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Late Pleistocene to Holocene eruptive activity of Pico de Orizaba, Eastern Mexico

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Abstract. The Late Pleistocene to Holocene eruptive history of Pico de Orizaba can be divided into 11 eurptive episodes. Each eruptive episode lasted several hundred years, the longest recorded being about 1000 years (the Xilomich episode). Intervals of dormancy range from millenia during the late Pleistocene to about 500 years, the shortest interval recorded in the Holocene. This difference could reflect either changes in the volcano's activity or that the older stratigraphic record is less complete than the younger. Eruptive mechanisms during the late Pleistocene were characterized by dome extrusions, lava flows and ash-and-scoria-flow generating eruptive columns. However, in Holocene time plinian activity became increasingly important. The increase in dacitic plinian eruptions over time is related to increased volumes of dacitic magma beneath Pico de Orizaba. We suggest that the magma reservoir under Pico de Orizaba is stratified. The last eruptive episode, which lasted from about 690 years BP until AD 1687, was initiated by a dacitic plinian eruption and was followed by effusive lava-forming eruptions. For the last 5,000 years the activity of the volcano has been gradually evolving towards such a trend, underlining the increasing importance of dacitic magma and stratification of the magma reservoir. Independent observations of Pico de Orizaba's glacier early this century indicate that some increase in volcanic activity occurred between 1906 and 1947, and that it was probably fumarolic.

Key words: Volcanism – Mexico – Holocene – History – Pico – Citlaltepetl – Volcano

Introduction

Pico de Orizaba is among the more voluminous volcanoes of the Trans Mexican Volcanic Belt (TMVB). It reaches an altitude of some 5700 m, rising 3500 m above its surroundings, the Altiplano or the Mexican plateau (Fig. 1). The volcano has been active since early Pleistocene time, most recently AD 1537–1687 (Simkin et al. 1981). The evolution of Pico de Orizaba during Pleistocene to Holocene time has been divided into three main sequences (Table 1). During early to late Pleistocene (Sequence I and II) basaltic andesite to dacite erupted to form a stratovolcano 50 km in diameter at its base (Fig. 2).

About 33000 years BP the cone of Pico de Orizaba collapsed, forming an 11-km^3 debris avalanche that flowed eastward some 60 km down the Tliapa and Tlacohuatl valleys to the plains of Cordoba. An amphitheater-shaped crater (here after named the Teteltzingo crater) 3.5 km in diameter, and facing northeast, was formed in this event (Fig. 2) (Hoskuldsson et al. 1990). The Xocotla ignimbrite, which formed in an eruption simultaneous with the collapse event, carries evidence of mixing between dacitic and adesitic magma. Such magma mixing has not been observed in older rocks from Pico de Orizaba. Furthermore it has been shown that volcanism in the surrounding area was activated around 36000–33000 years BP (Robin 1981; Negendank et al. 1985). This implies that an intense magma injection into the volcanic system was initiated at this time. Continuation of such an injection during late Pleistocene to Holocene time, as implied by volcanic activity in the area until around 4000 years BP, considerably increased Pico de Orizaba's eruption rate and frequency of pyroclastic ejecta (Hoskuldsson 1992).

Volcanism in the region is related to oblique subduction of the Cocos Plate under the North American Plate (Fig. 1) (Nixon 1982). An important sinistral transform fault system underlies the volcanic system of Pico de Orizaba. It has been suggested that this fault system may be generated due to friction between the

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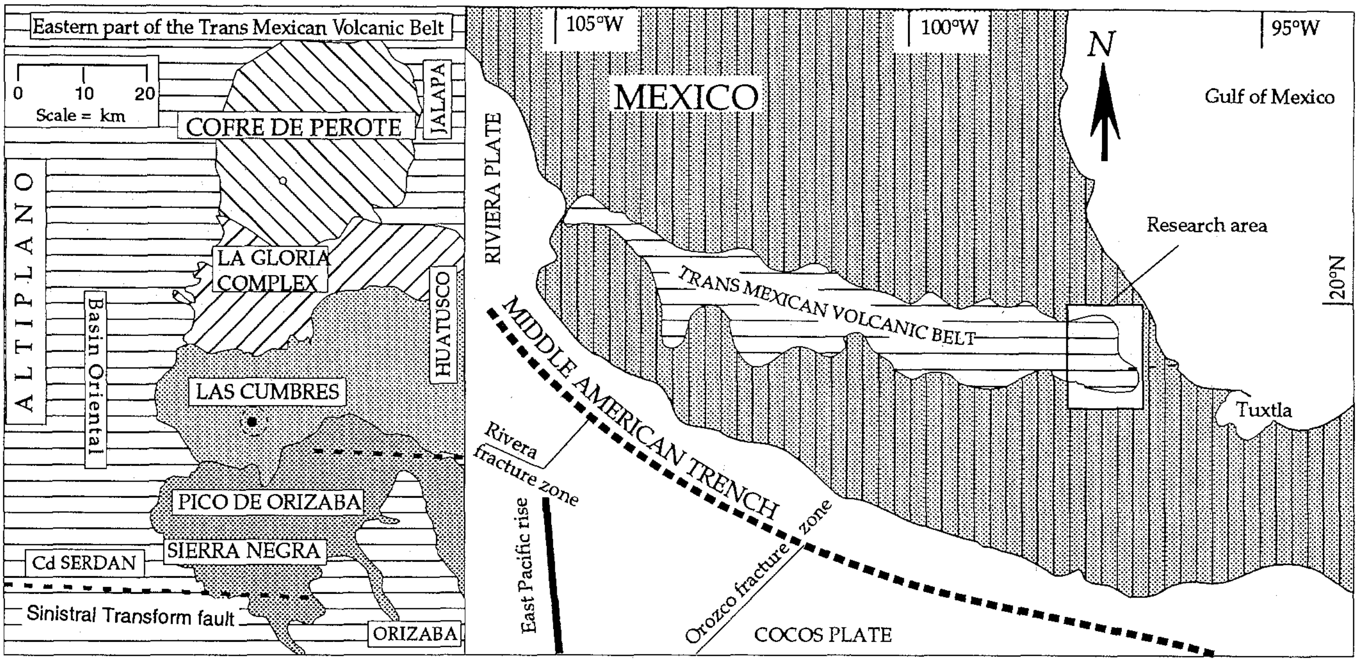

Fig. 1. Map of Pico de Orizaba, an area in the easternmost part of the Trans Mexican Volcanic Belt, and its tectonic setting. The Orizaba area has five principal volcanic fields which become progressively younger southward

Table 1. Stratigraphical division of eruptive activity at Pico de Orizaba

Sequence	Episodes	Age	Total volume	Eruption rate
Sequence III		AD 1687 32000 years BP	70 km^3	0.22 km^3/100 years
Sequence II	Teteltzingo Tecomale Orizaba	0.08–0.032 m.y. 0.15–0.08 m.y. 0.24–0.15 m.y.	100 km^3 (SN = 8 km^3)	0.05 km^3/100 years
Sequence I	La Perla Calcahualco Metlac	0.40–0.24 m.y. 0.60–0.40 m.y. 0.90–0.60 m.y.	200 km^3 (SN = 16 km^3)	0.04 km^3/100 years

SN = Sierra Negra volcano
Volume estimates are obtained by calculating a cone-shaped volcano during each sequence, and divided by the sequence time span we obtain average eruption rate (Modified after Hoskuldsson 1992)

subducted plate and the overriding American plate. It probably facilitates the ascent of magma to the surface through intensively fractured continental crust (Mooser and Maldonado-Koerdell 1961; Hoskuldsson 1992). Furthermore the regional volcanism is propagating southward; the oldest edifice, Cofre de Perote, is in the north. This propagation is probably related to steepening of the subducted slab underlying the volcanic chain (Cantagrel and Robin 1979; Robin 1981; Hoskuldsson 1992).

Several studies have recently been carried out on the late Pleistocene to Holocene activity of Pico de Orizaba. Robin and Cantagrel (1982) suggested that eruptive activity is periodic with intervals of some 1000 years supported by radiocarbon dating of pyroclastic ejecta and lava flows. Cantagrel et al. (1984) highlighted the importance of magma mixing during Holocene activity at both Pico de Orizaba and Popocatepetl. Calvin et al. (1989) concluded from Sr-isotope measurements that crustal contamination became increasingly important in Holocene eruptive products. Robin (1981), Cantagrel et al. (1984) and Negendank et al. (1985) showed that a major magma pulse occurred along the east TMVB in late Pleistocene to early Holocene. Siebe et al. (1991) reported a Holocene date on block-and-ash-flow deposits at the village of Avalos west of Pico de Orizaba, which they linked to summit-dome growth.

Here we give a detailed account of the eruptive activity of Pico de Orizaba during late Pleistocene to Holocene time. Rocks from this time having been grouped in Sequence III (Hoskuldsson 1992). We show that the activity of the volcano is periodic and can be divided into episodes of volcanism that last for several hundred years. These episodes are spaced hundreds to thousands of years apart when the volcano has only fumarolic or no activity (Fig. 3).

