite	59.16	5.34	30	7.80	260	0.16
1870	Trachy-dacite	68.58	11.44	100	7.70	77	1.14
							Total: 4.65

* SiO_2 content (H_2O normalized).

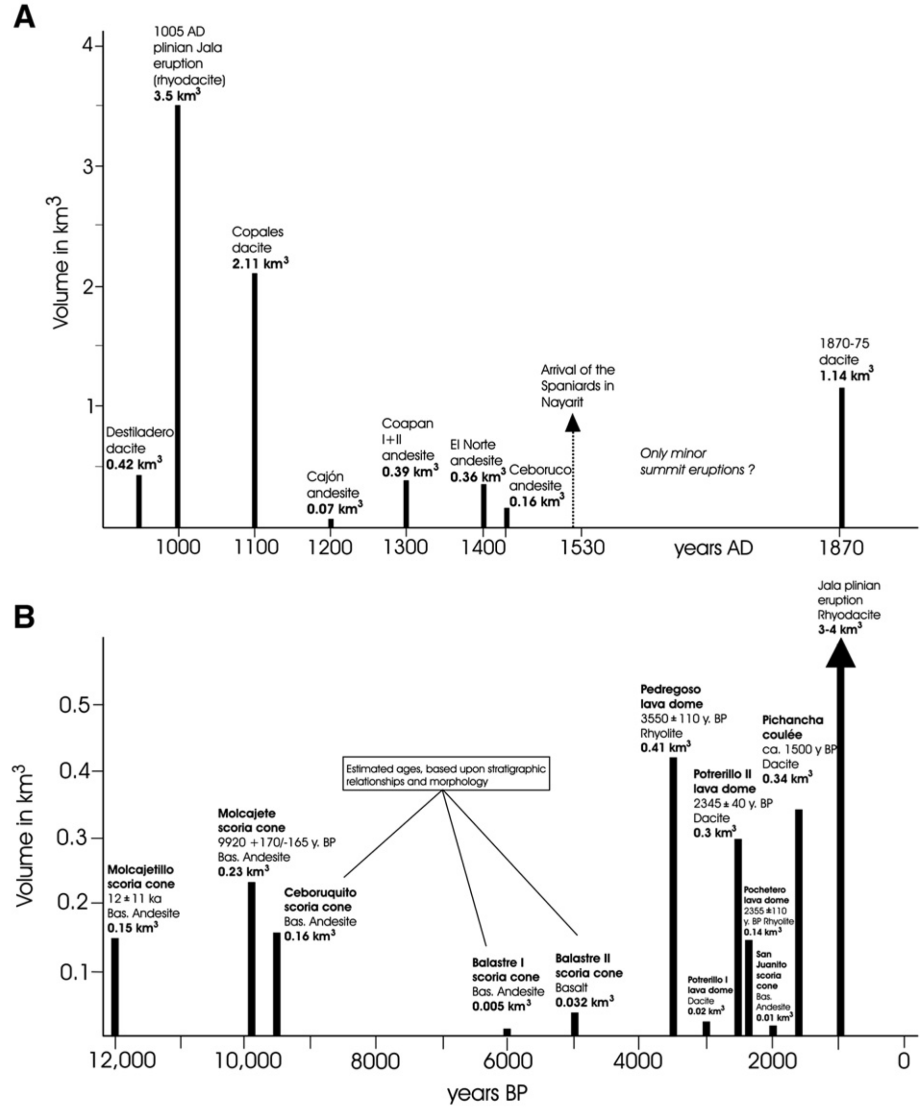

Fig. 10. (A) Volume vs. time diagram for eruptions from Ceboruco for the last 1100 years, and (B) volume vs. time diagram for Holocene monogenetic eruptions in the vicinity of Ceboruco.

magmatic activity that formed a small crater to the W of pyroclastic cone I (Figs. 7 and 8A). This activity partially removed the W wall of pyroclastic cone I, forming the E border of the new 1870 crater. The 1870 lava flow as well as two probably contemporaneous smaller domes emitted within the summit area are all of trachy-dacitic composition totaling a volume of 1.14 km^3 (Table 3). They formed along a zone of weakness and are aligned in a SSW–NNE direction (Fig. 7). The sliding of the W part of pyroclastic cone I might also have been fault-controlled (Fig. 7). Collapses of the unstable eastern 1870 crater walls were still observable at the final stages of the eruption in 1875 (Iglesias et al., 1877). Some of these lava flow-producing eruptions were probably accompanied by minor explosive activity and the emplacement of block-and-ash flows as suggested by historical evidence related to the emplacement of the El Ceboruco and 1870–75 lava flows.

Within the inner crater various small lava domes and flows, as well as pyroclastic cones occur in addition to the 1870–75 products (Fig. 7). A pyroclastic cone near the eastern rim represents the oldest structure within Ceboruco's inner crater. Apparently, phreato-magmatic activity that formed a circular crater preceded the extrusion of several small domes (pre-El Centro in Figs. 7 and 8C) that filled and overflowed the tuff ring to the N, E, and S. Much later, renewed activity probably contemporaneous to the eruption of El Norte lava flow (geochemically almost identical), formed the El Centro dome in the middle of the pre-El Centro complex. From the dome a small lava flow was issued extending to the NE.

The next structure to form was pyroclastic cone I, which formed in the NW sector of Ceboruco's inner crater. Pyroclastic cone I represents today the highest elevation (La Coronilla in Fig. 7B) of Ceboruco and was constructed by at least two phases of phreato-magmatic activity that resulted in two sequences of pyroclastic surge deposits. Products of this activity include ballistic bombs as large as 2 m in diameter. After the emplacement of the phreato-magmatic sequence, a small lava flow was emplaced to the NE. This flow can be observed on top of the crater walls of pyroclastic cone I. The activity ended with a third phreato-magmatic phase, which resulted in the formation of a smaller elliptical crater nested within the previous crater of cone I. Somewhat after the first phase of activity of pyroclastic cone I, pyroclastic cone II formed close to the SW wall of Ceboruco's inner crater (Fig. 7). Phreato-magmatic activity was followed by the emplacement of a small lava flow, which crops out at the base of its inner crater wall. Afterwards, the phreato-magmatic activity resumed depositing stratified surge deposits on the crater walls and rim. Pyroclastic cone II (Figs. 7, 8B, and D) is morphologically well-preserved and might have formed during and shortly after the Spanish conquest (see also Section 5).

Apparently, in addition to the eruptions producing voluminous lava flows, smaller eruptions within the summit area were often accompanied by phreato-magmatic activity. The three larger structures within the inner crater (El Centro dome, pyroclastic cones I and II) (Figs. 7 and 8) present sufficient evidence attesting to explosive phases during their construction.

In conclusion, post-plinian activity at Ceboruco was characterized by a variety of eruption styles and products, although the emission of lava flows predominated. During the last 1000 years a total of 7 lava flows were emplaced with individual volumes ranging between 0.07 and 2.11 km^3. A total volume of ~4 km^3 of lava was produced since the plinian Jala eruption. This yields an eruption rate of 0.004 km^3/yr for the last 1000 years. Since six of the seven lava flows with a total volume of ca. 3 km^3 were emplaced during the first 500 years after the Jala eruption, a much higher eruption rate of 0.006 km^3/yr is obtained for this time span.

The last major eruption (1870–1875) produced more evolved dacitic magma and was preceded by ca. 400 years of relative quiescence (for the exception of minor activity at the summit). The recognition of an evolutionary pattern (Fig. 10) might be useful in anticipating the timing, composition, and magnitude of future eruptions. When looking at the eruptive history for the last 1000 years it becomes clear that lava flows of andesitic compositions were produced in close sequence after short repose times (≤100 years), whereas repose times of several centuries (as was the case before the 1870 eruption) might result in a more evolved magma and more explosive eruptions.

