Journal of Volcanology and Geothermal Research 176 (2008) 7–15

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Late Holocene phases of dome growth and Plinian activity at Guagua Pichincha volcano (Ecuador)

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ARTICLE INFO

Available online 23 November 2007

Keywords:
Pichincha volcano
Ecuador
radiocarbon dating
Holocene volcanism
Plinian eruption

ABSTRACT

Since the eruption which affected Quito in AD 1660, Guagua Pichincha has been considered a hazardous volcano. Based on field studies and twenty ^{14}C dates, this paper discusses the eruptive activity of this volcano, especially that of the last 2000 years. Three major Plinian eruptions with substantial pumice discharge occurred in the 1st century, the 10th century, and in AD 1660. The ages of organic paleosols and charcoal from block-and-ash flow and fallout deposits indicate that these eruptions occurred near the end of 100 to 200 year-long cycles of discontinuous activity which was comprised of dome growth episodes and minor pumice fallouts. The first cycle took place from ~AD 1 to 140. The second one developed during the 9th and 10th centuries, lasted 150–180 yr, and included the largest Plinian event, with a VEI of 5. The third, historic cycle, about 200 yr in duration, includes pyroclastic episodes around AD 1450 and AD 1500, explosive activity between AD 1566 and AD 1582, possible precursors of the 1660 eruption in the early decades of the 17th century, and finally the 1660 eruption (VEI 4). A fourth event probably occurred around AD 500, but its authenticity requires confirmation. The Plinian events occurred at the end of these cycles which were separated by repose periods of at least 300 yr. Older volcanic activity of similar type occurred between ~4000 and ~3000 yr BP.

Because ash fallout and related mudflows represent a serious hazard for Quito's metropolitan area, the significance of the increasing phreatic activity observed from 1981 to 1998, and the 1999–2001 magmatic episode of dome growth and collapse are discussed. These probably represent a short step in a longer evolution which may result in a major Plinian event in the future decades or in the next century, comparable to that which occurred during the 1st, 10th, and 17th centuries.

1. Introduction

Owing to its location close to Quito, Guagua Pichincha volcano, the active centre of the Pichincha Volcanic Complex, is considered a hazardous volcano of the Northern Volcanic Zone of the Andes (Fig. 1A). In AD 1660, an eruption produced severe ash and lapilli fallout in the city as well as numerous lahars (Wolf, 1904; Hall, 1977; Simkin and Siebert, 1994). According to Geotérmica Italiana (1989) and Barberi et al. (1992), two additional large explosive events occurred near AD 550 and AD 970. Moreover, historic chronicles report notable eruptive episodes before the 1660 eruption, especially in 1566, 1575, and 1582, which also resulted in ash and lapilli falls in Quito, as well as pyroclastic flows and lahars in the valleys which descend the western flanks of the complex (Wolf, 1904). During the 19th century, episodic phreatic activity occurred in 1830–1831, 1868–1869, and 1881 (Estupiñán Viteri, 1998) while in the last two decades of the 20th century increased fumarolic activity developed and phreatic explosions took place at the vent (1980–81, 1988, 1993, and 1998).

In October 1999, a renewal of magmatic activity characterized by vulcanian explosions and dome growth broke a 340 year period of relative quiescence, and ash fallouts once again threatened Quito through May 2001. To assess the possible evolution of this activity, a study of the Late Holocene volcanic deposits has been carried out by the Geophysical Institute (EPN; National Polytechnic School) and the IRD (French Research Institute for Development). Fieldwork and twenty new calibrated ^{14}C dates go beyond former published works by specifying the timing of eruptive activity during the last 2000 years. In particular, new ^{14}C ages define long-lasting eruptive cycles which culminated in strong explosive events whose magnitudes are estimated from the tephra volumes. Overall, the results provide valuable information on past eruption patterns as well as on the ongoing cycle. This paper is dedicated to our colleague Michel Monzier, volcanologist at IRD, who largely carried out the sampling, but passed away during fieldwork in September 2004.

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doi:10.1016/j.jvolgeores.2007.10.008

2. The Pichincha eruptive centre

The Pichincha volcanic complex comprises two main edifices: Rucu Pichincha whose age is about 1 Ma, and Guagua Pichincha, constructed on the western flank of the older Rucu edifice (Fig. 1B; Geotérmica Italiana, 1989; Barberi et al., 1992). Recent field observations supplemented by petrologic data indicate the construction of three successive edifices by lava flows and domes during Guagua Pichincha's development since the Late Pleistocene: basal Guagua Pichincha, Toaza, and Cristal edifices (Monzier et al., 2002; Fornari et al., 2004). The development of the basal Guagua Pichincha and Toaza edifices ended with large sector collapses, whose resulting amphitheatres open towards the southwest and the west, respectively (Fig. 1B, C). The Cristal dome complex, mostly dacitic in composition (61.5–65.7 wt.% SiO_2) developed within the Toaza amphitheatre. This presently active, 1 km-wide complex, experienced recurrent episodes of dome growth and destruction, as well as Plinian activity. The new ^{14}C data presented in this paper emphasize two Late Holocene periods of important explosive activity: from ~4000 to 3000 yr BP and since ~2000 yr BP.

3. Methodology and sampling

Due to the orientation of both avalanche scars, pyroclastic flows and lahars from the Cristal dome complex are channeled towards the southwest and west into the valleys drained by the Ríos Blanco and Cristal, which form the Río Cinto further downstream (Fig. 1B). These valleys are densely forested up to 3800 m asl, and contain thick sequences of pyroclastic flow deposits that commonly carry charcoal and wood fragments. During the Late Holocene, important fallouts also occurred on the eastern side of Guagua Pichincha, in particular along the embankments of the Lloa–Refugio road, between 4000 and 4700 m (sites 35, 85, 86, 87, 97, 127, and 128, Fig. 1B) as well as at more distal localities on Rucu Pichincha, (sites 55 and 72). In both areas,