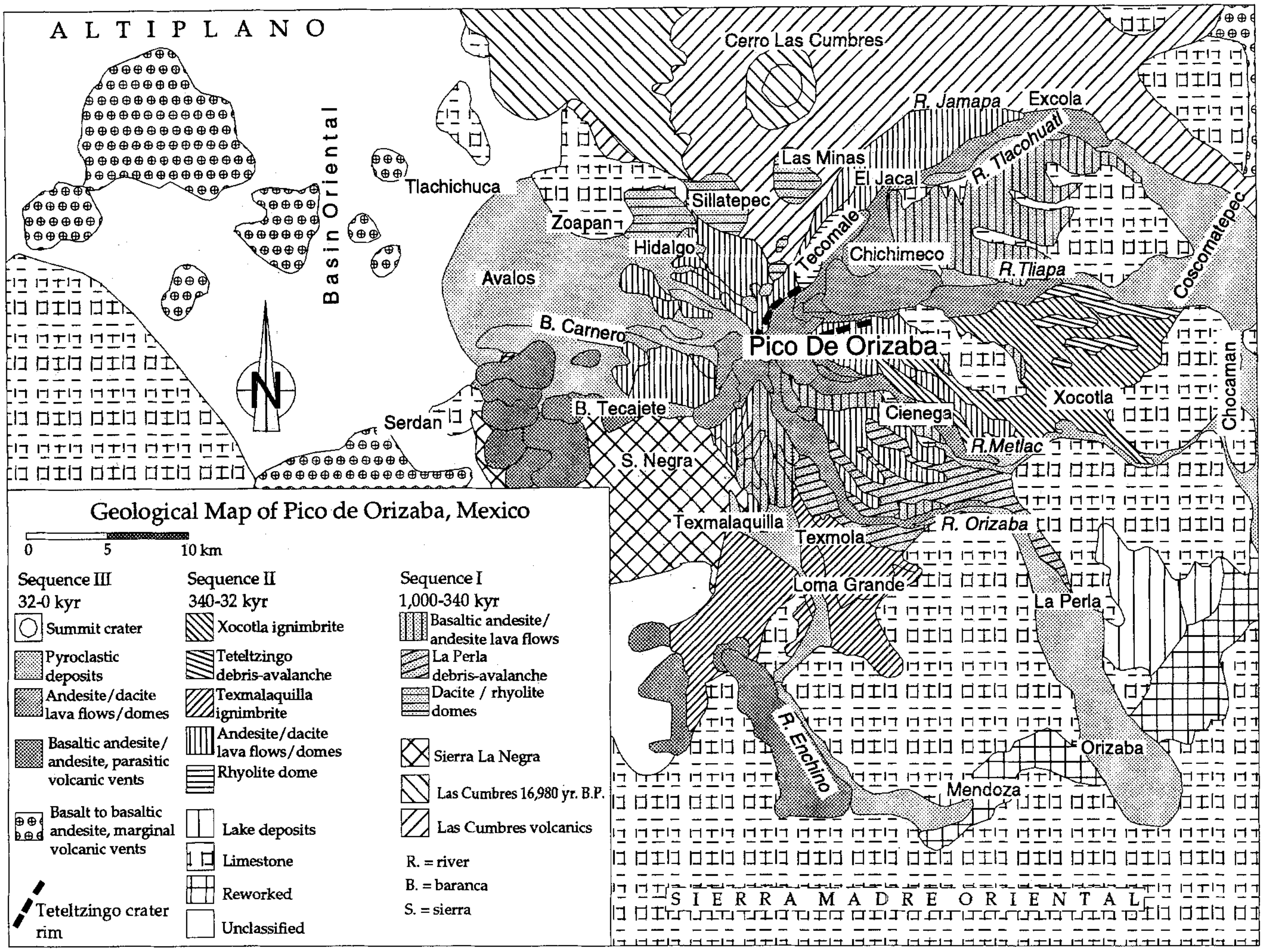

Fig. 2. Simplified geologic map of the volcanic complex Pico de Orizaba. This paper is concerned primarily with deposits from Sequence III

Methods and nomenclature

For the rock classification, schemes given by Le Maitre (1989) were used. The field classification scheme was used unless chemical analyses were at hand, then classification was made by the total alkali versus silica diagram (Fig. 4).

Pyroclastic material was classified as pyroclastic flow or airfall deposits. Pyroclastic-flow deposits were further classified by their inferred eruptive mechanism, according to Wright et al. (1980) and Smith and Roobol (1991). The classification of the airfall deposits was made according to criteria given by Fisher and Schmincke (1984).

Standard field methods were used to describe and measure sections and map different geological units. In volume calculations 1:50000 maps from INEGI, the Mexican geographic institute, were digitized into a GIS-system by which the surface area of each unit was calculated. Average thickness of the units is the mean thickness measured in field. Dense rock equivalent (DRE) corrections are based on 2.2 g/cm^3 as an apparent density of lavas, and 2.9 g/cm^3 as true density. For the pyroclastic-flow deposits we used 1.9 g/cm^3 for apparent density and 2.9 g/cm^3 for true density. It should be noted that the loose packing of pyroclastic deposits could further decrease their apparent density, thus the deposits could be the subject of a minimum error of up to 20% (Hoskuldsson 1986).

All ^{14}C dating was carried out at 'Centre des Faibles Radioactivities'. Gif Sur Yvette, France.

Stratigraphy and field relations of the deposits

To the west of Pico de Orizaba on the 'Altiplano' (Mexican plateau), sections of the deposits were measured in shallow erosion furrows. Figure 5 shows schematic cross sections through these deposits. Correlation between different eruptive units was based on key tephra layers and dated pyroclastic-flow deposits. In the western area a hiatus of lava flow and pyroclastic-flow deposits derived from Pico de Orizaba accumulated between 33000 and about 10000 years BP. During this time phreatomagmatic deposits from parasitic volcanic vents were also important (Fig. 5, A74). The de-

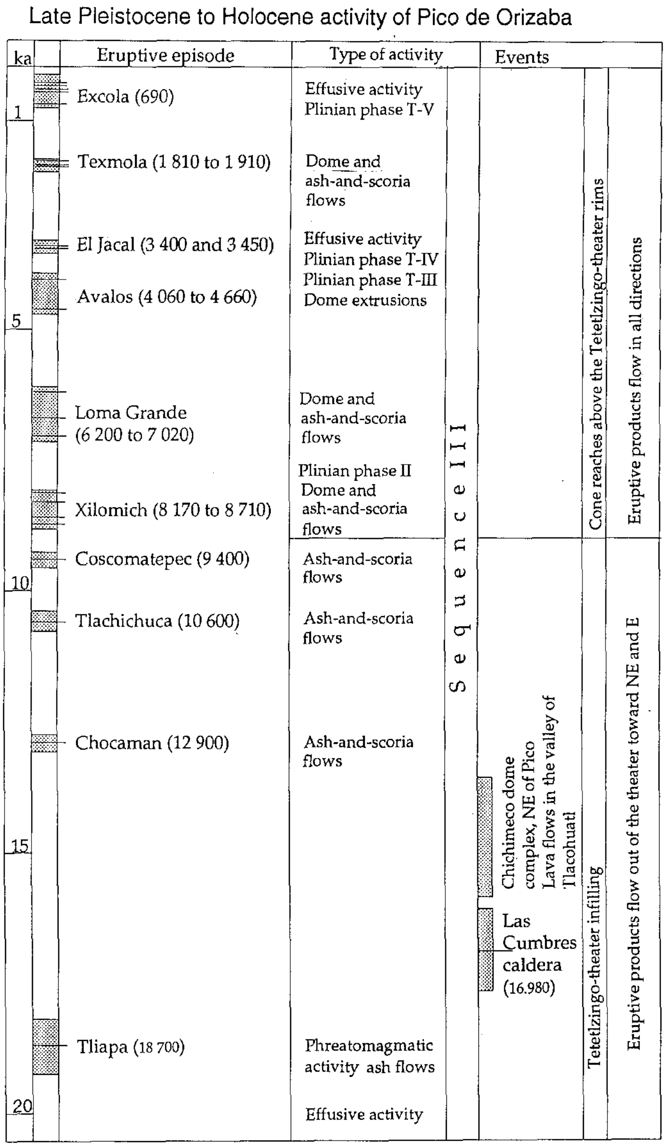

Fig. 3. Summary of the late Pleistocene to Holocene eruptive history of Pico de Orizaba. Regional volcanic events are shown to the right. *Dates in brackets* are ^{14}C in years before present. *Shaded areas* show the time length of an eruptive episode including the error associated with ^{14}C dating

posits from the parasitic vents diminished sharply by around 9000 years BP. (Fig. 5, R60 and A74) and are not again interbedded with volcaniclastics from Pico de Orizaba until about 4060 years BP, when andesitic scoriae is interbedded with plinian layer T-III (Fig. 5). This intercalation of andesitic and dacitic tephra was not found elsewhere in layer T-III, which suggests that the andesite originated from a vent in the west.

Descending east from Pico de Orizaba are six main valleys, from north to south: Jamapa, Tlacohuatl, Tliapa, Metlac, Orizaba and Enchino (Figs. 2, 6). Five of them have channeled pyroclastic- and lava-flows down the flanks of the volcano, and in the sixth (Jamapa valley) several lahars and till-like sediments were observed.

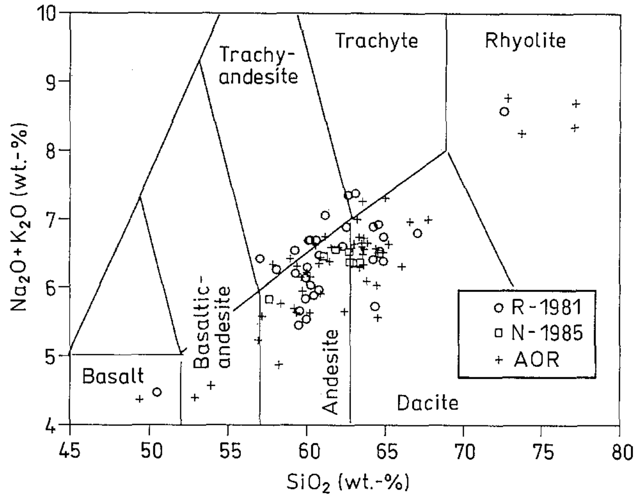

Fig. 4. Total alkali versus silica diagram illustrating the classification of eruptive products from Pico de Orizaba. Most rocks lie within the andesite and dacite field. A slight trachytic affinity is observed. Basaltic samples are from marginal vents, whereas the basaltic andesite samples come from parasitic vents. All analyses were normalized anhydrous before plotting. *R-1981* samples from Robin (1981), *N-1985* samples from Negendank et al. (1985) and *AOR* samples from Hoskuldsson (1992)

Sections in the valley of Tlacohuatl are shown in Fig. 7. Correlations between the sections were based on ^{14}C dating and stratigraphic position. The Tlacohuatl lava flows and block-and-ash flows, compositionally identical to the Chichimeco dome complex, form a succession in the middle of the valley. In an exposure running along the east side of the valley are two pyroclastic-flow units. The lower unit was dated at 8620 years BP. Two tephra layers, T-IV and T-V dated at 3450 and 690 years BP respectively (Table 2), were observed in all soil profiles.

Figure 8 shows the stratigraphic relations in the valley of Tliapa. The sections show field relations from the plains of Chocaman (Figs. 2, 6) up to the dome complex Chichimeco on the NE side of Pico de Orizaba summit. Four pyroclastic-flow sequences were dated at 18700, 12900, 9400, and 7020 years BP respectively (Table 2). From about 20000 until 13000 years BP is a major hiatus. Three tephra layers crop out in soil sections: T-III, T-IV, and T-V, T-IV, and T-V. They formed beds up to 1 m thick at 9 km from the summit, whereas the T-III was only a few centimeters.

Figure 9 shows the stratigraphic relation in the valley of Metlac. All deposits observed on the floor of the present valley are Holocene, the oldest being about 6600 years BP. Within this valley there is a hiatus between about 32000 years BP, the estimated time of emplacement of the Xocotla Ignimbrite, and 6600 years BP.