7. Ceboruco's edifice volume and eruption rates over time

The AD 990–1020 (1060±55 yr BP) plinian Jala eruption that formed the large outer crater marked the end of Ceboruco's first constructional stage. This constructional period initiated probably in the Late Pleistocene, when andesitic lavas were emitted predominantly in an effusive manner building an edifice that might have reached ca. 2700 m a.s.l. (if a conical shape is assumed, as proposed by Nelson, 1980).

Nelson (1980) and Frey et al. (2004) calculated the volume of Ceboruco's present edifice at 60 and 47 km^3 respectively. The volume determined by Frey et al. (2004) is more accurate, because it was obtained considering a sloping base level and by using high-resolution orthofotos and other information not available before.

We propose that a volume of 46 to 48 km^3 of andesitic lava was produced during the first constructional stage, before the occurrence of the plinian Jala eruption. This number was obtained by adopting the volume of 47 km^3 for the entire present edifice (calculated by Frey et al., 2004) and subtracting ca. 4 km^3 of post-plinian lava flows (see previous section and Table 3), and adding either 2.7 km^3 (flat-topped edifice) or 4.5 km^3 (conical edifice) of missing rock from the former summit area. The total volume (depending on the shape of the former summit area) would be either 45.7 for a flat-topped or 47.5 km^3 for a conical-shaped summit respectively. The considerable volume of missing rock (2.7 to 4.5 km^3) that resulted from the formation of the outer crater by the plinian Jala eruption can be largely explained by subsidence. A smaller part of the missing volume was ejected and occurs as lithic fragments in the plinian Jala deposits (Gardner and Tait, 2000; Browne and Gardner, 2004). The volume of rock lost by subsidence was calculated for the two possible pre-plinian eruption edifice shapes, using a cylinder with a diameter of 3.7 km (diameter of outer crater) and a depth of 250 m (see Nelson, 1980) for the flat shaped model (2.7 km^3) and the same cylinder plus a cone (2.7+1.8=4.5 km^3) with a base of 3.7 km and a height of 500 m, assuming an originally 2700 m-high edifice (see Nelson, 1980). In conclusion, the pre-plinian edifice had a volume of ~46 to 48 km^3 depending on the previous morphology of the summit area.

Post-Jala-eruption lava flow volumes were calculated by Nelson (1980) at ~7 km^3, by Frey et al. (2004) at ~9.5 km^3, and in this study at ~4 km^3. All of these values yield high eruption rates of roughly 0.007, 0.0095, and 0.004 km^3/yr respectively. These rates are within the same order of magnitude as the rate of 0.002 km^3/yr reported for Colima volcano by Luhr and Carmichael (1980). Extrapolation of these eruption rates (obtained for the period encompassing the last 1000 years) to pre-Jala times would imply that the pre-plinian edifice formed in 8800 years (60 km^3 pre-plinian edifice; Nelson, 1980), 4000 years (38 km^3 pre-plinian edifice; Frey et al., 2004), and ~11,500 years (47 km^3 pre-plinian edifice; this study). Although resulting hypothetical edifice ages vary by more than 50%, all range within the same order of magnitude.

A dike exposed at the outer crater walls cuts several exposed lava flows and therefore represents a relatively young feature of Ceboruco's constructional (pre-Jala) stage. This dike was Ar–Ar dated at 45±8 ka by Frey et al. (2004). Such an age essentially implies that extrapolation of eruption rates is not possible and that eruption rates must have varied considerably over time. In fact, it seems valid to assume that Ceboruco's construction occurred in cycles interrupted by longer periods of quiescence.

In conclusion, the calculated eruption rates determined for the last 1000 years certainly cannot be applied to the earlier constructional stage of Ceboruco. Additional radiometric dates of rocks forming the older edifice are needed in order to calculate pre-plinian eruption rates, and hence be able to obtain a reliable estimate of Ceboruco's age.

8. Marquesado block-and-ash fan

The Marquesado block-and-ash fan at the SW foot of Ceboruco (Figs. 4, 6, 11, and 12A) fills the Ahuacatlán valley between Tetitlán and Ahuacatlán (Figs. 3 and 4). The Sierra El Guamúchil to the S limits the extent of this fan, which experienced important aggradations during and after the plinian Jala eruption. The crater walls of Ceboruco are breached to the N and SW facilitating the frequent emplacement of pyroclastic deposits and lava flows along barrancas in these directions and thus formation of the Marquesado fan, which at present is drained by the Tetitlán and Ahuacatlán rivers. The older deposits contributing to the Marquesado block-and-ash fan can only be observed in its distal parts (about 10 km from Ceboruco's crater) and in the deeply incised valley of the Ahuacatlán river where they are underlain by a >20 m fluvial conglomerate (Fig. 12A). These pyroclastic deposits include pumice fallout, pumice-and-ash flow, as well as hyper-concentrated lahar deposits that originated from the San Pedro volcanic field to the W (Figs. 1 and 12A) and interfinger with the Ceboruco deposits from the NE. The paleosol overlying the fluvial conglomerates and underlying this old pyroclastic sequence was dated at 21,075+680/−625 yr BP (Table 1, Fig. 12A). Thus, most of the deposits from Ceboruco comprising the upper part of the fan are younger than this age.

A source from Ceboruco for this older pyroclastic sequence can be excluded because of strong geochemical differences in clast compositions. Comparison of chemical analyses published by Petrone et al. (2006) with our chemical results obtained on pumice clasts of this pyroclastic sequence allows a tentative correlation with the Las Cuevas pumice from the San Pedro dome complex.

The majority of pyroclastic flow deposits produced during the plinian Jala eruption was emplaced to the SW on the Marquesado fan, where they reach a total thickness of up to 60 m and a volume of ~0.2 km^3 DRE (Nelson, 1980; Gardner and Tait, 2000). Hence, in the proximal facies of the fan outcrops displaying deposits related to the Jala eruption dominate (Figs. 11 and 12A). The sedimentological characteristics of the deposits change with distance from the vent. Proximal facies pyroclastic deposits (e.g. Copales quarry, Fig. 11B) include lithic-rich pumice-and-ash flow deposits and surges overlain by coarse lahar deposits. The pumice-and-ash deposits show gas segregation pipes indicating a hot emplacement. Monolithologic breccias occur at the base and as lenses within the pumice-and-ash flow deposits of the proximal and medial facies. Medial facies deposits