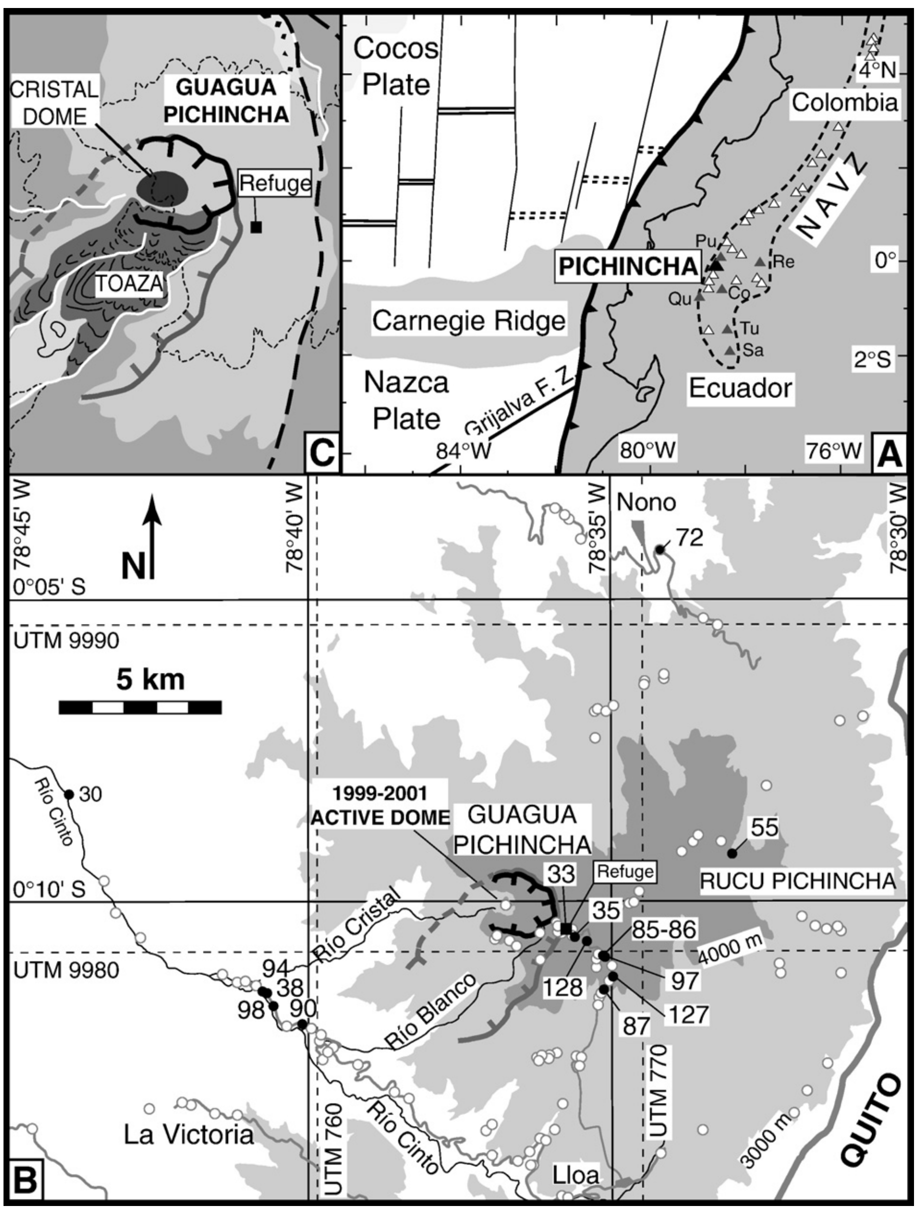

Fig. 1. A: Geodynamic setting of the North Andean Volcanic Zone (NAVZ). Pu = Pululahua; Qu = Quilotoa; Co = Cotopaxi; Re = El Reventador; Tu = Tungurahua; Sa = Sangay. B: Sketch map of the Pichincha volcanic complex showing the avalanche calderas. Solid circles with numbers refer to studied sites and ^{14}C sample locations cited in this paper; empty circles refer to other studied outcrops. C: Sketch map of Guagua Pichincha summit area.

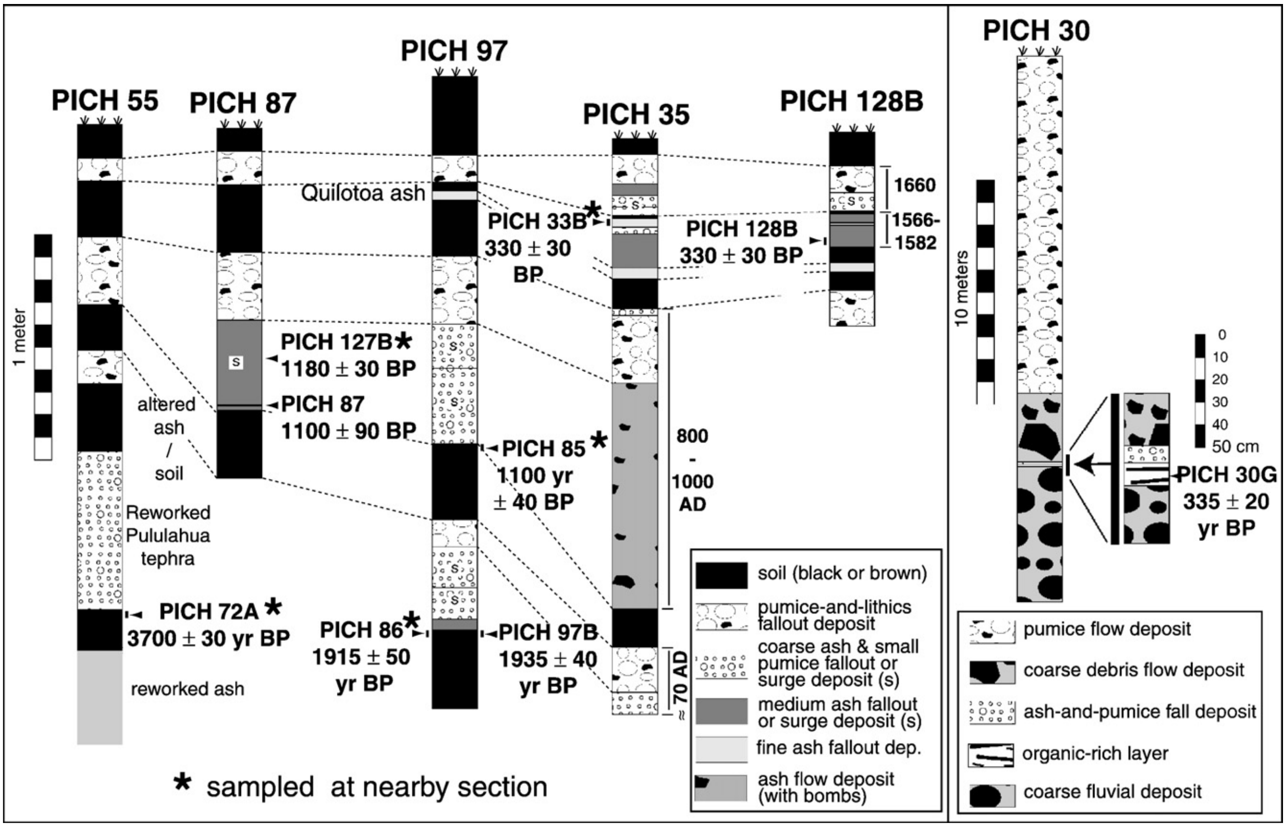

Fig. 2. Selected stratigraphic sections showing the main eruptive events for the last 2000 years of Guagua Pichincha volcano.