Stratigraphic relationships of the La Perla pyroclastic sequence are exposed in the valley of Orizaba (Figs. 2, 6, 7). The youngest deposit in the valley is a lava flow dated at 3400 years BP (Robin and Cantagrel 1982) and embedded within the pyroclastic sequence. Correlation with other sequences are based on the sim-

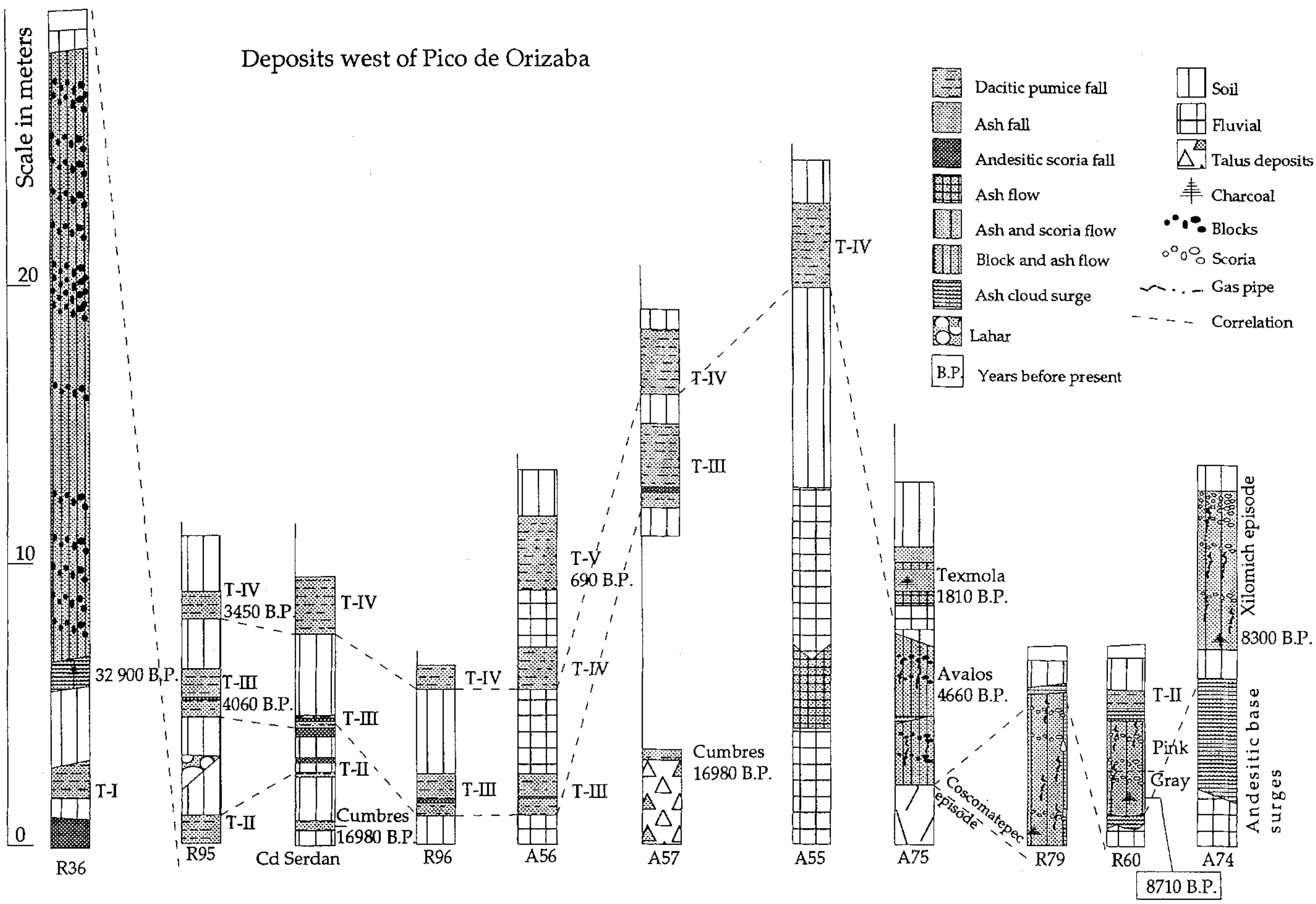

Fig. 5. Stratigraphic sections recorded on the west side of Pico de Orizaba. For more details on ^{14}C dates see Table 3. For locations of section see Fig. 6

ilarity of the uppermost flow series to its analog in the Metlac sequence which suggests that the flows descended both valleys.

South of Pico de Orizaba, deposition of pyroclastic material occurred along the ravine of the Enchino river. Near the village of Loma Grande (Figs. 2, 6), sections show two major cycles of pyroclastic deposits, the lower dated at 8200 years BP, the upper at 6200 years BP (Table 2, Fig. 10). Around the village of Texmalaquilla SSE of Pico de Orizaba, a young pyroclastic-flow sequence comprises the younger pyroclastic-flow deposits of Loma Grande and a sequence of pelean block-and-ash flows deposits covered by an ash-and-scoria-flow unit dated at 1860 and 1910 years BP (Table 2, Fig. 8).

Eruptive history of Pico de Orizaba

Division of eruptive episodes

The eruptive history of Pico de Orizaba is divided into ten eruptive episodes for the past 20000 years BP (Fig. 3), based on 20 ^{14}C dates (Table 2). The deposits of Pico de Orizaba will be discussed in stratigraphic order.

An eruption in the neighboring volcano Las Cumbres, situated 14 km north of Pico de Orizaba, draped the study area with a fine rhyolitic airfall ash layer rich in biotite and dated at 16980 years BP (Table 2). Owing to its unique characteristics this layer serves as a marker horizon for late Pleistocene deposits from Pico de Orizaba.

The Tliapa eruptive episode

The Tliapa eruptive episode is based on a section measured close to the village Chocaman east of Pico de Orizaba (Fig. 6). It is characterized by an andesitic ash-flow deposit, emplaced in an old channel of the Tliapa river eroded into the Teteltzingo debris-avalanche deposits. The ash-flow deposit forms a veneer as thick as 6 m. It has a coarse ash matrix with occasional andesitic blocks. A number of carbonized wood fragments in the deposits signify its high depositional temperature. A ^{14}C date on one of these fragments is 18700 years BP (Table 2). The ash-flow deposit is directly covered by a lahar deposit that generated load cast structures at its contact with the ash-flow deposits. No other deposits near Pico de Orizaba could be related to this eruptive episode.

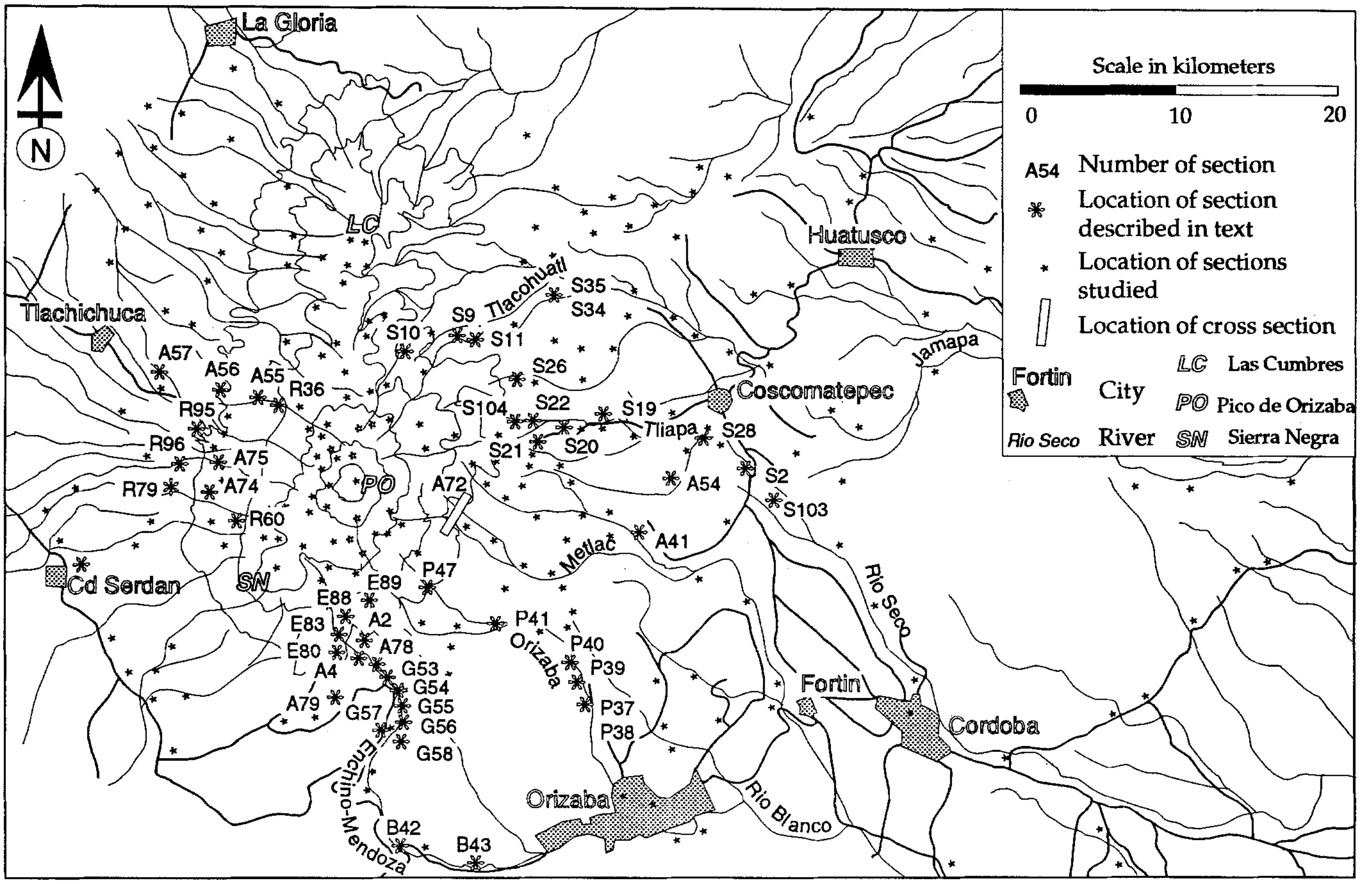

Fig. 6. Locations of stratigraphic sections recorded for this study. Selected sections are shown in Figs. 5, 7–12

The Tlacohuatl lavas and the Chichimeco dome complex

Somewhere between the eruption of Las Cumbres (17000 years BP) and the Chocaman eruption episode (Fig. 3), dated at 12900 years BP (Table 2) (Cantagrel et al. 1984), andesite lavas that flowed down the valley of Tlacohuatl and the dacitic dome complex Chichimeco, NE of Pico de Orizaba, were emplaced (Figs. 2, 7). These voluminous eruptions total about 9.3 km^3 of magma (Table 3). Absolute dating could not be carried out on the deposits, but their relative age can be estimated from their stratigraphic setting. The lava flows were deposited in a river channel cut into the Teteltzingo debris-avalanche deposits and ash-flow deposits that can be related to the Xocotla ignimbrite (Fig. 2). These deposits are about 33000 years BP old (Hoskuldsson 1992). Block-and-ash-flow deposits were observed in the Tlacohuatl valley, interbedded with the andesite lava flows (Fig. 7). The Cerro Las Cumbres tephra layer was not present within the sections of the lava flows in the Tlacohuatl valley, which suggests that the succession is younger than about 17000 years BP. Farther south Tliapa valley block-and-ash-flow deposits related to extrusion of the Chichimeco dome complex could not be identified with certainty. Many block-and-ash-flow units cover the Xocotla ignimbrite farther est on the plains of Coscomatepec (Fig. 2). These flows have been related to a dome extrusion on the floor of the Teteltzingo crater (Hoskuldsson 1992). However, the possibility that some of these flows originated from the Chichimeco dome complex cannot be excluded. No direct dating could be carried out on these deposits. The oldest deposits in Tliapa valley, besides those from the Tliapa episode and the block-and-ash-flow apron at Coscomatepec, are ash-and-scoria-flow deposits from the Chocaman episode dated 12900 years BP (Cantagrel et al. 1984). Thus there was a hiatus of about 4000 years between the Tliapa and Chocaman episodes. The Chichimeco dome complex nearly dams the Tliapa valley, leaving a narrow erosional ravine to the south where Holocene deposits later spilled through (Fig. 2). At the time of dome emplacement, the ravine was probably closed, since sedimentary terraces are observed on the basin side. Thus blocking by the dome complex was probably responsible for the depositional hiatus observed in the valley of Tliapa. This gives a time range of emplacement between 17000 and 12900 years BP for the Tlacohuatl andesite and the Chichimeco dacitic dome complex. The lavas that flowed as far as 30 km from the source have a volume of $200–600 \times 10^6$ m^3. Their large volume and long runout distance imply a high eruption rate. The dacitic dome complex Chichimeco is far more voluminous: the bigger dome complex with 14 eruptive vents has a volume of 6 km^3; the smaller and younger complex with at