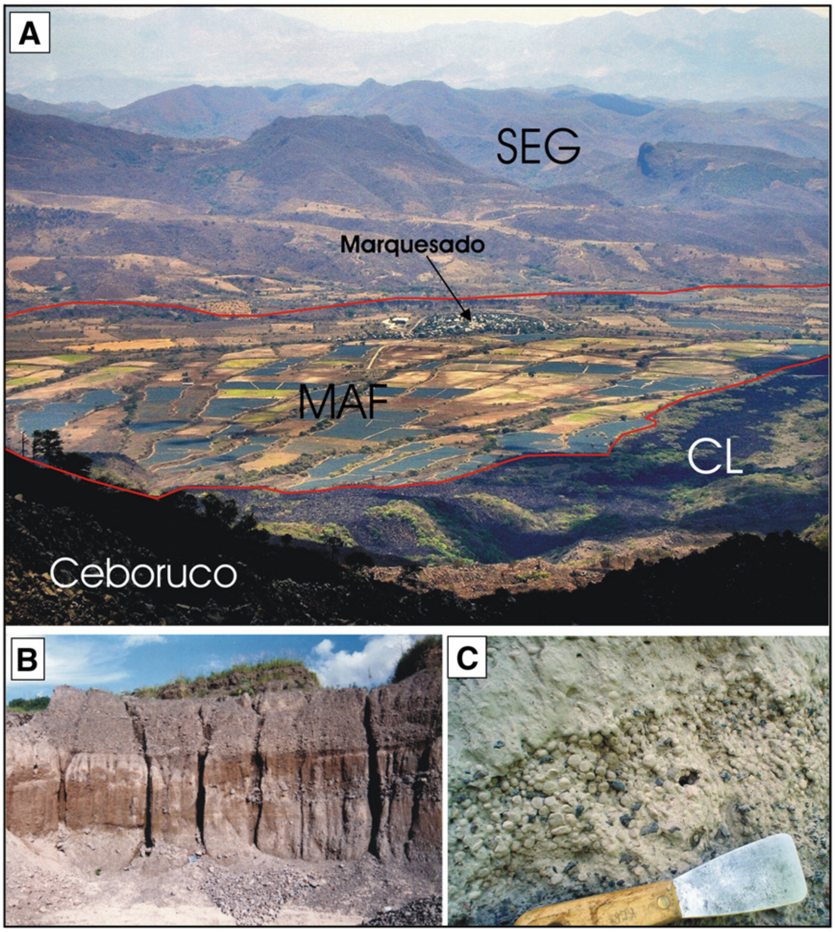

Fig. 11. (A) View from the 1870 crater rim toward the Marquesado ash-fan (MAF). Sierra El Guamúchil (SEG) and the Ceboruco lava flow (CL) are also indicated. (B) Outcrop displaying proximal facies deposits of the Marquesado fan (pyroclastic flows and surges) in a quarry near Copales village to the S of Ceboruco. (C) Close-up of the medial to distal facies deposits of the Marquesado ash-fan displaying a pyroclastic flow layer with abundant accretionary lapilli.

are often reworked or eroded and distal facies deposits include mostly ash-flow deposits with few lithics and rounded pumice clasts intercalated with minor lithic-enriched layers and fallout with abundant accretionary lapilli (Fig. 11C).

Data regarding the graben fill underneath the Marquesado fan was obtained at the CB-1 borehole (Fig. 4) drilled by CFE on the proximal part of the fan at an altitude of 1100 m a.s.l. (Ferrari et al., 2003). After drilling through 200 m of Ceboruco andesite lava flows, 50 m of rhyolite underlain by 160 m of basaltic lavas were encountered. Below that sequence a 70 m-thick fluvial conglomerate was reached at an altitude of 620–690 m a.s.l. Under the distal parts of the Marquesado fan conglomerates occur below 750 m a.s.l. while under the medial facies of the fan (in the deeply incised valleys of the Ahuacatlán river), conglomerates occur below 850 m a.s.l.. Such a distribution implies a southward shift in time of the Ahuacatlán river. Hence, major fluvial conglomerates seem to form the base of the Marquesado fan (Figs. 3 and 4). With this knowledge it is possible to estimate the maximum thickness of the fan by tracing the surface of the conglomerates found at CB-1 to outcrops in the present river system. A maximum thickness for the fan deposits of ca. 100 m is obtained. From these, ca. 60 m correspond to deposits formed by the Jala eruption. Multiplying the area occupied by the fan (38.75 km^2) with an estimated average thickness of Ceboruco deposits of ca. 30 m results in a total volume of 1.1 km^3.

The present day summit morphology of Ceboruco with large notches on the S and SW outer and inner crater walls will further facilitate the emplacement of gravity driven flows toward the Marquesado block-and-ash fan in the future. The associated high risk for the population dwelling on the fan is obvious.

The availability of water from the rivers has allowed the development of sugar cane plantations, despite of the sandy–gravelly nature of the fan's substrate. In addition, the villages of Marquesado and Uzeta (total population of ca. 2340 inhabitants, not counting scattered ranches; INEGI census, 2005) are situated within the depositional realms of the Marquesado block-and ash-fan. Furthermore, Ahuacatlán, Valle Verde, and Tetitlán (total of 8017 inhabitants, INEGI census, 2005) are located at short distances from the fan's margins. In this context it should be mentioned that the village of Ahuacatlán has existed for hundreds of years during which it has been destroyed by floods and subsequently rebuilt on several occasions (e.g. Tello, 1968). Tetitlán means "stony place" in Nahuatl but its present location on fertile clayey soils does not match this description. The historians de Arregui (1946) and de Ciudad Real (1976) hint that Tetitlán was originally located on the bouldery fan before it was abandoned and moved to its present position. In short, the Marquesado block-and-ash fan should certainly not be the first choice for future projects involving construction of major infrastructure.

9. Monogenetic vents

Late Quaternary eruptions in the study area are not limited to Ceboruco's crater but also concentrated along a 2-km wide and ca. 30 km long stripe within the Ceboruco graben. Monogenetic

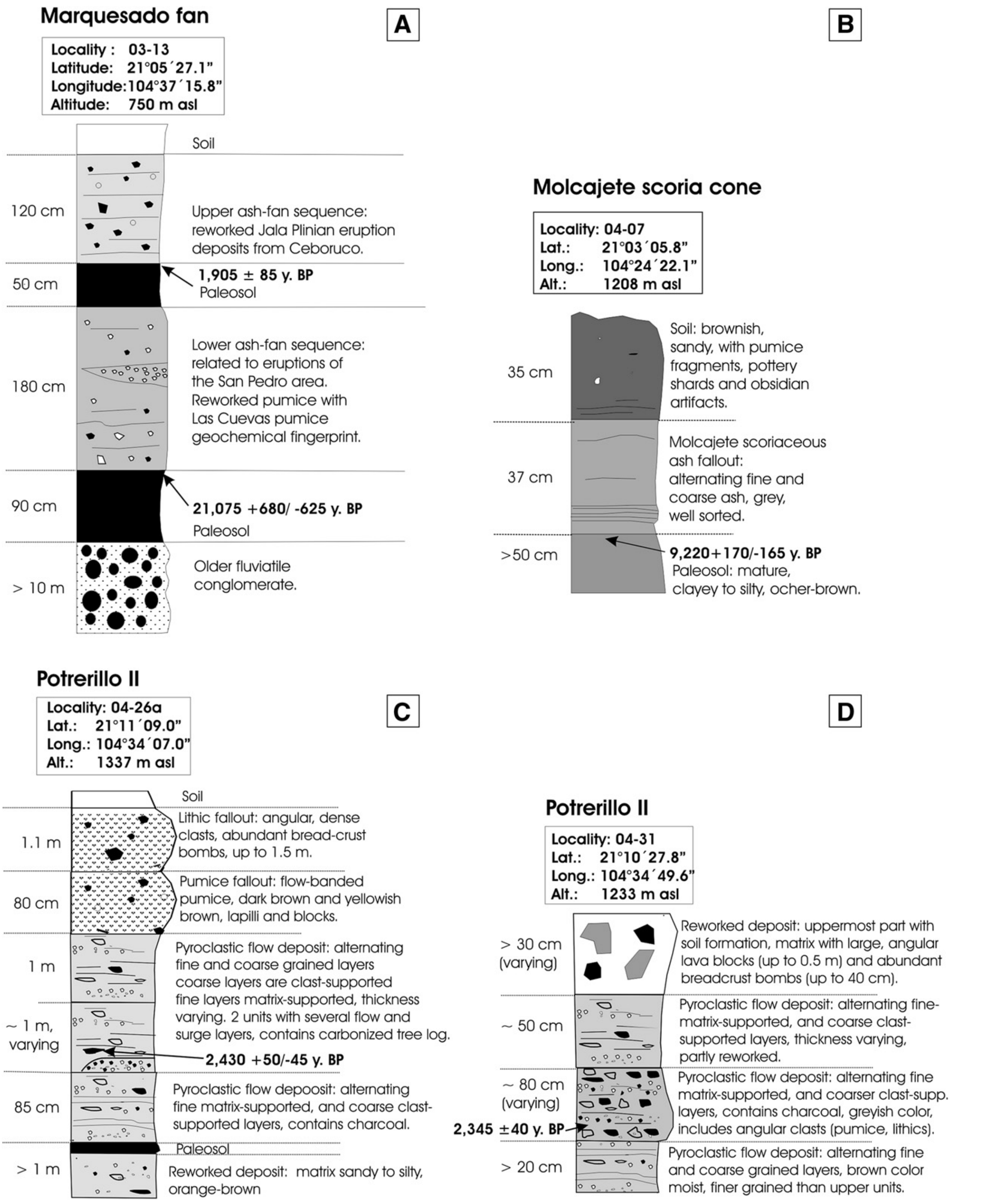

Fig. 12. Stratigraphic sections of outcrops where radiocarbon samples dating the Marquesado fan (A), the Molcajete scoria cone (B) and Potrerillo II tuff cone (C and D) were obtained.