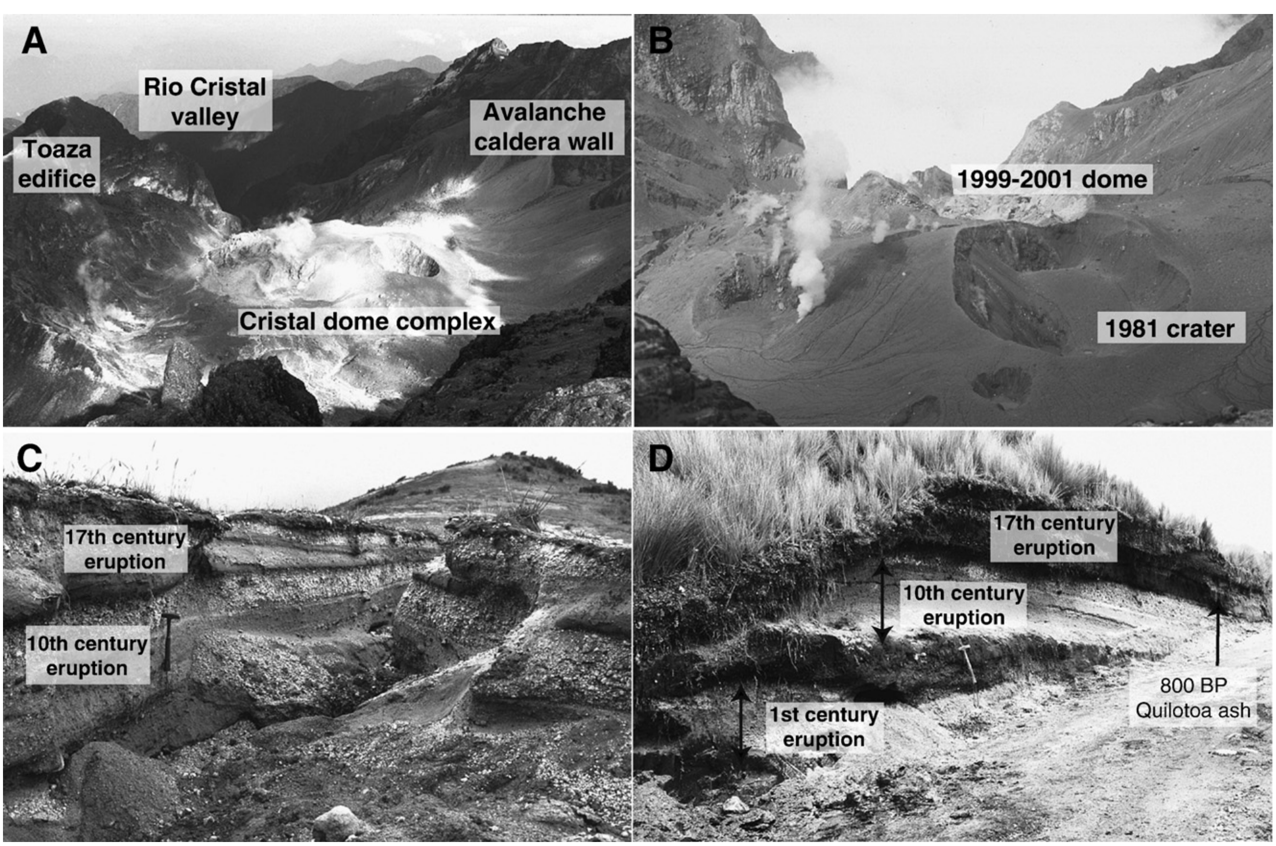

Fig. 3. A. The Cristal dome complex as seen from the east in 1998. B. The 1999–2001 active part of the Cristal dome complex as seen in 1999. C. Late Holocene tephra fall and flow deposits near Refugio. D. Late Holocene tephra fall and flow deposits on the upper flank of Guagua Pichincha edifice (Sections PICH 87 and 97).

black soils, rich in organic material and charcoal debris, have been collected for radiocarbon dating. Figs. 2 and 3 show typical sections of these deposits. The thickness of the main fall layers was measured at numerous sites, and with complementary data from Geotérmica Italiana (1989), isopach maps in the range 4–40 cm were constructed (Fig. 4). Minimum fallout tephra volumes were estimated using the method of Fierstein and Nathenson (1992). In addition, a rough volume estimate of pyroclastic flow deposits was attempted, based on field measurements, principally in the Río Cristal succession (e.g. section 30, Fig. 2). Finally, a bulk volume of the deposits and the Volcanic Explosivity Index (VEI, Newhall and Self, 1982) were determined for each large explosive event.

A geochemical study of clasts was carried out in order to correlate fallout deposits on the upper volcano's flanks with pyroclastic flow deposits in the valleys. In addition, two well-constrained regional stratigraphic markers – the Pululahua and the Quilotoa ash layers – were identified and used for correlations. On the Pichincha complex, the Pululahua ash, dated at 2400–2600 yr BP, is a 30 to 50 cm-thick, reddish-grey, partially reworked ash layer related to the caldera-forming eruption of the nearby Pululahua volcano (Papale and Rosi, 1993). The Quilotoa ash is a 5 to 10 cm-thick layer of fine biotite-rich yellow ash, formed by the ca. 800 yr BP eruption at Quilotoa volcano, located 75 km to the south (Mothes and Hall, 1998; Mothes and Hall, 2008-this issue). In the Pichincha area, this layer lies between two 6 to 10 cm-thick dark soils.