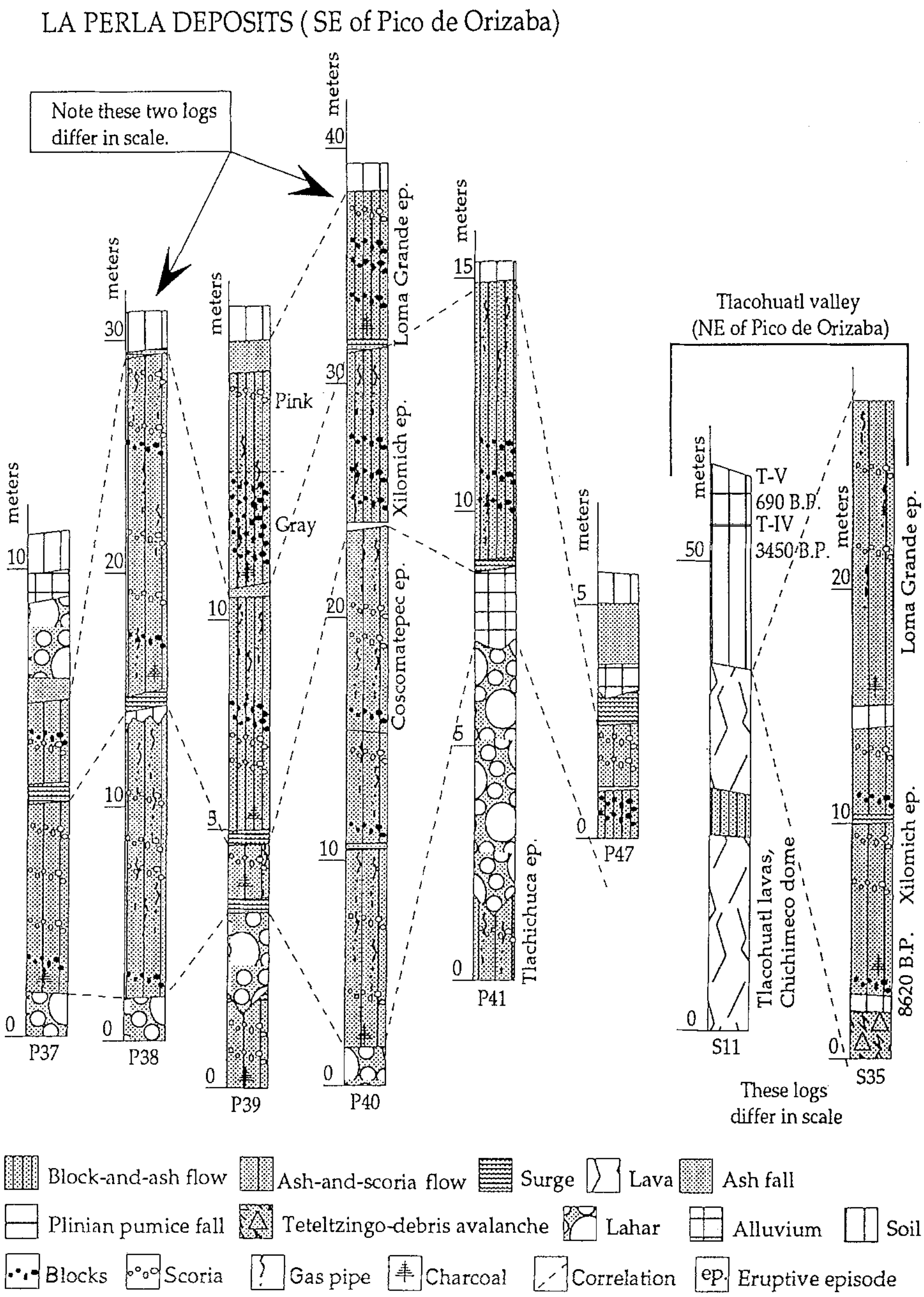

Fig. 7. Stratigraphic sections in Orizaba valley just south of the village La Perla, southeast of Pico de Orizaba, and from the Tlacohuatl valley, northeast of the volcano. No ^{14}C dates were obtained from the La Perla succession, but the uppermost deposits in section P40 are correlated with units in the Metlac valley. For more details on ^{14}C dates see Table 3. For locations of sections see Fig. 6

least two eruptive vents has a volume of about 2 km^3 (Table 3). Together the dome complexes total 8 km^3 in volume, extruded during a period of about 4000 years.

The Chocaman eruptive episode

The Chocaman eruptive episode has been dated at 12000 years BP by ^{14}C on a charcoal fragment (Robin and Cantagrel 1982). A complete section through the deposits characterizing the episode is exposed in the Tliapa river gorge just north of the village Chocaman, east of Pico de Orizaba (Figs. 2, 8). This section is divided into five successive pyroclastic-flow units, of which the lowermost is the thickest, 20 m in places (Fig. 11). The deposits are ash-and-scoria flows (Cantagrel et al. 1984). In the lowermost unit, bands rich in andesite blocks probably originated from the eruptive conduit or a pre-existing dome, whereas the upper four units are entirely of ash and scoriae. Each of the four upper units shows reverse grading of the scoriae towards the top of the ash body and in places scoria-dunes are present at the interface between flow units. The lower part of the basal flow unit is dark gray but changes sharply midway to a salmon-pink color. The four overlying units are all salmon pink. The continuous pink color from the middle of the basal unit to the top of the section implies that all the flows were deposited during the same eruption, since the color transition is a post-depositional phenomena related to degassing of the deposits (Fisher and Schmincke 1984).

Table 2. ^{14}C dates of carbonized wood and roots from deposits at Pico de Orizaba

Deposits	Sample #	Sect. #	Location in deposits	Material dated	^{14}C-Age	Error	Eruptive Episode
Plinian airfall/El Jacal (NE)	A83.1	S11	Below	C-roots	690	±50	Excola
Ash airfall/San José (W)	A75.2	A75	Below	C-roots	1810	±50	Texmola
B&A flow/Texmalaquilla (S)	A78.2	A78	Within	C-wood	1860	±40	Texmola
A&S flow/Texmalaquilla (S)	A78.3	A78	Within	C-wood	1910	±40	Texmola
Lava flow/Orizaba valley (E)	PU132		Below	C-wood	3400*	±110	El Jacal
Plinian airfall/El Jacal (NE)	A84-1	S11	Below	C-roots	3450	±70	El Jacal
Plinian airfall/Summit (NE)	PU139		Below	C-roots	4060*	±120	Avalos
B&A flow/Avalos (W)				C-wood	4660Ý	?	Avalos
A&S flow/Loma Grande (S)	PU127		Within	C-wood	6200*	±120	Loma Grande
B&A flow/Metlac valley (E)	A80.1	A72	Within	C-wood	6640	±290	Loma Grande
A&S flow/Coscomatepec (E)	PU110b		Within	C-wood	7020*	±120	Loma Grande
B&A flow/Loma Grande (S)	PA72.2	G54	Within	C-wood	8170	±70	Xilomich
A&S flow/Baranca Carnero (W)	PA82	A74	Within	C-wood	8300	±70	Xilomich
Lower A&S flow/Tlacohuatl (NE)	PA46	S35	Within	C-wood	8620	±140	Xilomich
A&S flow/Baranca Tecajete (W)	A74.2	R60	Within	C-wood	8710	±70	Xilomich
A&S flow/Coscomatepec (E)	PU146		Within	C-wood	9400*	±170	Coscomatepec
Ash airfall/Summit (NE)	PU141		Below	C-wood	10600*	±190	Tlachichuca
A&S flow/Chocaman (E)	PU111		Within	C-wood	12900*	±150	Chocaman
Ash flow/Las Cumbres (N)	PA97		Within	C-wood	16980§	±870	Cumbres event
Ash flow/Tliapa, Loma Bonita (E)	PA04	S2	Within	C-wood	18700	±500	Tliapa
B&A flow/Hidalgo (NW)	PA48		Below	C-wood	32900§	+2200/−1700	Sequence II
Plinian airfall/Hidalgo (NW)	PU107		Below	C-wood	≥38000*		Sequence II
B&A flow/Xocotla (E)	A40.2		Within	C-wood	≥40000§		Sequence II
B&A flow/Boqueron (E)	Rob-1		Within	C-wood	≥40000§		Sequence II

B&A, block-and-ash-pyroclastic flow deposits; A&S, ash-and-scoria-pyroclastic flow deposits; C-wood, carbonized wood fragments; C-root, carbonized roots from the soil below deposits; Sect. #refer to sections in Figs. 5, 7–10.

* Cantagrel et al. 1984
ÝSiebe et al. 1991
§ Hoskuldsson 1992

The scoriae contained in the deposits have a banded structure of mixed dacite and andesite. This banded structure is characteristic of late Pleistocene and Holocene ash-and-scoria-flow deposits at Pico de Orizaba (Cantagrel et al. 1984). The Chocaman deposits have a maximum estimated DRE-volume of some 30×10^6 m^3 (Table 3), somewhat less than Robin and Cantagrel (1982) suggested.

The Tlachichuca eruptive episode

The Tlachichuca eruptive episode is marked by a tephra layer in the NE summit area of Pico de Orizaba and dated at 10600 years BP (Robin and Cantagrel 1982). The lowermost pyroclastic-flow units in the La Perla sequence in the Orizaba valley (Figs. 2, 7) are related to this episode. These are the oldest deposits to have been emplaced beyond the rims of the Teteltzingo crater. The sequence consists of two flow units, of which the lower one is an andesite/dacite block-and-ash-flow deposit directly covered by an ash-and-scoria-flow unit. The former has a matrix of coarse ash with bands of abundant andesite/dacite blocks, whereas the latter has a basal layer rich in andesite/dacite blocks similar to those observed in the underlying block-and-ash-flow deposit. Its upper part, however, is rich in banded scoria that contain evidence of magma mixing identical to that described above. Because exposure is scarce, the volume of these deposits could not be estimated.