volcanoes are aligned NW–SE along this zone of crustal weakness that parallels the northern limit of the graben and crosses the Ceboruco summit area (Figs. 3 and 4). They include basaltic-andesite scoria cones, silicic lava domes, and pyroclastic tuff cones, whose eruption styles were quite diverse. All monogenetic volcanoes are older than the plinian Jala pumice that covers them. Existing K–Ar and Ar–Ar ages (Petrone et al., 2001; Ferrari et al., 2000, 2002; Frey et al., 2004) have confirmed this. Scoria cones were typically built by an initial "strombolian" phase, followed by the emission of lava flows (Martin and Németh, 2006). Lava domes occur as isolated edifices or are agglutinated in dome complexes (Figs. 4, 13, and 14). Some domes were constructed solely by effusive activity, while others were preceded by phreato-magmatic and/or sub-plinian magmatic explosive activity. Three well-preserved pyroclastic tuff cones (Potrerillo I, Potrerillo II, and San Juanito) are located to the NW of Ceboruco (Figs. 3, 4, and 13).

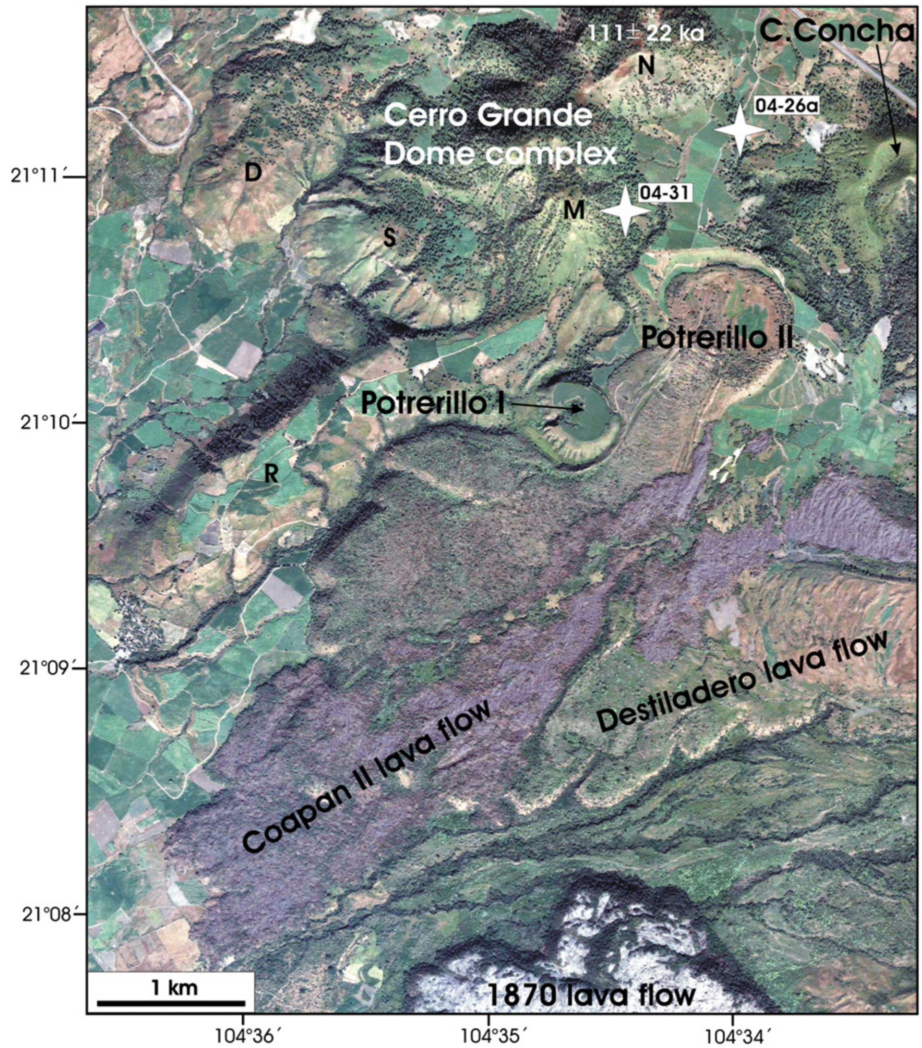

Fig. 13. Satellite image showing the Potrerillo tuff cones and associated domes, as well as locations of radiocarbon samples 04-31 and 04-26a. Cerro Grande dome complex (N, M, S) and associated lava flows (D and R) as well as Destiladero lava flow, Coapan II lava flow, and Cerro de la Concha scoria cone are also depicted.

Stratigraphic relations and products of Holocene monogenetic volcanoes dated in this study will be described in more detail below. Morphometric parameters determined following the methods described by Porter (1972) and Wood (1980) as well as compositions characterizing monogenetic vents are summarized in Table 4.

Volumes of monogenetic edifices were calculated using GIS programs (ILWIS and ArcViewGis). Each monogenetic edifice was outlined and its volume calculated by TIN (Triangulated Irregular Network) interpolation using the ArcViewGis program (Table 4). This volume calculation procedure is adequate for geometrically regular bodies with a more or less planar base. Since lava flows are often characterized by a highly irregular emplacement area, their volumes were calculated with a simpler method (in the same manner as the Ceboruco lava flows, see Section 6). A graph depicting ages, compositions, and volumes of Holocene monogenetic edifices is shown in Fig. 10B.

9.1. Scoria cones

A total of 18 scoria cones and associated lava flows occur in the Ceboruco graben within the study area (Fig. 3). Cone volumes vary between 0.007 and 0.15 km^3 and volumes of associated lava flows range between 0.01 and 0.65 km^3 (Table 4). Their compositions also vary considerably ranging from basalt (Balastre I, Fig. 14) to high-silica andesite (Cerro de la Concha, Fig. 13) (see also Figs. 3 and 4, Table 4). Their ages (Frey et al., 2004) range between 521±15 ka (Pedregal cones, Fig. 15) and 2±31 ka (San Juanito). Based on existing C-14 and Ar–Ar ages it can be said that during the last 12,000 years at least 6 scoria cones (Molcajete, Molcajetillo, Balastre I, Balastre II, Ceboruquito, San Juanito) were emplaced, which yields an average recurrence interval of ca. 2000 years (Table 5).

To the SE of Ceboruco, at the margins of the study area, recent monogenetic volcanism within the Ceboruco graben is concentrated in the area SE of Ixtlán del Río where six basaltic-andesite scoria cones (Cristo Rey, Pedregal I and II, Pata de Gallo, La Atarjea, and Pilareño) occur aligned in a NW–SE direction (Fig. 15).

Unfortunately, only two dates are available for products of these scoria cones. Cristo Rey located within the urban area of Ixtlán del Río was dated at 403±15 ka (Frey et al., 2004) and an older lava flow probably associated to La Atarjea (Fig. 15) was dated at 521±15 ka (Frey et al., 2004). This flow consists of at least to flow units, which cover a vast area of ca. 22.30 km^2 and have a total volume of 1.8 km^3 (Figs. 4 and 15). The lava shield emitted from Pata de Gallo scoria cone covers this older flow. The Pedregal II scoria cone was surrounded by the Pata de Gallo shield lavas and is therefore older than Pata de Gallo. More radiometric dates are needed in order to establish a detailed eruptive chronology in this zone.

Other older scoria cones in the study area are Gavilán (108±22 ka), Molcajetito, Cerro de la Concha (76±18 ka) and Tunita to the NW, and Peña Colorada (85±19 ka) to the SE of Ceboruco (Frey et al., 2004). Of these, only Gavilán produced a visible small lava flow.