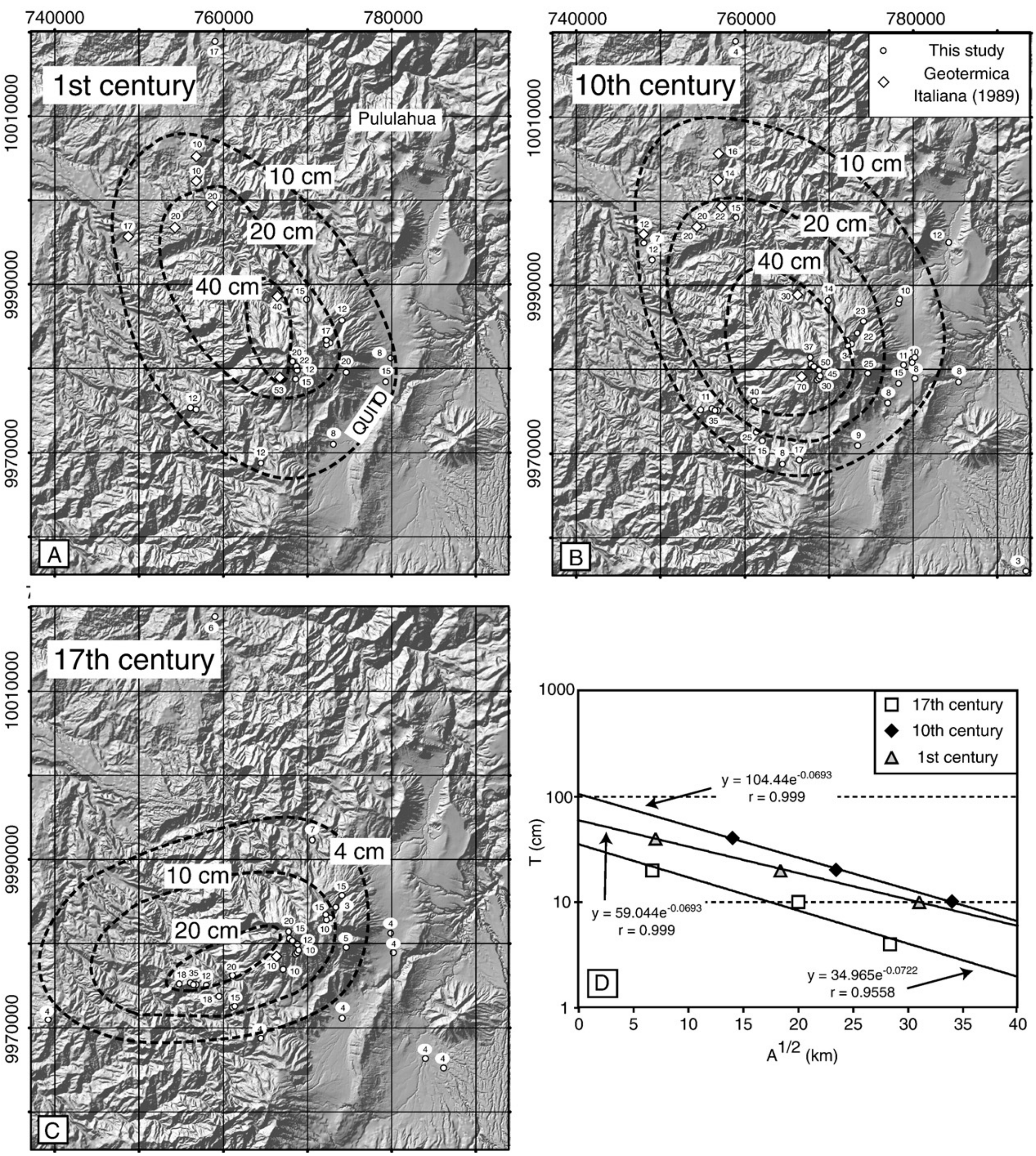

Fig. 4. Isopach maps of the three Plinian fallout deposits related to the 1st (A), 10th (B) and 17th (C) centuries eruptions. D: Log$T$ versus $A^{1/2}$ diagram (Fierstein and Nathenson, 1992) for the three Plinian fallout deposits. Digital information for the relief image, based on 1:50,000 topographic maps (Instituto Geográfico Militar, Quito), was provided by M. Souris (IRD).

Table 1
^{14}C conventional ages and calibrated dates

Sample	Dated fract.	Lab #* (GrN)	^{14}C yr BP	1s	δ^{13} (‰)	Cv (%)	Calibrated	Range	(1 sigma)	Calibrated	Range	(2 sigma)
								68.3% confidence level			95.4% confidence level	
PICH 98C	c.r.	25522	240	20	−25.00	68.2	**1645–1665**	1785–1795		**1640–1670**	1780–1800	
PICH 98B1	c.r.	25521	290	20	−25.98	67.4	**1525–1555**	1630–1650		**1520–1595**	1615–1655	
PICH 90A	c.r.	25517	320	20	−23.60	68.0	**1515–1595**	1615–1640		**1480–1645**		
PICH 33B	c.r.	32951	330	30	−25.97	60.0	1495–1505 1615–1635	1510–1530	**1540–1605**	**1475–1645**		
PICH 128B	c.r.	32953	330	30	−23.32	62.7	1500–1505 1615–1635	1510–1530	**1540–1600**	**1475–1640**		
PICH 30G	c.r.	25508	335	20	−27.72	48.8	1495–1510 1615–1635	1510–1530	**1555–1605**	**1480–1640**		
PICH 94B	c.r.	25519	450	40	−25.42	64.7	**1420–1465**			**1405–1515**	1600–1620	
PICH 36C	a.e.	30187	930	60	−26.86	–	**1030–1160**			995–1010	**1010–1225**	
PICH 127C	c.r.	30189	1020	25	−22.25	66.0	**990–1025**			**970–1040**	1110 – 1115	
PICH 85	a.e.	25513	1100	40	−24.85	–	895–925	**935–990**		785–790	825–840	**865–1025**
PICH 87	c.r.	25515	1100	90	−25.69	35.0	780–790	815–845	**855–1025**	690–750 1130–1155	**760–1055**	1080–1130
PICH 38E	c.r.	24776	1120	30	−27.00	68.3	890–905	**910–970**		780–790	820–845	**860–995**
PICH 127B	c.r.	25809	1180	30	−22.87	66.7	780–790	**805–890**		**770–900**	915–965	
PICH 127A	c.r.	26206	1260	70	−18.63	68.4	**670–785**	785–815	840–860	**645–900**	920–945	
PICH 97C	a.e.	30188	1640	70	−27.96	–	**335–465**	480–535		**245–565**		
PICH 86	a.e.	25514	1915	50	−25.66	–	**20–135**			−40–30	−25 −10	**1–225**
PICH 97B	a.e.	25520	1935	40	−25.04	–	**20–90**	100–125		**−45–140**	195–210	
PICH 132B	c.r.	25810	2990	20	−23.53	68.5	−1295–1280 −1140–1130	**−1270–1205**	−1205–1195	**−1310–1150**	−1150–1125	
PICH 29B	c.r.	25507	3540	30	−25.84	68.1	**−1930–1875**	−1845–1815	−1800–1780	**−1955–1765**		
PICH 72A	a.e.	25512	3700	30	−24.07	–	−2140–2110	**−2105–2035**		−2200–2165	**−2155–2015**	−1995–1980