The lava flow in the valley of Tliapa (Fig. 8) is covered by pyroclastic deposits from the Coscomatepec eruptive episode and therefore flowed into the valley at the end of the Tlachichuca episode. It has a DRE-volume of about 80×10^6 m^3 (Table 3).

The Coscomatepec eruptive episode

Deposits of the Coscomatepec eruptive episode begin with the first ash-and-scoria flow that covers the Tliapa lava flow. It flowed down the Tliapa valley, where it crops out along the river down to the plains of Coscomatepec (Fig. 8). The deposit is dated at 9400 years BP (Cantagrel et al. 1984); its maximum DRE-volume is about 7×10^6 m^3 (Table 3). The deposit is identical to other ash-and-scoria flows with abundant banded scoria.

In the La Perla sequence in the Orizaba valley, ash-and-scoria flow deposits rich in andesite/dacite blocks fill erosional furrows cut into pyroclastic-flow deposits from the Tlachichuca episode (Fig. 7).

In the west, an ash-and-scoria flow unit around the village of Zoapan (Figs. 2, 5) is probably of this episode. First, as indicated by a pseudocrater (secondary explosion crater) just south of the village Zoapan, the Zoapan pyroclastic flow was fed into a lake occupying

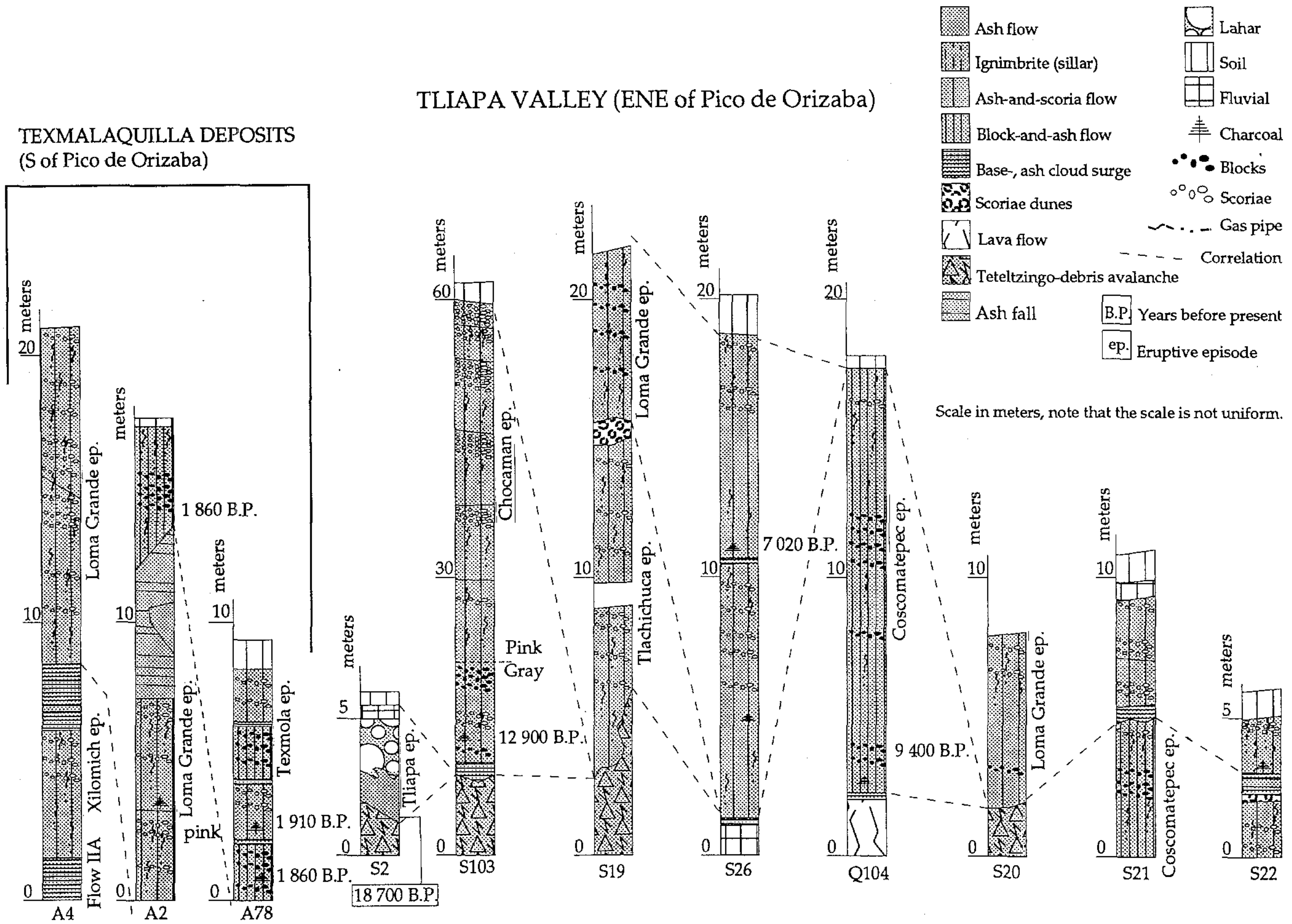

Fig. 8. Stratigraphic sections observed in Tliapa valley, east-northeast of Pico de Orizaba, and from the surroundings of Texmalaquilla village, south of the volcano. For more details on ^{14}C dates see Table 3. For locations of sections see Fig. 6

the Basin Oriental. Heine (1989) estimated that the Basin Oriental was last occupied by water at the beginning of Holocene time. Second, the flow was directed down the NW flank of Pico de Orizaba, a route that has been closed ever since the Teteltzingo collapse about 33 000 years BP and is still closed today by topographic barriers. However if the glacier currently occupying Pico de Orizaba had been larger, this route would have remained open. At the end of the late Pleistocene time a glacial advance occurred at Pico de Orizaba (Heine 1989), during which the increased ice thickness would have evened out the topographic barriers closing the NW route. Thus the deposition of the Zoapan ash-and-scoria flow could take place along this route. These two arguments support the hypothesis that the Zoapan ash-and-scoria-flow deposites were emplaced at the end of Pleistocene time, most likely during the Coscomatepec episode. Its DRE-volume is estimated about 50×10^6 m^3 (Table 3).

The Xilomich eruptive episode

The Xilomich eruptive episode occurred between 9000 and 8000 years BP (Fig. 3), based on four pyroclastic-flow deposits produced by different eruptions. The age range is between about 8710 and 8170 years BP (Table 2). The deposits erupted during the Xilomich episode have much greater dispersal all around the volcano than deposits from previous episodes. This indicates that the new cone of Pico de Orizaba had reached its maximum elevation before the onset of the Xilomich episode.

In the Barranca Tecajete, west of Pico de Orizaba, an ash-and-scoria-flow deposit covers the southernmost parts of the western plains (Figs. 2, 5). It contains carbonized wood with a ^{14}C age of about 8710 years BP (Table 2). The deposit is identical to the earlier ash-and-scoria-flow units. The flow has an estimated DRE-volume of 80×10^6 m^3 (Table 3). Underlying the ash-and-scoria-flow deposits are fluvial, laharic, and phreatomagmatic deposits from nearby parasitic vents.

In the Tlacohuatl valley are two ash-and-scoria-flow deposits (Fig. 7). The lower flow unit gave a ^{14}C age of 8620 years BP (Table 2). The two flow units are separated by a thin layer of soil that indicates a hiatus between their formation. The soil layer is thin, however, and little erosion had occurred before the second unit was emplaced, which implies that the hiatus was short. The two units therefore, are considered to be from the

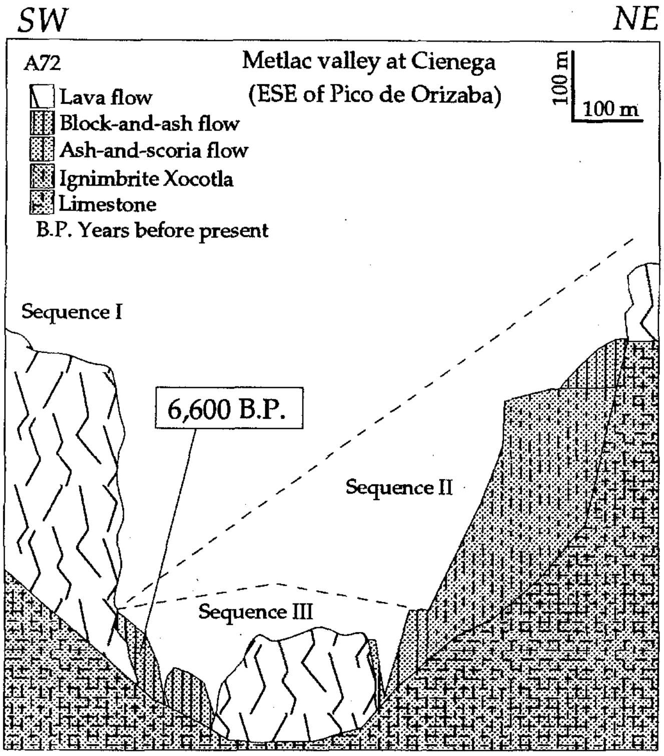

Fig. 9. Cross section through the valley of Metlac, east-southeast of the volcano. The section is characteristic of the valley deposits, where younger units are juxtaposed with older ones. For location see Fig. 6

same eruption episode, although from two different eruptive phases. The lower flow is estimated to be 5×10^6 m^3 in volume DRE (Table 3).

North of Baranca Tecajete in the west, the Baranca Carnero is cut into an ash-and-scoria-flow deposit overlying fluvial, and laharic sediments (Figs. 2, 5) similar to the sequence observed in Baranca Tecajete. Wood carbonized by the pyroclastic flow gave a ^{14}C age of about 8300 years BP (Table 2). The DRE-volume of the deposits is estimated to be of the order of 50×10^6 m^3 (Table 3).

To the south of Pico de Orizaba, around the village Loma Grande, is a ravine cut into the Texmalaquilla ignimbrite (Hoskuldsson 1992). The basal units in this ravine are a block-and-ash flow overlain by an ash-and-scoria flow (Figs. 2, 10). Andesite/dacite blocks from the block-and-ash-flow deposite are incorporated in the ash-and-scoria-flow deposits, which suggests nearly simultaneous deposition. Carbonized wood from the lower unit gave the ^{14}C age of about 8170 years BP (Table 2). On top of this sequence, separating it from the pyroclastic flows of the Loma Grande eruptive episode (Cantagrel et al. 1984), is a plinian pumice-fall layer consisting of two continuous normally graded dacitic pumice layers (Fig. 10). These layers mark the end of the Xilomich eruptive episode and are the second major plinian eruption of Pico de Orizaba (Fig. 3, 12). This plinian phase is called T-II.