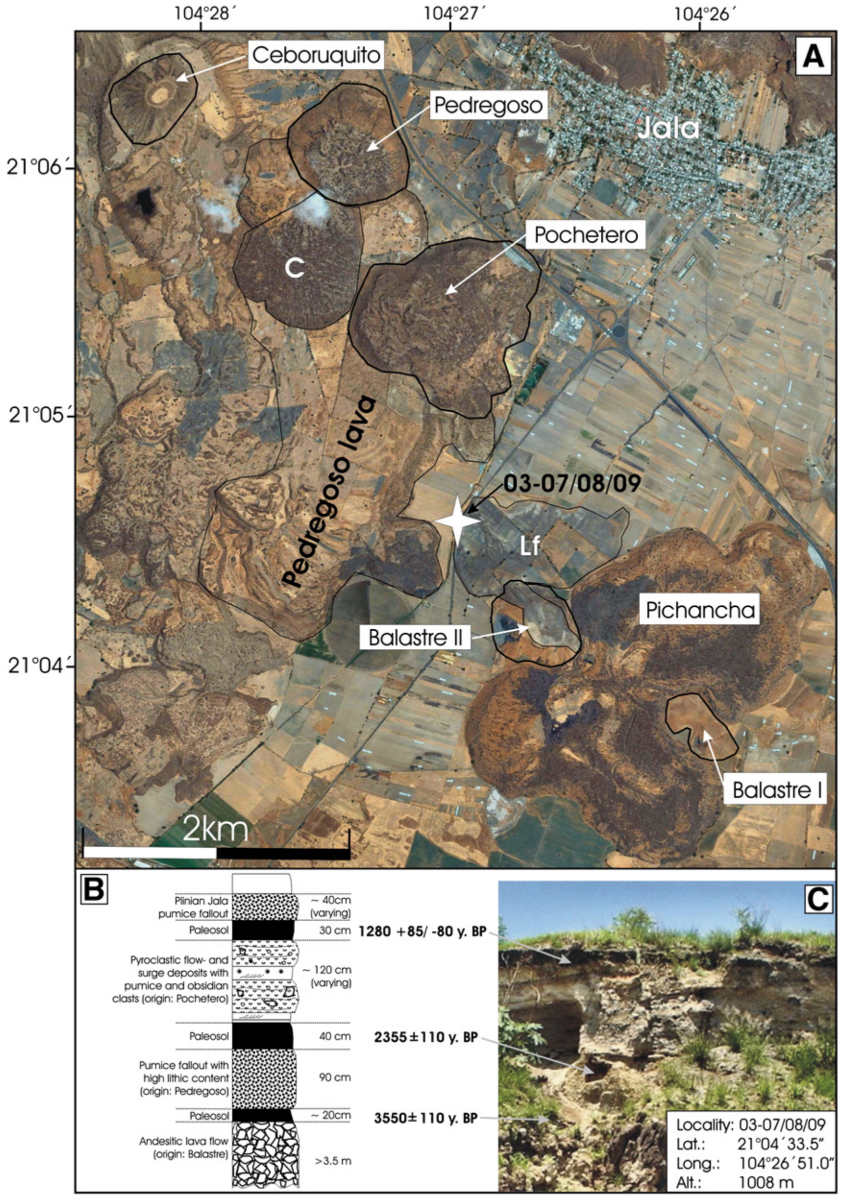

Fig. 14. (A): Satellite image showing monogenetic vents (domes and scoria cones) on the SE flank of Ceboruco. Stratigraphic section (B) and photo (C) indicating location of dated paleosols (location 03-07/08/09 in A).

In contrast, Los Amoles scoria cone (Figs. 3 and 4) dated at 0.14± 0.08 Ma (Petrone et al., 2001) produced at least two up to 13.4 km long lava flows with a combined volume of ~0.6 km^3. El Agujerado scoria cone (Figs. 3 and 4) dated at 34±7 ka (Frey et al., 2004) also emitted a lava flow with a volume of 0.1 km^3.

Holocene scoria cones include Molcajete, Balastre I and II, and Ceboruquito (Fig. 14) on the eastern side of Ceboruco, and Molcajetillo and San Juanito on the western side (Table 4). We dated the Molcajete scoria cone located 10 km to the SE of Ceboruco's crater at 9220+170/−165 yr BP (Tables 1 and 4, Figs. 3 and 12B). The Molcajete scoria cone was previously Ar^{40}/Ar^{39} dated at 54±20 ka (Frey et al., 2004). Considering the uncertainties inherent to the different dating methods as well as the nature of the dated materials, the new radiocarbon date for Molcajete is beyond doubt more precise and reliable. The Molcajetillo scoria cone is morphologically similar to Molcajete and might therefore be similar in age. Ages determined by Frey et al. (2004) are available for Molcajetillo scoria cone (12±11 ka) and for San Juanito (2±31 ka). Due to their large errors these ages are not of much use for establishing a refined chronology, yet they confirm the youthfulness of these cones (Figs. 3 and 4).

Finally, it is worth pointing out that the El Nogal scoria cone (No. 9 in Fig. 3) has not been mentioned in the literature before. This cone is located on the fault scarp delimiting the northern border of the graben near the villages of Las Coles and El Nogal (Figs. 3 and 4).

9.2. Pyroclastic tuff cones

In addition to pyroclastic cones (Pyroclastic cone I, Pyroclastic cone II, and Pre-El Centro) within Ceboruco's inner crater (described in Section 6), a total of three tuff cones (SW–NE aligned Potrerillo I and II, and San Juanito) occur to the NW of Ceboruco (Figs. 3, 4, and 13). In the case of San Juanito an initial phreato-magmatic phase produced a tuff cone whose crater was later occupied by a scoria cone. In a similar fashion the Potrerillo lava domes were emplaced after a phreato-magmatic phase that had previously built a tuff ring (Figs. 12C, D, and 13). San Juanito and Potrerillo II also erupted abundant dm-sized bread-crust bombs up to 1.5 m in diameter. The Potrerillo II is younger than Potrerillo I since its lava flow was forced to surround Potrerillo I dome which was an obstacle to its emplacement (Fig. 13). The Potrerillo II phreato-magmatic deposits

Table 4
Morphometric parameters (determined following the methods of Porter, 1972; Wood, 1980) characterizing monogenetic vents (scoria cones and lava domes) located in Ceboruco's vicinity (Fig. 3). Radiometric dates from Petrone et al. (2001), Ferrari et al. (2003), and Frey et al. (2004)