Analyst: J. van der Plicht (Centre for Isotope Research, Radiocarbon Laboratory, Groningen University, The Netherlands). "Alkali extract" means that the sample was not fully pre-treated by the AAA method (Acid/Alkali/Acid) and contamination removal cannot be guaranteed. $^{13}\delta$ value of PICH 127A and low C_v values of samples 30G and 87, as well as calibrated ranges reported in bold, are discussed in text. For six samples, only the alkali extract was dated.
a.e.: alkali extract fraction dated, c.r.: charred remains (charcoal) fraction dated.
*All samples were analysed by the conventional method except PICH 33B and PICH 128B (AMS determinations).

Twenty samples of charcoal were dated by the radiocarbon method at the Groningen Laboratory, Netherlands. Pre-treatment, analytical, and calibration procedures for the samples are summarized in Appendix A; short sample descriptions and UTM locations are reported in Appendix B. Table 1 shows the ^{14}C conventional ages, 1 sigma errors, the $^{13}\delta$ values, the organic carbon content (C_v in %), and the calibrated date ranges at the 68.3% and 95.4% confidence levels. The $^{13}\delta$ values (generally around −25‰) and C_v values (around 68%) are quality parameters characterizing the sample material. The $^{13}\delta$ values are also used for the correction of ^{14}C dates for isotopic effects.

4. Field and ^{14}C data

4.1. Explosive activity between 3000 and 4000 yr BP

The older volcanic deposits of the Late Holocene are represented by scarce outcrops of block-and-ash flow units and related debris-flow deposits, which are exposed in the Río Cristal and Río Cinto valleys. Each 15 to 20 m-thick pyroclastic flow unit is massive to crudely stratified, with gas-escape pipes. Blocks are grey silicic andesites to dacites (62–65% SiO_2) with a mineral assemblage of plagioclase, hornblende, orthopyroxene, and Fe–Ti oxides. These deposits locally contain carbonized trunks. Three new ^{14}C ages (3700±30, 3540±30, and 2990±20 yr BP) indicate recurrent and important dome growth activity between 4000 and 3000 yr BP (Table 1). Related to this period of explosive activity, several thin dacitic ash-fall layers were found in sections on the upper flanks of the volcano, below the Pululahua stratigraphic marker bed (stratigraphic section No. 78 in Geotérmica Italiana, 1989).

4.2. The first cycle of the last 2000 years (1st and 2nd centuries)

Outcrops along the Lloa–Refugio road show a complete stratigraphic sequence comprising the last eruptive events of Guagua Pichincha, as well as the Pululahua tephra and the Quilotoa ash layer. In this area, the deposits of the first eruptive cycle of the last 2000 years are exposed above a 20 to 30 cm-thick, dark, organic-rich soil. A 20 to 50 cm-thick, lithic-rich, laminated sequence of surge deposits with cross-bedding is overlain by a ~30 cm-thick layer of whitish-grey, poorly vesiculated pumice lapilli and coarse ash (base of sections 35, 87 and 97, Fig. 2). This fallout layer, deposited to the NW (Fig. 4A), includes juvenile vitric clasts whose composition is similar to that of clasts from contemporaneous pyroclastic flow deposits in the Río Cristal valley (64.1–64.8% SiO_2). The minimum bulk eruption volume was estimated at 0.5 km^3, that ranks the eruption at VEI 4.

The age of this eruption is not well constrained. Geotérmica Italiana (1989) and Barberi et al. (1992) dated a soil sample overlying the surge and fall layers on the northern side of the volcano at 1450±80 yr BP. They correlated both deposits to a block-and-ash flow deposit exposed near the junction of the Cristal and Cinto rivers that they had dated at 1470±80 yr BP on charcoal. In this study, we dated the uppermost fraction of the soil underlying the surge and fall layers at two neighbouring sites (86 and 97B, Fig. 2). Both samples yielded consistent results of 1915±50 and 1935±40 yr BP, with normal $\delta^{13}C$ values (Table 1). A third sample (PICH 97C) yielded a younger age of 1640±70 yr BP. Because buried soils are sensitive to contamination by younger charcoal and humic acids percolating from overlying soils ($\delta^{13}C$ for this sample is −27.96), we suspect that rejuvenation might have occurred and consequently we discarded this age.

At a 95.4% (2σ) confidence level, the calibrated dates of samples 86 and 97B overlap in the ranges cal. BC 40–30, BC 25 to AD 10, AD 1–140, and AD 195–210 (Fig. 5). Eliminating the brackets of the probability function with small relative areas, we retain the calendar ages in the intervals AD 1–140 at the 2σ level (midpoint: AD 70, see the grey field in Fig. 5), and AD 20–90 at the 1σ level. For the sake of convenience this event is referred to as *the first century eruption*.