The Loma Grande eruptive episode

A series of eruptions between 7000 and 6000 years ago has ben named the Loma Grande eruptive episode, because of pyroclastic-flow deposits of the ash-and-scoria type in the ravines around the village of Loma Grande south of the volcano (Robin 1981; Robin and Cantagrel 1982; Cantagrel et al. 1984; Gourgaud 1985). The Loma Grande sequence comprises five separate ash-and-scoria-flow units that form veneer deposits as much as 40 m thick in erosion furrows on the plains around Loma Grande (Fig. 2). The two lowermost units are rich in andesite blocks derived from pre-existing domes or underlying lava blown out during the opening of the eruptive conduit (Fig. 10). The next three successive units are, however, rich in scoriae and have occasional blocks close to their base. Each flow unit shows grading of the larger clasts, with the blocks concentrated close to the base and just below the middle of each units. The scoriae, however, concentrate towards the top, and in places form dunes in the uppermost levels. Quite similar characteristics may be observed in the Chocaman sequence. The Loma Grande sequence has been dated at about 6200 years BP (Cantagrel et al. 1984). The blocks floating in a matrix of coarse ash are of high-silica andesite and the scoriae are the banded type representing a mixture of dacite and andesite magma.

Two other flow units were found to be related to this eruptive episode. One is an ash-and-scoria-flow deposit in the Tliapa valley and dated at about 7020 years BP (Fig. 8) (Cantagrel et al. 1984). This deposit crops out in a few places downvalley (Fig. 8), separated from other units by a soil layer. It is identical to the ash-and-scoria-flow deposits at Loma Grande. Its volume could not be estimated. The second flow sequence, dated at about 6640 years BP, is of the block-and-ash-flow type (Table 2), and was observed in the Metlac valley (Fig. 9). The deposits are made up of angular andesite blocks floating in a matrix of coarse ash and lapilli. This unit is directly covered by ash-and-scoria-flow deposits that have incorporated blocks identical to those in the underlying unit, which shows that the two flows are probably from the same eruptive episode if not the same eruptive event (Fig. 9). Flow deposits related to this eruptive episode are the uppermost units in the Orizaba valley just south of La Perla, which have the same characteristics as in Metlac valley (Fig. 7).

DRE volume could only be estimated for the Loma Grande and Metlac deposits, which combined are in the range of 16×10^6 m^3 (Table 3).

The Avalos eruptive episode

The Avalos eruptive episode is based on dating of two types of eruptive deposits: block-and-ash-flow units covering the plains west of Pico de Orizaba and a plinian pumice-fall that is distributed all around the volcano (Fig. 5). The plinian tephra layer was dated at about

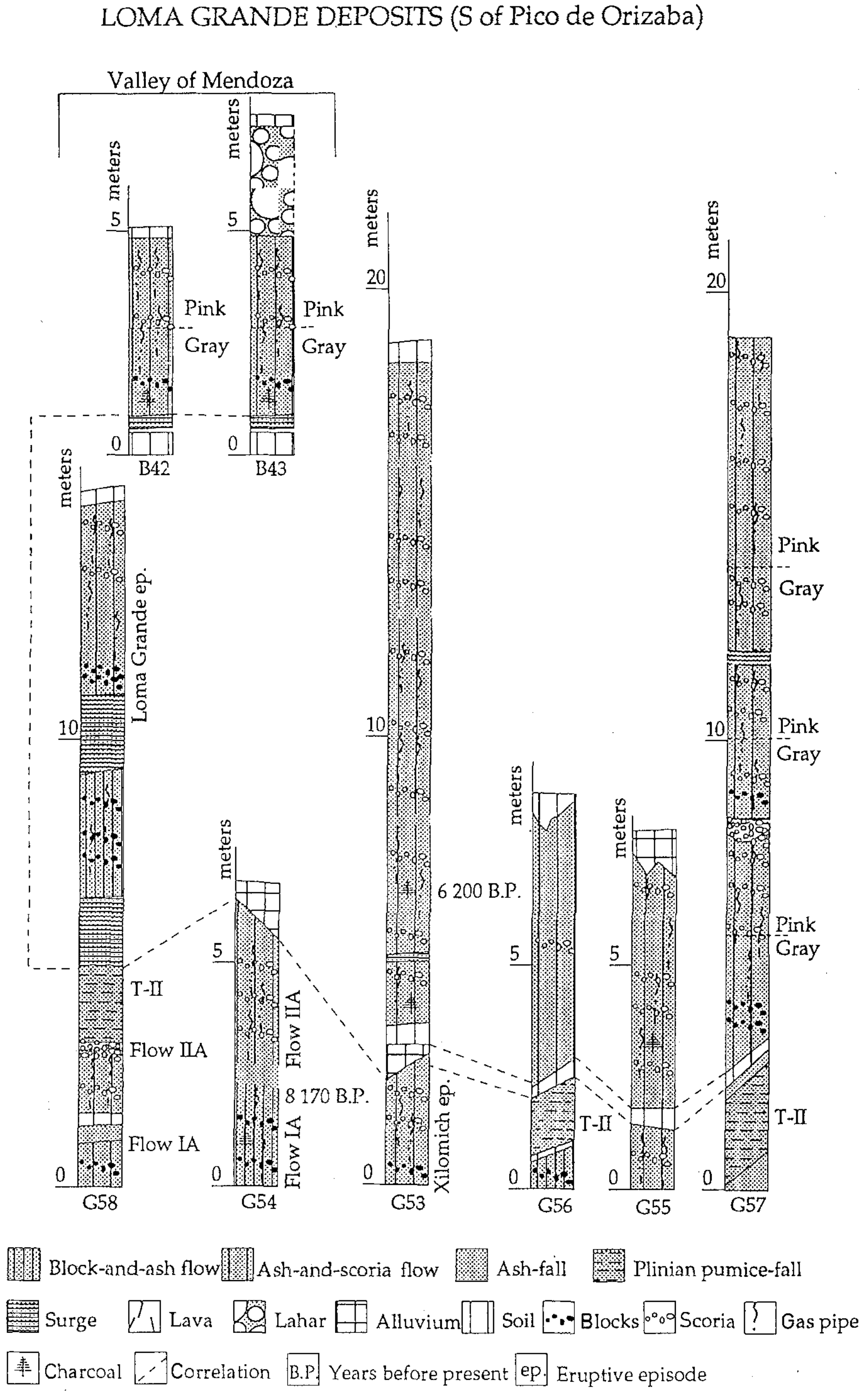

Fig. 10. Stratigraphic sections in Enchino river ravine and from Mendoza valley just outside the Mendoza village. Sections G53–G58 are from the vicinity of Loma Grande south of Pico de Orizaba. For more details on ^{14}C dates see Table 3. For locations see Fig. 6

4060 years BP (Cantagrel et al. 1984). The block-and-ash flow was direced toward the village of Avalos (Fig. 2) and is dated at about 4660 years BP (Siebe et al. 1991).

The block-and-ash-flow deposits form an apron in the west consisting of at least two thin units, each around 5 m thick (Fig. 5). Siebe et al. (1991) argued that they originated from the collapse of the summit dome. We think it more likely, however, that thick dacitic lava flows that flowed west over the rim of the Teteltzingo crater (Fig. 13), have generated this flow sequence by flow-front disintegration, similar to that observed at Santiaguito volcano in Guatemala (Rose et al. 1976) or a collapse of the flow's front on the steep slopes of the volcano.

The dacitic plinian tephra layer is the third major tephra deposit observed in the area of Pico de Orizaba, called T-III. Preliminary mapping of the layer shows its major SW-trending dispersion axis (Fig. 12).

The last known unit belonging to this eruption episode is a lava flow from the Metlac valley east of Pico de Orizaba. The lava sits in a ravine cut into the pyroclastic-flow deposits from the Loma Grande eruptive episode (Fig. 2).

Table 3. Volume estimates of volcanic deposits at Pico de Orizaba

Deposit	Area km^2	Thickness (meters)			Volume km^3	DRE m^3	Eruptive Episode
		min	max	mean			
Lava flows, AD 1566 and 1613	2.7	10	90	60	0.16	1.5×10^8	Excola
Lava flow AD 1545	2.4	20	80	40	0.10	1.0×10^8	Excola
Lava flow/Tlacohuatl	3.0	20	80	30	0.09	9.0×10^7	Texmola
Scoria flow/Texmalaquilla (S)	16.0	0.5	8	1.8	0.03	2.0×10^7	Texmola
Lava flow/Orizaba valley (E)	10.4	20	200	48	0.50	4.8×10^8	El Jacal
Metlac lava flow (E)	7.3	25	200	85	0.62	5.9×10^8	Avalos
Scoria flow/Loma Grande (S)	18.4	1	15	2.8	0.05	4.0×10^7	Loma Grande
Pelean flow/Metlac valley (E)	6.3	0.5	30	1.6	0.01	8.0×10^6	Loma Grande
Pelean flow/Loma Grande (S)	11.2	0.5	6	0.8	0.01	8.0×10^6	Xilomich
Scoria flow/Baranca Carnero (W)	12.6	2.5	10	5.5	0.07	5.0×10^7	Xilomich
Lower Scoria flow/Tlacohuatl (NE)	6.2	1.2	15	1.6	0.01	5.0×10^6	Xilomich
Scoria flow/Baranca Tecajete (W)	15.6	3.5	10	6.8	0.11	8.0×10^7	Xilomich
Scoria flow Zoapan (W)	9.3	2	10	7.5	0.07	5.0×10^7	Coscomatepec
Scoria flow/Coscomatepec (E)	7.0	0.9	8	1.4	0.01	7.0×10^6	Coscomatepec
Lava flow Tliapa valley (E)	11.4	30	300	70	0.80	8.0×10^7	Tlachichuca
Scoria flow/Chocaman (E)	12.2	1	70	3.2	0.04	3.0×10^7	Chocaman
Chichimeco done complex II (NE)	6.6	200	400	300	1.98	2.0×10^9	Tlacohuatl
Chichimeco dome complex I (NE)	12.6	250	700	476	6.00	6.0×10^9	Tlacohuatl
Tlacohuatl lava flow III (NE)	7.8	10	40	25	0.20	2.0×10^8	Tlacohuatl
Tlacohuatl lava flow II (NE)	14.0	15	70	40	0.56	5.0×10^8	Tlacohuatl
Tlacohuatl lava flow I (NE)	14.9	15	150	40	0.60	6.0×10^8	Tlacohuatl

Area is calculated by means of GIS-system; average thickness is calculated from field measurements for each unit. DRE calculations are based on the apparent density of 2.2 g/cm^3 to true density of 2.9 g/cm^3 for lavas and domes and 1.9 g/cm^3 to 2.9 g/cm^3 for pyroclastics

Fig. 11. Photograph showing the pyroclastic succession at the Chocaman village in the east of Pico de Orizaba. About midway up section (*long arrow*) there is a sharp colour change from gray to salmon pink. The lower part is also crudely columnar jointed, whereas jointing becomes less prominent towards the surface. Note person for scale (*at short arrow*)

The El Jacal eruptive episode

The El Jacal eruptive episode occurred between 3500 and 3300 years BP (Table 2). The beginning of the El Jacal eruptive episode was a highly explosive plinian eruption that formed a thick dacitic tephra layer (T-IV) near Pico de Orizaba (Fig. 5). The tephra layer was dated at about 3450 years BP (Table 2) from carbonized detritus sampled just beneath it at the village El Jacal on the NE flank of the volcano. Preliminary mapping of the layer shows its principal dispersion axis to the northwest (Fig. 12).