Scoria cones

Name	Age	Composition SiO_2 (wt.%)	Cone basal diameter (Wco) (m)	Cone height (Hco) (m)	Crater diameter (Wcr) (m)	Hco/Wco	Wcr / Wco	Direction max. Wco	Area covered by lava (km^2)	Average thickness (m)	Maximum lava flow length (km)	Aspect ratio (L/T)	Volume cone (km^3)	Volume total (km^3)
Cerro Colorado	430±0.17 ka	B 52.00	445 (430–460)	60	182.5 (180–185)	0.13	0.41	NW–SE	–	–	–	–	0.009	0.009
Cristo Rey	403±15 ka	BA 56.78	665 (650–680)	100	200	0.15	0.30	NW–SE	1.88	50	–	–	0.01	0.1
El Nogal	n.d.		215?	80	?	?	?	?	–	–	–	–	0.003	0.003
Pedregal I	n.d.	A 57.90	640 (630–650)	80	205 (130–280)	0.13	0.27	NW–SE	–	–	–	–	0.02	0.02
Pedregal II	n.d.	A 57.30	680 (660–700)	120	170 (160–180)	0.18	0.26	NW–SE	–	–	–	–	0.02	0.02
Gavilán	108±22 ka	A 58.17	665 (630–700)	80	190 (180–200)	0.12	0.32	NNE–SSW	0.9	80	1.7	17	0.02	0.09
Peña Colorada	85±19 ka	BA 54.09	690 (660–720)	100	270	0.14	0.39	NW–SE	–	–	–	–	0.02	0.02
Molcajetito	n.d	A 57.18	410	80	245 (240–250)	0.20	0.60	–	–	–	–	–	0.007	0.007
C. de la Concha	76±18 ka	A 59.30	750 (740–760)	140	285 (275–295)	0.19	0.38	NNE–SSW	–	–	–	–	0.05	0.05
La Tunita	n.d	BA 53.54	470 (420–520)	80	140	0.17	0.30	NNE–SSW	–	–	–	–	0.01	0.01
Los Amoles	~57±50 ka	BA 52.56	865 (840–890)	220	295 (280–310)	0.25	0.34	N–S	18.84	30	13.4	134	0.08	0.65
Agujerado	~34±7 ka	B 51.90 (1)	705 (630–780)	120	290 (280–300)	0.17	0.41	NW–SE	6.61	15	7.03	117.2	0.02	0.12
Molcajetillo	12±11 ka	BA 53.49	1250 (1200–1300)	240	495 (450–540)	0.19	0.40	NNE–SSW	–	–	–	–	0.15	0.15
Molcajete	9920+170/−165 yr BP	BA 54.00	805 (780–1130)	240	215 (210–220)	0.25	0.23	NW–SE	6.74	15	7.3	486.7	0.13	0.23
Ceboruquito	n.d	BA 53.34	585 (490–680)	120	210 (180–240)	0.21	0.36	NNE–SSW	9.93	15	8.5	566.7	0.01	0.16
Balastre II	n.d	BA 55.74	705 (670–740)	100	315 (300–330)	0.15	0.45	NW–SE	0.8	15	1.9	126.7	0.02	0.032
Balastre I	n.d	B 51.69	460 (320–600)	80	195 (160–230)	0.17	0.42	NW–SE	–	–	–	–	0.005	0.005
San Juanito**	2±31 ka	BA 53.66	300	80	142.5 (135–150)	0.27	0.48	–	–	–	–	–	0.01	0.01

Lava domes

Name	Age	Composition SiO_2 (wt.%)	Area covered by lava (km^2)	Average thickness (m)	Maximum lava flow length (km)	Volume dome (km^3)	Volume total (km^3)
Cerro Grande N	111±22 ka	D/67.9(1)	1.44	120	1.44		
Cerro Grande M		R/70.33	3.26	100	3.26		
Cerro Grande S		R/–	–				
						1.85	2.35
Cerro Alto lava dome	63±7 ka	R 69.82	–	–	–	0.14	0.14
Pedregoso lava dome	3550±110 yr BP	R 70.81	4.27 (LF) +1.44 (Do+C)	50	4.8 1.1	0.2 (Do+C)	0.41
Pochetero obsidian dome	2355±110 yr BP	R 74.14	–	–	–	0.14	0.14
Potrerillo I* lava dome	>Potrerillo II	D n.d	–	–	–	0.02	0.02
Potrerillo II* lava dome	2345±40 yr BP 2430+50/−45 yr BP	D 64.5	3.34	100	4.05	–	0.3 (Do+LF)
Pichancha coulée	>1060±55 yr BP <2355±110 yr	D 63.4				–	0.34

(1) SiO_2 content from Frey et al. (2004) + SiO_2 content (after normalization).
Do = dome, LF = lava flow, C = coulée.
* Lava dome in tuff ring.
** Scoria cone in tuff ring.
? Cone destroyed by mining.
B basalt.
BA basaltic-andesite.
A andesite.
D dacite.
R rhyolite.
n.d not determined.

Table 5
Erupted volumes, compositions, recurrence intervals, and eruption rates for different types of Holocene eruptions at Ceboruco and surrounding areas. Note that the volume of the Marquesado ash-fan (1.1 km^3 in ca. 21,000 yr) as well as volumes of pyroclastic surge, ash fallout, etc. are not considered in these simplified calculations

	No. of eruptions	Total volume (km^3)	Composition	Recurrence interval (years)	Eruption rate (km^3/1000 years)	% of total eruption rate
Scoria cones	6 in 12,000 yr	0.6	Basaltic-andesite	2000	0.05	1.11
Monogenetic domes	5 in 10,000 yr	1.2	Dacite and rhyolite	2000	0.12	2.65
Ceboruco lava flows	7 in 1000 yr	4	Andesite and dacite	143	4.0	88.50
Ceboruco Plinian pumice	1 in 10,000 yr	3–4	Rhyodacite	10,000 (?)	0.35(?)	7.74
					Total: 4.52	100%

contain abundant charcoal dated at 2345±40 yr BP at site 04-26a and at 2430 +50/−45 yr BP at site 04-31 (Fig. 12C and D) on the flanks of Cerro Grande dome complex (Figs. 3, 4, and 13). The slight difference of these ages is probably related to the nature of the carbonized pieces that include a branch with a diameter of 4 cm and a larger trunk with a diameter of about 15 cm.

The sequence of the Potrerillo II tuff cone (Fig. 12C and D) includes multiple phreato-magmatic surge and pyroclastic flow deposits overlain by a fallout sequence containing banded pumice followed by a second pumice fallout sequence with abundant trachy-dacitic bread-crust bombs. The subsequently emplaced Potrerillo II lava dome and associated flow are also trachy-dacitic in composition, but have slightly lower silica contents (Table 4).

9.3. Lava domes

The area to the W of Ceboruco is occupied by the Tetitlán and Ixletes lava dome complexes (Fig. 3) that are associated to the larger San Pedro dome complex.

Lava domes in the study area are dacitic to rhyolitic in composition and their volumes range between ca. 0.02 (Potrerillo I) and 0.6 km^3 (Cerro Grande).

Older lava domes include a cluster of three domes forming the Cerro Grande complex (Fig. 13) and the rhyolitic Cerro Alto dome (Fig. 3) dated at 64±7 ka (Frey et al., 2004). The northernmost dome of the Cerro Grande complex erupted 111±22 ka ago (Frey et al., 2004). A dacitic and a rhyolitic lava flow with a combined volume of 0.5 km^3 are associated with this dome complex (D and R in Fig. 13).

Younger lava domes reveal complex eruptive histories, as is the case of the Potrerillo lava domes (see Section 9.2). The silicic Pedregoso and Pochetero domes (Fig. 14) on the eastern flanks of Ceboruco were dated at 3550±110 and 2355±110 yr BP respectively (Table 1). The emission of both lava domes was preceded by explosive activity (Fig. 14B) whose deposits are underlain by paleosols displayed in outcrop 03-07/08/09 located at the road connecting Ahuacatlán and Jala (Fig. 14A). This outcrop revealed the eruptive sequence of nearby monogenetic domes Pedregoso and Pochetero, and Balastre I scoria cone. Based on direct observations and radiocarbon dates obtained at this specific outcrop (Fig. 14C) the eruptive sequence is the following:

After formation of scoria cones Balastre I and II, and the emplacement of an associated lava flow (Lf in Fig. 14A) a paleosol developed. This paleosol was dated at 3550±110 yr BP. This date represents a maximum age for an overlying pumice fallout deposit. Analyzed lapilli clasts from this fallout have a chemical fingerprint that points towards the nearby