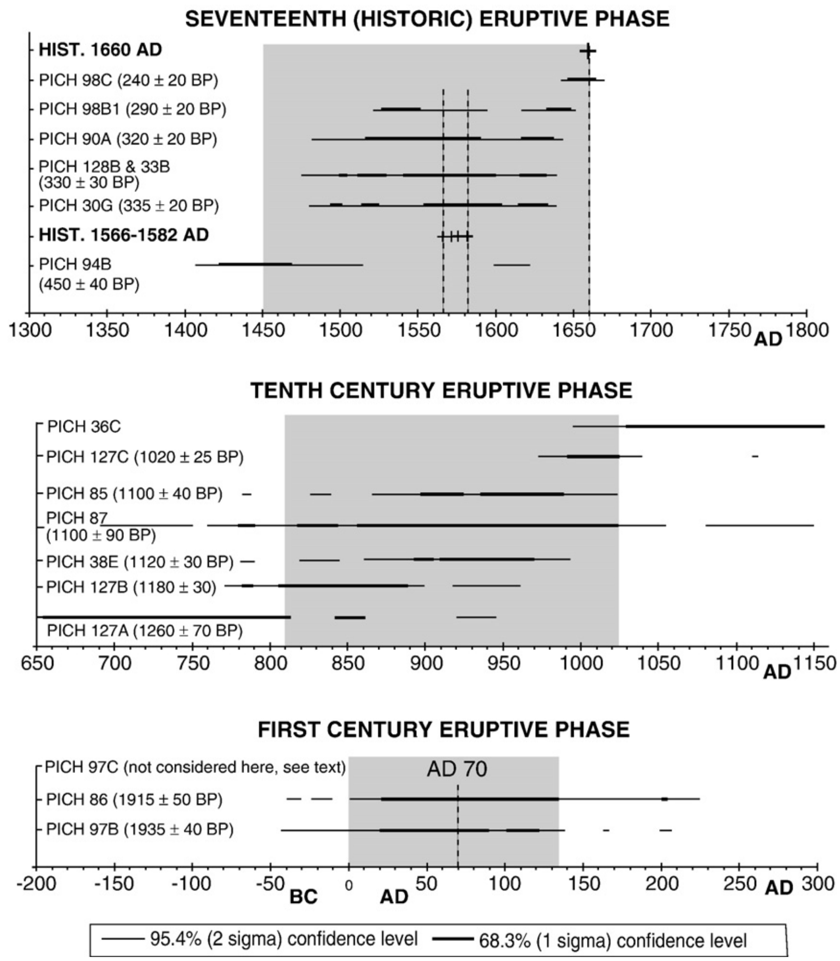

Fig. 5. Graphic representation of radiocarbon results. Samples are ordered from younger to older radiocarbon ages. The grey field represent the time span for each eruption based on 1 sigma.

4.3. The intermediate eruptive cycle (9th and 10th centuries)

Coarse ash and lapilli layers, which locally show cross-bedding and lamination, and another thick pumice lapilli fall layer with a dispersal toward the NW (Fig. 4B), were deposited during the second eruptive cycle. At ~15 km from the vent, in the WSW (La Victoria area), and at 15–20 km north and northwestwards (Nono and Mindo areas), the fallout deposit is 15 cm thick. On the upper flanks (Figs. 2 and 3), it reaches 30 cm in thickness, shows pumice with typical plagioclase phenocrysts and hornblende clots, and bears abundant oxidized xenoliths from the basement. The pumices and juvenile clasts from underlying surge deposits show homogeneous compositions (65.1–65.7% SiO_2) similar to those of block-and-ash pyroclastic flow deposits sampled in the Río Cristal valley, in the same stratigraphic position.

The remaining volume of the deposits is estimated at 0.6 km^3, corresponding to a VEI of 4. Because we have no constraint on the extent of the distal fallout layer beyond the 10 cm isopach, the total eruption volume is significantly underestimated. Moreover, due to the severe erosion of the western flanks, the initial volume of pyroclastic flow deposits in the Río Cinto valley is unknown. Considering such uncertainties, the original bulk volume was probably much greater than that calculated on the observed deposits. This would rank the eruption at VEI 5, making it the largest eruption of Guagua Pichincha during Late Holocene times.

Seven samples were dated. On the upper slopes, the uppermost layer of a 30–40 cm-thick, organic-rich soil underlying the deposits yielded two ages of 1100±40 yr BP and 930±60 yr BP (PICH 85 and 36C, Table 1). Plant debris and charred twigs from the surge deposits above this soil yielded four ^{14}C ages between 1260±70 yr BP and 1020±25 yr BP (samples 87, 127A, B, and C). Considering that the PICH 87 and PICH 127A ages show a large standard deviation and that sample PICH 36C has possibly suffered contamination and rejuvenation ($\delta^{13}C$= −26.86), we discarded the dates of these three samples. On the contrary, due to the good quality of the twig samples PICH 127B and 127C, and eliminating the brackets of the probability function with a small relative area, the surges would have been produced between cal. AD 770–900, or between cal. AD 970–1040 (see the ages of these samples at a 2σ level, reported in bold in Table 1). A seventh sample, PICH 38E, was collected in a charcoal-rich, block-and-ash flow deposit, exposed near the junction between the Ríos Cristal and Cinto (site 38, Fig. 1B). This sample yielded a conventional ^{14}C age of 1120±30 yr BP, corresponding to calibrated dates of AD 860–995, at the 95.4% confidence level (Table 1).

On the basis of these data, and since the age of the underlying soil PICH 85 (cal. AD 865–1025 at a 2σ level) must be considered as a minimum age, we retain the calendar ages in the intervals of cal. AD 770–1040 at the 2σ level, and 805–1025 at the 1σ level (grey field, Fig. 5). This points to the 9th and 10th centuries as the most probable epoch. This time span could be reduced if one only considers the overlap of the samples of good quality (PICH 38E, 85, 127B, and 127C).

4.4. The historic eruptive cycle (15th to 17th centuries)

Accounts of volcanic episodes in AD 1566–1582 and of the 1660 eruptions are reported in Wolf (1904) and Estupiñán Viteri (1998). In 1566, 1575, and 1582, ash fell on Quito and neighbouring areas. Ash fallout was particularly heavy during the second and third episodes. Toribio de Ortiguera (cited by Estupiñán Viteri, 1998) provided descriptions of the damage in the valleys located west of the volcano that were seriously affected by pyroclastic flows, a phenomenon not known at that time but whose effects were unambiguously well-described. The greatest historical eruption of Guagua Pichincha occurred on October 27th 1660, that saw a high eruptive column, dense ash and pumice lapilli fallout in Quito (a «40 hour-long night» affected the area, and «if all the ash could be possibly grouped together, this would form a mountain as high as the same Pichincha»). Remnants of this eruption include conspicuous ash and pumice fallout deposits on the upper parts of the cone (Figs. 2 and 3) and pyroclastic flow deposits within the western valleys. Ash falls reached several hundred kilometres from the volcano. Thunder and subterranean noises accompanied this eruption, and strong earthquakes were felt in Quito during the following year.