The latest eruptive products of the episode were andesitic lavas that flowed into the Orizaba valley (Figs. 2, 14). These lava flows have been dated at about 3400 years BP (Cantagrel et al. 1984).

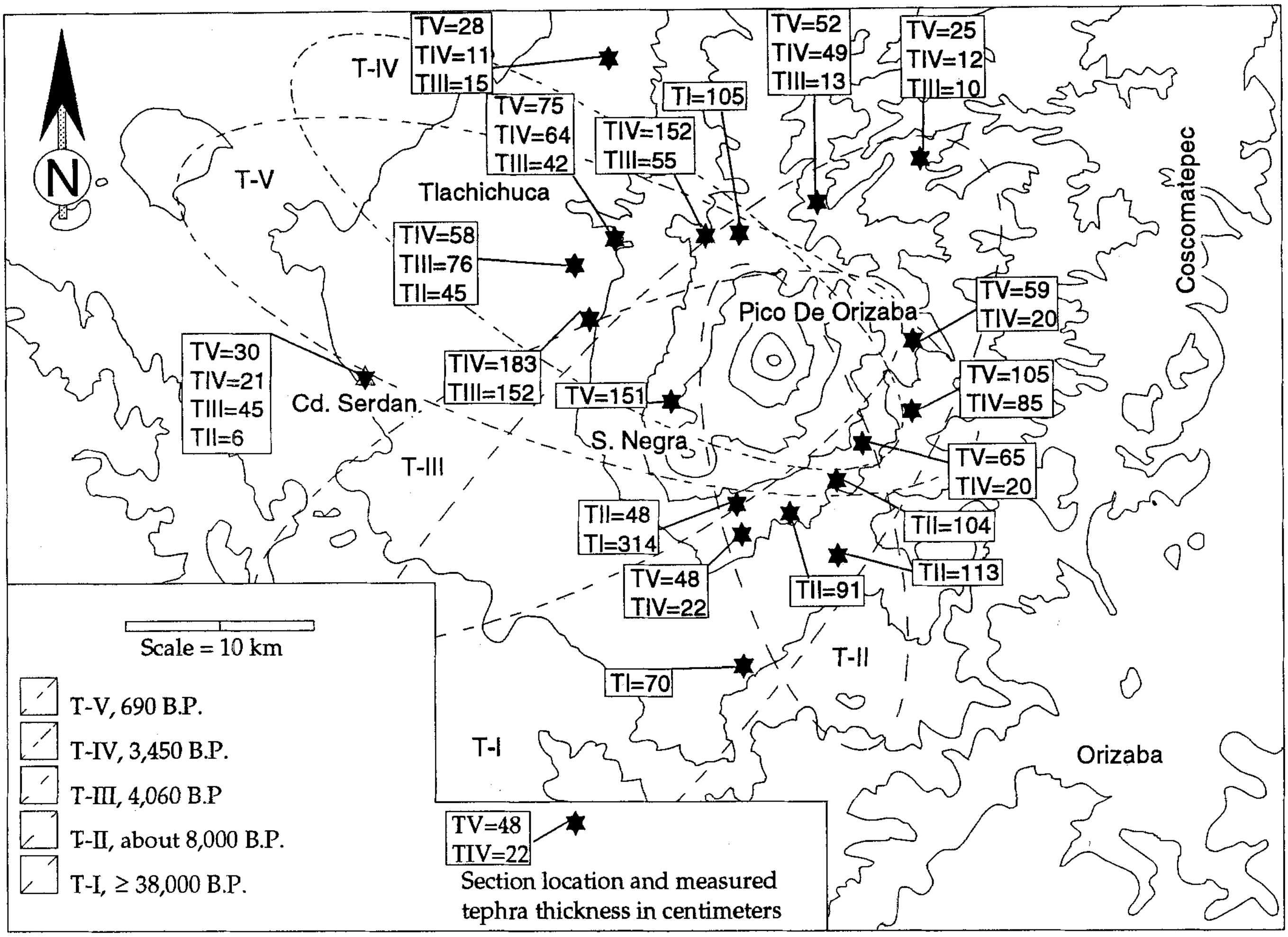

Fig. 12. Map showing the principal dispersal axes of the five tephra fall layers observed in the surroundings of Pico de Orizaba. Isopachs that are drawn around sections measuring 50 cm or more give an idea of individual tephra dispersal directions

Fig. 13. Photograph of dacitic lava flows from the Avalos episode. These lavas are probably responsible for the block-and ash-flow deposits around the village of Avalos, west of the volcano. The steep lava front is about 100 m high. The photograph is taken at an altitude of 5000 m; the summit can be seen in right upper corner

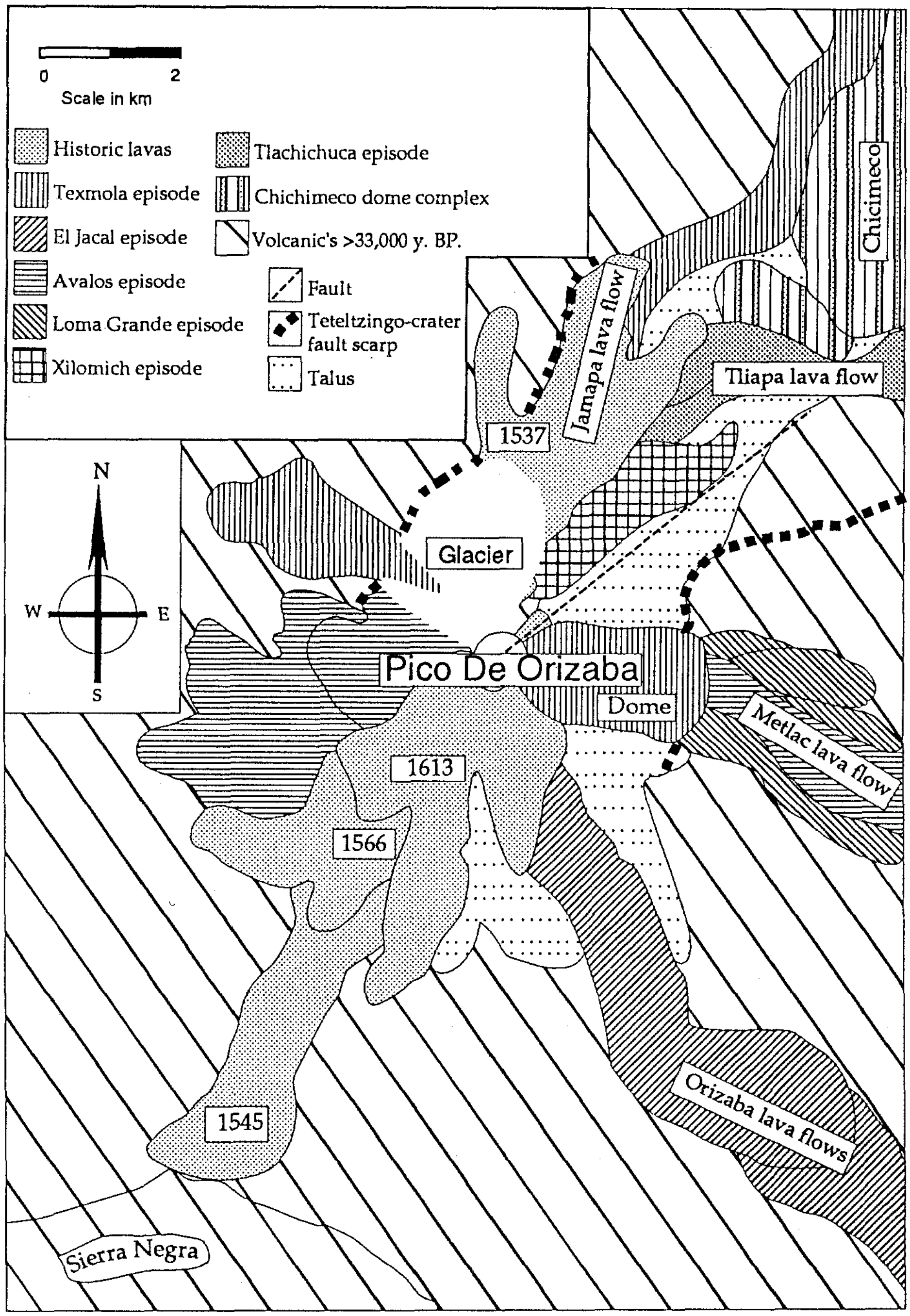

Fig. 14. Map of the summit region of Pico de Orizaba. The stratigraphy is based on field observations and aerial photographs. Historical stratigraphy is valid if the southernmost lava flow is from AD 1545 and if no effusive eruptions have occurred since AD 1613

The Texmola eruptive episode

The Texmola eruptive episode began around 2000 years BP. A series of block-and-ash-flow deposits and ash-and-scoria-flow deposits in the gullies just north of the village of Texmalaquilla to the south of Pico de Orizaba characterize the beginning of this eruptive episode (Figs. 2, 8). Two ^{14}C dates were obtained here: 1860 years BP for lower deposits of block-and-ash-flow type and 1910 years BP for overlying deposits of ash-and-scoria type (Table 2). Sections along the barrancas towards the village Loma Grande south-southeast of the volcano reveal the interaction between these two pyroclastic flows during deposition (Fig. 8, A2, A4, and A78). Commonly at their contact, blocks from the block-and-ash-flow deposits were incorporated into the overlying ash-and-scoria-flow deposits. This and the two ^{14}C dates argues for a nearly simultaneous deposition. These flow deposits directly cover eroded deposits from the Loma Grande eruptive episode and form veneer-like lenses along the channel of the Enchino river south-southeast of the volcano. The block-and-ash-flow deposits consits of dacitic blocks in a coarse-ash matrix. The ash-and-scoria-flow deposit is identical to other pyroclastic-flow units observed at Pico de Orizaba, which contain abundant banded scoria (andesite mixed with dacite) in a coarse-ash matrix. Remains of a dome that possibly generated the block-and-ash-flow deposites lie in the summit area of the volcano (Fig. 14). Manmade artifacts (sculptured wood