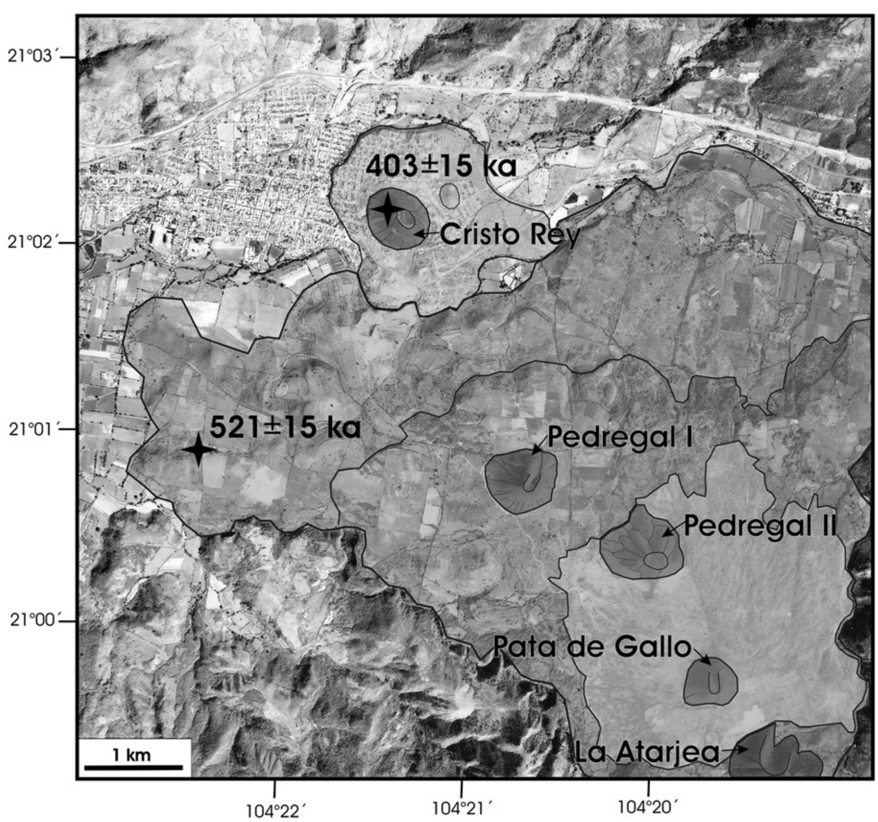

Fig. 15. Aerial photograph showing the NW–SE aligned scoria cones SE of Ixtlán del Río (Cristo Rey, Pedregal I, Pedregal II, Pata de Gallo, and La Atarjea) as well as the limits of two associated lava flows. The locations of Ar–Ar (Frey et al., 2004) and K–Ar (Petrone et al., 2001) dated samples are indicated by stars.

trachy-dacitic Pedregoso lava flow (Fig. 14A). This flow was emplaced during the early stages of the Pedregoso dome eruption. We speculate that the vent from which the pumice fallout originated is the same as that from which the Pedregoso flow and dome were emitted during later stages of the eruption (Fig. 14). The pumice fallout includes a variety of xenolithic clasts including abundant red scoria that is similar to scoria from the nearby older Ceboruquito cone. In short, we believe that the lapilli pumice fallout corresponds to an initial sub-plinian explosive phase that preceded the emplacement of the Pedregoso trachy-dacitic lava flow and subsequent Pedregoso rhyolite dome. The red scoria clasts were picked up from older Ceboruquito deposits at the vent. The granulometry (mostly lapilli) and distribution of the pumice fallout deposit, which occurs around La Pichancha coulée as well as in the entire Jala valley (Fig. 14) also favor an origin from a vent buried underneath Pedregoso dome.

A soil above the pumice fallout deposit (Fig. 14B) was radiocarbon dated at 2355±110 yr BP. This soil is overlain by a sequence of pyroclastic flow-and-surge deposits that originated at the Pochetero rhyolite dome (Figs. 3, 4, and 14A). Proximal facies deposits of this sequence crop out directly underneath the Pochetero rhyolite dome. Finally, the last eruption in this zone produced the La Pichancha coulée (Fig. 14), which is neither covered by Pedregoso nor by Pochetero deposits, but is covered by Jala plinian fallout. This means that La Pichancha is younger than 2355±110 yr BP (Pochetero) but older than 1060±55 yr BP (Jala).

From the above it can be concluded that during the last 10,000 years a total of 5 silicic monogenetic domes (Pedregoso, Potrerillo I, Potrerillo II, Pochetero, and Pichancha) formed in the surroundings of Ceboruco with a total volume of 1.2 km^3. This yields a recurrence interval of 2000 years and an average eruption rate of 0.12 km^3/1000 years (Table 5). Furthermore, it is interesting to note that these 5 domes were all emplaced within a period of time that lasted only 2000 years (between 3550±110 yr BP and ca. 1500 yr BP).

10. Conclusions and implications for hazard studies and archaeology

13 new radiocarbon dates were obtained during this study. The six dating the plinian Jala eruption helped to further constrain the age of this most important eruption of Ceboruco and furthermore to determine an exact calibrated age of AD 990–1020. Also, the ages of one scoria cone (Molcajete), two lava domes (Pochetero and Pedregoso) as well as a pyroclastic cone (Potrerillo II), which were previously not dated (or the ages included large errors), were obtained. A paleosol underneath ash fallout from the Molcajete scoria cone (SE of Ceboruco) yielded an age of 9220+170/−165 yr BP, and paleosols underneath pyroclastic deposits related to the Pochetero obsidian and Pedregoso rhyolitic domes yielded ages of 2355±110 and 3550±110 yr BP respectively. Two charcoal samples in pyroclastic flow deposits from the Potrerillo dacitic dome were dated at 2345±40 and 2430±50/−45 yr BP. Finally, the oldest age of 21,075+680/−625 yr BP was determined on a paleosol underneath a sequence of pyroclastic flows and lahars that form the stratigraphically lower part of the prominent Marquesado ash-fan to the SW of the volcano. These new radiocarbon dates, the study of historical documents together with the geologic map and the stratigraphic data, determination of erupted volumes and eruption rates, all helped to contribute to already existing data and therefore to move a step further towards the important goal of obtaining a more complete age-supported eruptive history of Ceboruco and the surrounding monogenetic vents.

Volcanic activity is distributed unevenly along the TMVB. In the western TMVB eruptions occur most frequently at Colima volcano, but this study shows that Ceboruco volcano should be considered as another probable source of potential activity in the near future.

Although Ceboruco's early eruptive history still remains largely in the shadows, its most recent history could be partly unraveled. Accordingly, its activity increased substantially and peaked around AD 990–1020 in an unprecedented plinian eruption of high magnitude (VEI=6) that ejected a large volume (3–4 km^3 DRE) of pumiceous rhyodacitic materials (Gardner and Tait, 2000).

During the next 500 years the volcano remained quite active until the arrival of the Spaniards in the early 16th century. During this time span a total of 6 lava flows with accompanying block-and-ash flow activity were emplaced. Volume and composition of these lavas changed systematically through time. The first lava flow (Copales) was dacitic with a large volume of 2.11 km^3 while the last lava flow (Ceboruco) was andesitic with a small volume of only 0.16 km^3 (Figs. 6, 10; Table 3). After a period of more than 300 years of relative quiescence, Ceboruco reawakened in 1870 and remained active until 1875. The principal product of this historic eruption is a 7.7 km long dacite lava flow with a volume of 1.14 km^3 (Table 3). Its emplacement was again accompanied by the frequent production of block-and-ash flows that detached from the advancing lava flow front.

With the above background in mind, it seems safe to assume that the next period of activity will again most likely produce a lava flow with accompanying block-and-ash flows. The historical documentation of the 1870–75 eruption sheds some light on the possible course of events and approximate duration of such a hypothetical future eruption, which will certainly be preceded by months of seismic activity and increased fumarolic activity prior to the actual emergence of viscous lava near the summit area. Due to the present morphology of the crater area, a new andesite/dacite lava flow will most probably flow downhill on Ceboruco's SW flanks. Accompanying block-and-ash flows will also be channeled along barrancas draining the volcano towards the SW. Such lethal pyroclastic flows will deposit their load primarily on the area presently occupied by the Marquesado ash-fan. Preventive evacuation of villages and closure of roads (including freeway no. 15) would cause serious disruptions.