On the upper eastern flanks of Guagua Pichincha, the main deposit consists of a 10 to 20 cm-thick, whitish-yellow or light-grey fallout layer of pumice lapilli and ash. Isopach maps indicate that the plume drifted to the WSW (Fig. 4C). Near the eastern caldera rim, decimetre-thick surge deposits underlie this pumice layer. This deposit also overlies a series of centimetre-thick horizons of partially altered ash and pumice lapilli, including a conspicuous greyish-pink horizon of fine ash, interlayered with 1 to 2 centimetre-thick soils and lenses of carbonized organic material (sections 35 and 128; Fig. 2). This sequence is interpreted to be the result of the AD 1566–1582 eruptive activity reported in the colonial chronicles.

Pumices from this sequence are andesitic to dacitic in composition (62.6–64.2% SiO_2). Pumices from the AD 1660 fallout layer show incipient magma mixing with occasional andesitic bands (57.5–59.7% SiO_2), but are essentially dacitic (63.5–64.8% SiO_2) and slightly more silicic than those of the 1566–1582 eruptions or those from flow deposits in the Río Cristal valley. Moreover, similar silicic compositions and age determinations suggest that greyish-pink pumice-flow deposits up to 15 m-thick and associated debris flows in the Río Cinto valley belong to the same 1660 eruption (section 30; Fig. 2). A bulk tephra volume of 0.2 km^3 is estimated as a minimum value for the 1660 deposits. Accordingly, a VEI of 4 is assigned to this eruption.

Radiocarbon dating was performed on four charcoal samples from ash-flow deposits exposed in the Río Cinto valley and along the Lloa–Río Cristal road, and on one organic soil. A piece of charcoal within a pyroclastic flow deposit (PICH 94B) yielded the oldest conventional age of 450±40 yr BP. At the 95.4% (2σ) confidence level, ages range between cal. AD 1405 and 1515, and between 1600 and 1620, whereas the 68.3% confidence level (1σ) indicates an eruption in the middle of the 15th century (1420–1465). Considering the older and wider 2σ brackets and the 1σ results, a date about 1450 is probable, suggesting an important episode one century before the activity reported in 1566–82.

Sample PICH 30G is a piece of wood collected in an organic soil exposed at the base of a thick volcanic sequence, 18 km down river from the crater (section 30, Fig. 2). This layer, dated at 335±20 yr BP, was buried under a 2 to 8 cm-thick ash-and-pumice fallout deposit, that may have destroyed, but not burnt, part of the forest, higher up on the volcano. Calibrated dates at the 95.4% confidence level correspond to the bracket cal. AD 1480–1640, prior to the AD 1660 eruption. Thus, this sample likely corresponds to the 1566–82 eruptive episodes, when strong ash fallout affected Quito or, if the younger bracket is considered, to an earlier unreported episode before the large AD 1660 eruption.

Two charcoal samples collected within surge deposits underlying the AD 1660 Plinian fall layer (PICH 33B and 128B) yielded an age of 330±30 yr BP, corresponding to the calibrated interval AD 1475–1640 at the 95.4% (2σ) confidence level, whereas the 68.3% confidence level (1σ) ages range within the intervals AD 1510–1530, 1540–1600, and 1615–1635. Thus, we state that these surges were produced by the AD1566 to 1682 volcanic activity.

The radiocarbon analysis of PICH 90A, a piece of charcoal from another pyroclastic flow sequence at the Río Blanco and Río Cinto junction, confirms important pyroclastic flow episodes, either during the second half of the 16th century or during the first part of the 17th century. The conventional age of this charcoal (320±20 yr BP) and the 2σ confidence level indicate an age in the range cal. AD 1480–1645 (1515–1595 and 1615–1640 at 1σ); in any case, at least a few decades before the AD 1660 eruption.

Finally, the ages obtained on samples PICH 98C and 98B1, collected in the Río Cinto valley, indicate that the climax of the AD 1660 eruption emitted large ash flows, as also shown by the ~5 m-thick ash-flow deposits observed along the Lloa–Rio Cristal road (e.g. at 2180 m asl), and the 15 m-thick debris flow deposit at the top of section 30, which bears pumice blocks up to 25 cm in size.

4.5. Possible additional event near AD 500

The age of 1470±80 yr BP obtained from the charcoal collected by the Italian team in a block-and-ash flow deposit near the junction Río Cristal–Río Cinto seems unusual. In this study we found no radiocarbon evidence for an eruptive event around this date. But we do not discard an additional eruptive cycle between cal. AD 410–685 (2σ) related to the emplacement of these pyroclastic flows in the Río Cristal valley, with possible fallout deposits too thin to be preserved, as occurred during the AD 1999–2001 eruptive episode.

5. Concluding comments

5.1. Characteristics of the Late Holocene eruptive activity

The Late Holocene eruptive activity of Guagua Pichincha was mainly dome-forming and explosive. Ash-flow activity and fallout deposits occurred from ~4000 to ~3000 yr BP and during the last 2000 years. Three well-defined Plinian eruptions with pumice discharge occurred in the 1st century, in the 10th century, and in AD 1660. Eruptive columns, 25 to 30 km-high were estimated by Geotérmica Italiana (1989) for these eruptions, with conspicuous fallout pumice layers covering the high parts of the volcano. The 10th century event was the largest in magnitude, with a VEI of 5 (versus VEI of 4 for the 1st and 17th century events). The eruption previously known as the «AD 550» event occurred between AD 1 and 140 with a high probability of occurrence during the second part of the 1st century. A fourth eruption might have occurred near AD 500.

These large explosive events occurred at the end of eruptive cycles which lasted 100 to 200 yr. The first cycle lasted about one century. A possible span of activity of 150–180 yr is proposed for the second cycle, before its climax near AD 970. As a whole, the third cycle lasted ~200 yr and ended with the AD 1660 eruption. These cycles are separated by repose periods of the order of 300–500 yr and were initiated with phases of dome emplacement and explosive episodes. The latter (e.g. the episodes which occurred in 1566–1582), are shown by the block-and-ash flow deposits, as well as the minor pumice fallouts.