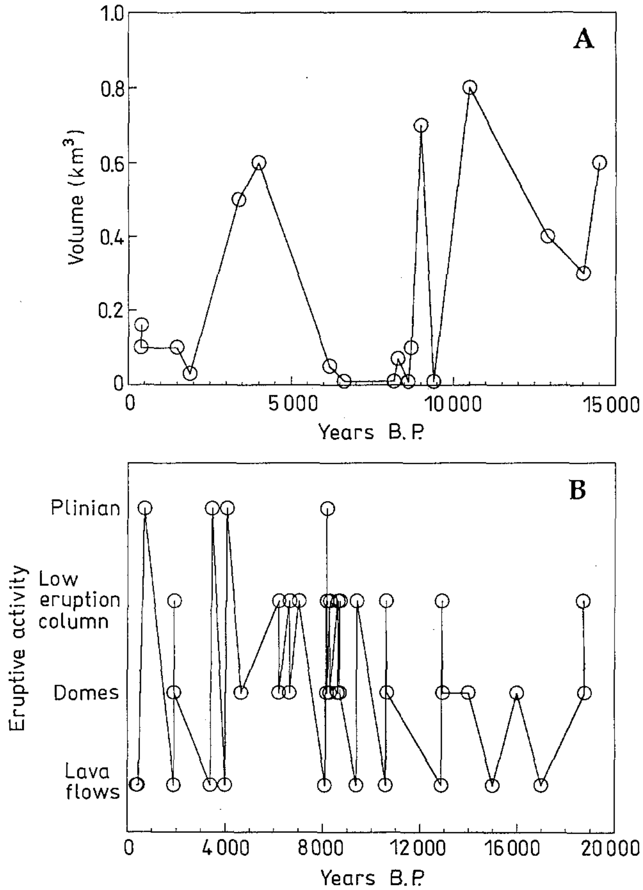

Fig. 15. **A** Diagram illustrating the volume emitted during eruptions of Pico de Orizaba during the last 15000 years. Only eruptions the volume of which could be reasonably estimated are included in this summary. There are two distinct periods (12000–8000 and 5000–3000 years BP) that show high erupted volume, possibly related to magma transfer within the volcano's plumbing system. **B** Diagram illustrating the evolution of eruptive mechanisms at Pico de Orizaba. It is apparent that plinian eruptions have become more important towards modern time. This diagram also shows that eruptive episodes begin more frequently with explosive eruptions and end with effusive ones

fragments, verified by archeologists at CEMCA, Mexico City) were found in the block-and-ash-flow deposits, the first evidence of human distress caused by the volcanic activity of Pico de Orizaba. A fine ash layer west of the volcano dated at 1810 years BP (Table 2) probably represents distal fallout from the eruption that generated the pyroclastic-flow sequence mentioned above. The last product of this eruption episode are two lava flows in the summit area. One flowed northeast towards the Tlacohuatl valley between the domes Tecomale and Chichimeco; the other flowed west over the rim of the Teteltzingo crater (Figs. 2, 14).

The Excola eruptive episode

The last eruptive episode of Pico de Orizaba began about 700 years ago, with a dacitic plinian eruption that produced the uppermost pumice layer (T-V) in the region. Carbonized wood fragments sampled from beneath the pumice layer in a section close to the village of Excola on the NE flank of Pico de Orizaba (Fig. 2) gave a ^{14}C age of 690 years BP (Table 2). Figure 12 shows the WNW axis of the tephra thickness drawn at the 50-cm isopach.

The historic activity of Pico de Orizaba belongs to this eruptive episode. Of the seven eruptions reported between AD 1537 and 1687, four were described as effusive and three were considered weakly explosive (Mooser et al. 1958; Simkin et al. 1981; Robin 1981). The following stratigraphy of the seven eruptions is based upon the lava flow from AD 1545 (Fig. 14), which was reported to have flowed south (Mooser et al. 1958; Robin 1981). From aerial photographs and a stratigraphic section in the summit crater, wall, we are able to sort out the stratigraphic relation of summit's flows, if the lava flow we take for the AD 1545 lava is correct. The first effusive eruption was reported in AD 1537. Our observations suggest that this is the lava that flowed to the northeast (Fig. 14), called by local people 'the Jamapa lava flow', whereas it flowed towards the Jamapa valley. The second is the AD 1545 lava flow and in AD 1566 a third lava flow was reported along with explosive activity in the central crater. We suggest that it is the lava that overlies the AD 1545 lava (Fig. 14). The last effusive eruption was reported in AD 1613. The lava that partially covers the AD 1545 and 1566 lava flows and a small tongue that goes towards the northeast would accordingly belong to this eruption (Fig. 14). In AD 1569 explosive activity in the central crater was reported to be highly diluted by steam. Robin and Cantagrel (1982) interpreted this activity as phreatic. In AD 1630 and 1687 activity in the central region was reported but its nature is uncertain (Simkin et al. 1981).

Since AD 1687 no activity has been reported at Pico de Orizaba and the volcano is therefore considered dormant. However, reports from the early this century on Pico de Orizaba indicate some activity between the years 1906 and 1941. Ordonez (1906) and Waitz (1910) wrote in their reports on Pico de Orizaba's ascent, that the summit area was covered by a glacier. Flint (1949) mentioned that although Pico de Orizaba and Popocatepetl were higher than Ixtaccihuatl, neither of them had glaciers. Popocatepetl was at the time active and Pico de Orizaba in solfataric phase. On the summit of Sierra Negra about 7 km southwest of Pico de Orizaba (Fig. 2), we found a ballistic bomb in a well-preserved impact crater. The crater rims are made of loose sand indicating that the impact could be quite young, possibly from this century. At present we cannot state if Pico de Orizaba erupted between 1910 and 1949; however, the glacier behavior does indicate some increase in activity, possibly only fumarolic. Local people report fumarolic activity in the summit region along the Jamapa lava flow until 1972.

Discussion

Eruptive activity of Pico de Orizaba

The Teteltzingo crater affected the distribution of gravitationally driven eruptive products for 20000 years after its formation, until a new cone had risen above the amphitheater's rims. Fanning out from the breach to the northeast is a succession of volcanic deposits that span the time interval from the formation of the Teteltzingo crater until about 10000 years BP. In the west, however, a major hiatus represents the same period of time (Fig. 4).

The period from 32000 to about 19000 years BP was marked by dome growth within the Teteltzingo crater; block-and-ash-flow deposits originating from these domes cover the Xocotla ignimbrite on the plains of Coscomatepec and make up the upper-most part of the Coscomatepec pyroclastic delta (Fig. 2). Today the domes are no longer visible because they were destroyed during extrusion as Merapi-type block-and-ash flows or they are buried by younger deposits. A part of this pyroclastic delta is probably related to the extrusion of the Chichimeco dome complex as well.

The period between 19000 and 13000 years BP was characterized by emission of andesitic magma at Pico de Orizaba, as shown by andesite lava flows and pyroclastic-flow deposits on the slopes and plains of the volcano towards the northeast. On the NE part of the volcano within the graben faults (Fig. 2), dacitic magma was erupted to form the Chichimeco dome complex. Volcanic activity had been ongoing in this area since about 0.5 Ma (Hoskuldsson 1992). Southwest of Pico de Orizaba at about 7 km distance form the central vent is a sister volcano, Sierra Negra (Fig. 2), which has been called a parasitic volcano to Pico de Orizaba (Robin 1981; Negendank et al. 1985). It has been shown that volcanism at Pico de Orizaba is aligned along a NE-SW tectonic lineament, which is a superficial tectonic system generated by a buried E-W sinistral shear fault (Hoskuldsson 1992). It is probable that magma is accumulating at the interface between the shear faults and the superficial NE-SW extensional faults, where the regime goes from compressional to extensional. However, it is not clear if the surface volcanic alignment reflects several individual magma reservoirs or the shape of a single reservoir under the whole volcanic complex.

The period between 13000 and about 4500 years BP was characterized by eruptive activity generating low eruption columns and related ash-and-scoria flows, except for a plinian eruption at the end of the Xilomich episode. This type of eruption may be related to the extrusion of amphibole-rich andesites (Bardinzeff and Bonin 1987). Because of amphibole breakdown, the melt becomes enriched in H_2O, which increases its explosivity. Two physical factors can affect the stability of amphibole. First, depressurising of magma due to its rise to surface leads to amphibole breakdown, which is frequently observed in lava flows at Pico de Orizaba where amphibole has been completely dissolved. Because these changes occur near the surface, they probably do not add substantially to the explosive nature of the eruption. Second, the injection of new hot magma into a pre-existing magma reservoir could by its excess heat cause dehydration of amphibole. Such alteration of amphibole is observed in the mixed scoria samples from the ash-and-scoria-flow deposits at Pico de Orizaba. Such dehydration of the amphibole would occur under pressure and therefore increase the explosive nature of the magma. The total erupted volume (Table 3, Fig. 15a) and frequency of eruptions forming ash-and-scoria-flow deposits (Fig. 15b) do indicate that during these periods magma from deeper levels was injected into the magma system under Pico de Orizaba. Observation of simultaneous activity on the Altiplano shows that when replenishment from deeper levels occurs, marginal and parasitic vents are also activated.

The first major plinian eruption to occur during Holocene time was T-II at the end of the Xilomich episode. This change in eruptive mechanism was then maintained during the Avalos eruptive episode. Previously the eruptive mechanism had been moderately explosive, forming low eruption columns with andesite dominating. During the Avalos episode the eruptive activity included extrusion of mixed dacitic and andesitic lava flows to a climax of dacitic plinian eruption. This dacitic plinian activity continued during the El Jacal episode. The increasing frequency of plinian eruptions may indicate that the magma reservoir, which until the Xilomich episode produced compositionally uniformly mixed rocks, was becoming richer in dacitic magma. Four times in the Holocene a dacitic plinian eruption was followed by andesitic to dacitic lava flows (Fig. 15b). This type of transition may represent eruption from a stratified magma reservoir (Hildreth 1981; Fisher and Schmincke 1984). It can be suggested, therefore, that the volcanic system under Pico de Orizaba has developed a stratified magma reservoir.

During Holocene time the eruptions of Pico de Orizaba demonstrated periodic behaviour, with reposes ranging from 1500 to 500 years. During the late Pleistocene, however, the response are as long as 3000 years (Fig. 15b). It is also noteworthy that the frequency of explosive activity increases towards modern time (Fig. 15b), best observed in continuous profiles that show tephra layers as far back as 17000 years BP (Fig. 5, A56 and A57). These changes in both time and explosive activity are perhaps related to the evolution of the magma system beneath the volcano. The time difference could as well be related to the fact that the older products are buried by younger, and are therefore less dominant in our study. We suggest that a maximum repose period of 500 years is realistic for the present state of the volcano.

Conclusion

The eruptive activity of Pico de Orizaba can be divided into 11 episodes during the late Pleistocene to Holocene time (Fig. 3). Each eruptive episode lasted for several hundreds of years, giving rise to several eruptions. The eruptive style of the volcano has changed progressively this period. These changes are related to evolution of the magmatic plumbing system beneath the volcano, since the importance of dacitic magma increases with time.

Erupted volume was high between 13000 and 8000 years BP and then again around 4000 years BP. This is believed to indicate increased magma transfer from deeper levels. Deposits from vents on the surrounding Altiplano were observed to be interbedded with deposits of these ages from Pico de Orizaba. This suggests increased magma injection beneath the Altiplano as well as the main edifice of Pico de Orizaba.

Repose periods at Pico de Orizaba range from 3000 to 500 years. The lower number is probably representative for the present state of the volcano, but it must be taken with caution since time of repose seems to have decreased towards present time.

Pico de Orizaba has been in the state of dormancy since AD 1687, about 300 years, which is close to the observed maximum repose time of the volcano. Today about two million people live within a 50-km radius of the volcano. Pico de Orizaba is worth special attention in the near future to avoid a major catastrophe in the event of its wakening.

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