A repeat of the plinian Jala eruption seems unlikely but should not be entirely discarded. Such an eruption would not only have devastating effects on nearby towns (e.g. Jala and Ahuacatlán) and surrounding agricultural areas, which would become buried underneath several m of pumice and ash, but also lay waste to freeway no. 15 connecting Guadalajara with the Pacific coast. If prevailing winds during the eruption would be blowing toward the NE (as occurred during the Jala eruption), substantial amounts of pumice and ash would become deposited within the catchment area of the Río Santiago (Fig. 16), which represents the most important drainage of western Central Mexico toward the Pacific. The Río Santiago (Fig. 16) is located only 23 km (shortest distance to the NE) from Ceboruco. There, at 34 km distance from the volcano, the recently built El Cajón dam and hydroelectric power plant (750 MW, one of the largest in Mexico) as well as the La Yesca dam (750 MW, presently under construction) would both certainly become affected by copious lahars derived from the plinian fallout deposits. Although the lifetime of such dams is limited to several decades, such a scenario would have severe implications and remains to be elucidated in more detail in the future. The study of Jala lahar deposits along the banks of the Río Santiago represents an important project that will not only produce valuable information in regard to potential future hazards, but also contribute to the archaeology of this region. In this context it should be mentioned that the plinian Jala eruption roughly coincides in time and magnitude with Popocatépetl's last plinian eruption, which occurred ca. 1100 yr BP in Central Mexico (e.g. Siebe et al., 1996a; Siebe and Macias, 2006). Lahars derived from the primary plinian fallout of the 1100 yr BP eruption at Popocatépetl laid waste to the valley of Puebla severely affecting important pre-Hispanic cities such as Cholula and Xochitécatl (Siebe et al., 1996b).

Both eruptions, Jala and Popocatépetl, fall within the transition from the Classic period to the Post-Classic period of Mesoamerican archaeology. These times were characterized by migrations and important cultural changes. Unfortunately, the role and impact of

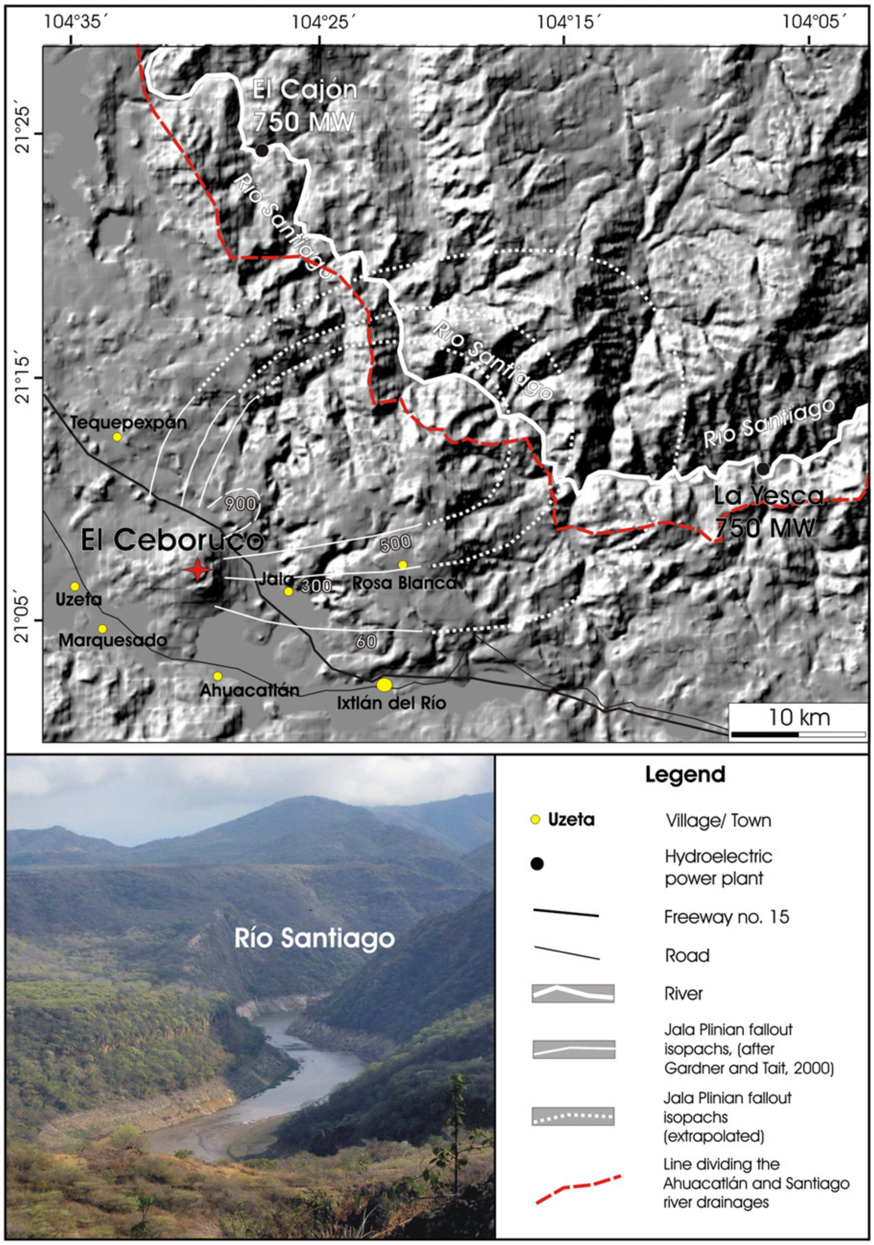

Fig. 16. Sketch map showing Ceboruco's position and Jala plinian pumice fallout isopachs with respect to the Río Santiago catchment area. Lahars derived from primary plinian fallout could seriously affect the operation of existing El Cajón and La Yesca (presently under construction) hydroelectric power plants. Wet ash falling on electric lines could also cause serious transmission problems and power outages.

volcanic eruptions on the development of pre-Hispanic civilizations still remains largely unexplored.

A plinian eruption from Ceboruco would certainly also have an impact on more distal locations. Ash fallout could easily reach Guadalajara (~1.6 million inhabitants; INEGI census, 2005), located 130 km to the E where it would cause interruptions to transportation, most notoriously to aviation safety, among other serious annoyances.

From the present study, it also becomes clear that future eruptions should not only be expected from Ceboruco's crater area, but to a minor extent also from adjacent areas to the NW and SE. At least 11 monogenetic eruptions have occurred during the Holocene along a 2 km narrow and ca. 30 km long stripe that intersects Ceboruco's crater in a NW–SE direction (Fig. 4, Table 4). During the first half of the Holocene 6 basaltic-andesite scoria cones formed (Fig. 10B). These eruptions initiated mostly in a “strombolian” fashion and terminated with the emplacement of lava flows. During the second half of the Holocene (last 5000 years) monogenetic activity consisted in the emplacement of 5 silicic domes, most of which were preceded by violent explosive activity that was either phreato-magmatic (e.g. Potrerillo I and II) or sub-plinian (e.g. Pedregoso) in character. This means that on average one monogenetic eruption occurred every 1000 years (Fig. 10B,Table 5). Although a wealth of radiometric dating remains to be done, the presently existing data-base allows to conclude with all certainty that Ceboruco volcano and surrounding areas are one of the most active in the entire TMVB. In consequence, geophysical monitoring (especially installment of a seismic network) and construction of a hazard map should be mandatory. Furthermore, civil protection authorities should initiate a program geared towards the mitigation of volcanic hazards in this region. Such a program should include legislation in regard to land use, implementation of rational economic development policies, and an efficient public information campaign.

More than 130 years have elapsed since the end of Ceboruco's last eruption. All this time the volcano has remained in a state of weak fumarolic activity. At this point it is not possible to anticipate the timing of its next reawakening but it would be desirable that minimum measures of preparedness will be implemented by then.

Acknowledgements

This research was funded by grants CONACyT-50677-F and UNAM-DGAPA IN-101006 to Claus Siebe. We thank Chris Eastoe (Radiocarbon Laboratory, Tucson, Arizona) for dating charcoal samples and Michael Abrams (Jet Propulsion Laboratory, Pasadena, California) for providing Landsat imagery funded by NASA. This work is part of K. Sieron's doctoral thesis work funded by a scholarship from Posgrado en Ciencias de la Tierra, UNAM. Some of the radiocarbon dates were defrayed by DFG-project Ma-2440/1 (Ulrike Martin, principal investigator). E. Widom kindly reviewed an early version of the manuscript. Journal reviewers Lee Siebert and Dawnika Blatter made constructive suggestions for improving this paper.

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