5.2. Significance of the 1999–2001 eruptive episodes

The most serious hazards for Quito is tephra fall such as that which was reported in AD 1660, with a thickness of as much as 10 cm (Fig. 4). Rain-triggered reworking of tephra, producing lahars on the eastern flanks of Guagua and Rucu Pichincha, represents another dangerous phenomenon that could affect the western and central parts of Quito (Canuti et al., 2002; Hall and von Hillebrandt, 1988) as well as Nono village on its northern flank. During the 1660 eruption, witnesses reported that «stones, mud and snow dammed the rivers for some time. Then, the waters broke the dams and flooded the countrysides around Quito». In contrast, Quito cannot be affected by pyroclastic flows, due to the protection of the natural barrier formed by the El Cinto ridge and the Rucu Pichincha massif.

This study has shown that minor block-and-ash flows occurred as precursors several decades or more prior to the main Plinian events. The well-documented historic cycle is the clearest example of this behaviour: it includes the pyroclastic episodes around AD 1450 and AD 1500, the reported 1566–82 episodes, possible precursors in the earlier decades of the 17th century, and finally the AD 1660 eruption. During the latter, the typical eruptive behaviour included the emplacement of pyroclastic surges that swept across the cone's upper slopes, followed by regional ash and pumice fallouts (by sustained Plinian discharge), and finally by pumice flows. This Plinian phase typically represents the climax of the whole eruptive cycle.

From AD 1660 to 1981, the volcano was mostly quiet, with occasional fumarolic and rare phreatic activities in AD 1830–1831 and 1868–1869 (Hall, 1977; Simkin and Siebert, 1994). Between AD 1981 and 1998, phreatic explosions formed small craters in the Cristal dome complex. This renewed activity increased during 1998, while significant seismic activity occurred 15 km NE of the caldera (Legrand et al., 2002). At the end of September 1999, the first dome emplacement and magmatic explosions occurred. The 1999–2001 crisis was marked by eight successive dacitic extrusions which were destroyed after a few weeks of growth by vulcanian explosions and dome collapses (Garcia-Aristizabal et al., 2007). Frequent block-and-ash flows descended the Río Cristal valley up to 12 km downstream. These new deposits fed lahars in the valleys of the Río Cristal and Río Cinto, and additionally, significant ash fell upon Quito several times. These episodes resemble those of the 16th century (e.g. AD 1566, 1575, and 1582) or those of the first part of the 17th century. Thus, the increasing phreatic activity observed between 1981 and 1998, and the 1999–2001 dome-forming activity represent a step in the course of a longer evolution which may result in the mid-term occurrence (i.e. in a few decades or one century) of a major Plinian event, such as those that occurred during the first, tenth, and seventeenth centuries.

Aknowledgements

This contribution is part of a Ecuadorian–French cooperation program carried out between the Geophysical Institute (EPN; National Polytechnic School of Ecuador) and the UR 031 "Processes and volcanic Hazards" of IRD (today UMR 163: "Magmas et Volcans"). We warmly thank C. Siebe and an anonymous referee for constructive reviews.

Appendix A. Radiocarbon analysis

Before the actual ^{14}C measurement, the sample materials were chemically pretreated in order to isolate the datable fraction, and to remove contaminants (Mook and Streurman, 1983; Mook and Waterbolk, 1985). The treatment (referred to as the "AAA" treatment) consists of the following steps: (1) with acid (HCl) in order to remove soil carbonate and possibly infiltrated humic acids; (2) with alkali (NaOH) to remove e.g. soil humates; (3) with acid (HCl) to remove any CO_2 absorbed during step (2). The extracts are separated from the residue (in this case, the charcoal). The alkali extract can be precipitated by acidification, washing and drying. When necessary, this extract (containing humic acids) can be dated as well in order to check sample homogeneity. The extracted fraction (charcoal) is combusted to purified CO_2 gas. This gas is used in proportional counters, which measure the ^{14}C decays. This is the so-called Conventional Radiocarbon method (Mook and Streurman, 1983).

The ^{14}C ages are calculated using a conventional half-life for ^{14}C, and corrected for mass dependent effects (isotope fractionation) using the stable isotope ^{13}C. The results are reported in yr BP. This ^{14}C timescale deviates from the calendar timescale, because the ^{14}C content in nature has varied significantly in the past. The ^{14}C timescale has been calibrated using wood, dated absolutely by dendrochronology. The calibration curve establishes the relation between the ^{14}C timescale (in BP) and the calendar timescale (reported in cal AD or cal BC). The variations in the natural ^{14}C content cause the calibration procedures to be complicated. The measured ^{14}C dates show a Gaussian error distribution; the error can be expressed as the standard deviation σ. Because of the variations, the calibrated error distribution is not Gaussian shaped; there can be even multiple solutions. For calibrated dates, the error ranges (with 1σ or 2σ probability) are calculated. In this paper, we used the program developed in Groningen (van der Plicht, 1993; 2004). The presently recommended calibration curve is Intcal04 (Reimer et al., 2004).

Appendix B. Sampling for radiocarbon measurements

Sample number	Location (UTM zone 17)*	Sample type and stratigraphic unit
PICH 98C	758.6–9978.3	Charcoal in pumice flow deposit
PICH 98B1	758.6–9978.3	Charcoal in pumice flow deposit
PICH 90A	759.5–9977.8	Charcoal in pumice flow deposit
PICH 33B	767.7–9980.7	Charred twigs in surge deposit
PICH 128B	768.2–9980.4	Charred twigs in surge deposit
PICH 30G	752.4–9984.8	Wood. Organic layer below pyr. flow deposit
PICH 94B	758.3–9978.8	Charcoal in block-and-ash flow deposit
PICH 36C	768.6–9979.9	Soil below the Plinian fallout layer
PICH 127C	769.0–9979.2	Charred twigs in surge deposit
PICH 85	768.8–9979.9	Black organic soil under surge deposit
PICH 87	768.8–9978.9	Charred plant debris in surge deposit
PICH 38E	758.4–9978.8	Charred trunk in block-and-ash deposit
PICH 127B	769.0–9979.2	Charred twigs in surge deposit
PICH 127A	769.0–9979.2	Charred twigs in surge deposit
PICH 97C	768.8–9979.9	Soil under surge deposit
PICH 86	768.8–9979.9	Organic soil under surge deposit
PICH 97B	768.8–9979.9	Organic soil under surge deposit

* Topographic map — Pichincha (1:50,000).

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