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Late Holocene eruptive activity at Nevado Cayambe Volcano, Ecuador

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Abstract Four Late Holocene pyroclastic units composed of block and ash flows, surges, ashfalls of silicic andesite and dacite composition, and associated lahar deposits represent the recent products emitted by domes on the upper part of Nevado Cayambe, a large ice-capped volcano 60 km northeast of Quito. These units are correlated stratigraphically with fallout deposits (ash and lapilli) exposed in a peat bog. Based on ^{14}C dating of the peat and charcoal, the following ages were obtained: ~910 years BP for the oldest unit, 680–650 years BP for the second, and 400–360 years BP for the two youngest units. Moreover, the detailed tephrochronology observed in the peat bog and in other sections implies at least 21 volcanic events during the last 4000 years, comprising three principal eruptive phases of activity that are ~300, 800, and 900 years in duration and separated by repose intervals of 600–1000 years. The last phase, to which the four pyroclastic units belong, has probably not ended, as suggested by an eruption in 1785–1786. Thus, Cayambe, previously thought to have been dormant for a long time, should be considered active and potentially dangerous to the nearby population of the Interandean Valley.

Key words Tephrochronology · Pyroclastic flow · Holocene · Cayambe Volcano · Ecuador

Introduction

Glacier-clad Nevado Cayambe volcano (Latitude 00° 01′.72 N, Longitude 77° 59′.13 E; 5790 m elevation) lies in the northern part of the eastern Cordillera of Ecuador, 60 km northeast of Quito (Fig. 1). During the last centuries, the only signs of activity on this large edifice have been strong sulphur smells reported by mountaineers. However, in a paper summarizing the Holocene tephrostratigraphy of the principal Ecuadorian volcanoes, Hall and Mothes (1994) report six regional fallout deposits probably related to recent activity of Nevado Cayambe (i.e., <10000 years BP). Moreover, a letter written in 1802 to A. Von Humboldt, relating a volcanic event at Nevado Cayambe in 1785-1786, has recently been published (Ascásubi, 1802, in "Briefe aus Amerika" by Ulrike Moheit, 1993). This event, previously unknown to the volcanological community, seems to be the only historic eruption of the volcano.

The geological and petrological study of the whole Cayambe volcanic complex is in progress; in this paper we present the results of a detailed study of Nevado Cayambe's Holocene activity, focusing on the relationship of the pyroclastic flows generated by dome collapses in the summit area to the tephrochronology observed in sections on the volcano's flanks. Special attention is given to the block and ash flow deposits and the ^{14}C dating of their fallout equivalents interbedded with peat layers in a bog.

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Structure of the Cayambe volcanic complex

Cayambe is a composite volcano that rises from a quasi-rectangular base (24×18 km) at elevations of 3000 m on its western side and almost 3600 m on its eastern side to its summit at 5790 m (Fig. 2). Above 4800 m, the volcano is covered by a 22-km^2 glacial cap. From this ice cap, glaciers extend down to 4200 m on the very wet, eastern Amazonian side, but only to 4600 m on the drier western side.

Fault systems oriented N35E and N125E control the location and shape of the volcanic complex, the most important being the La Sofia-Rio Chingual fault system, which ends in the northeast sector of the volcano

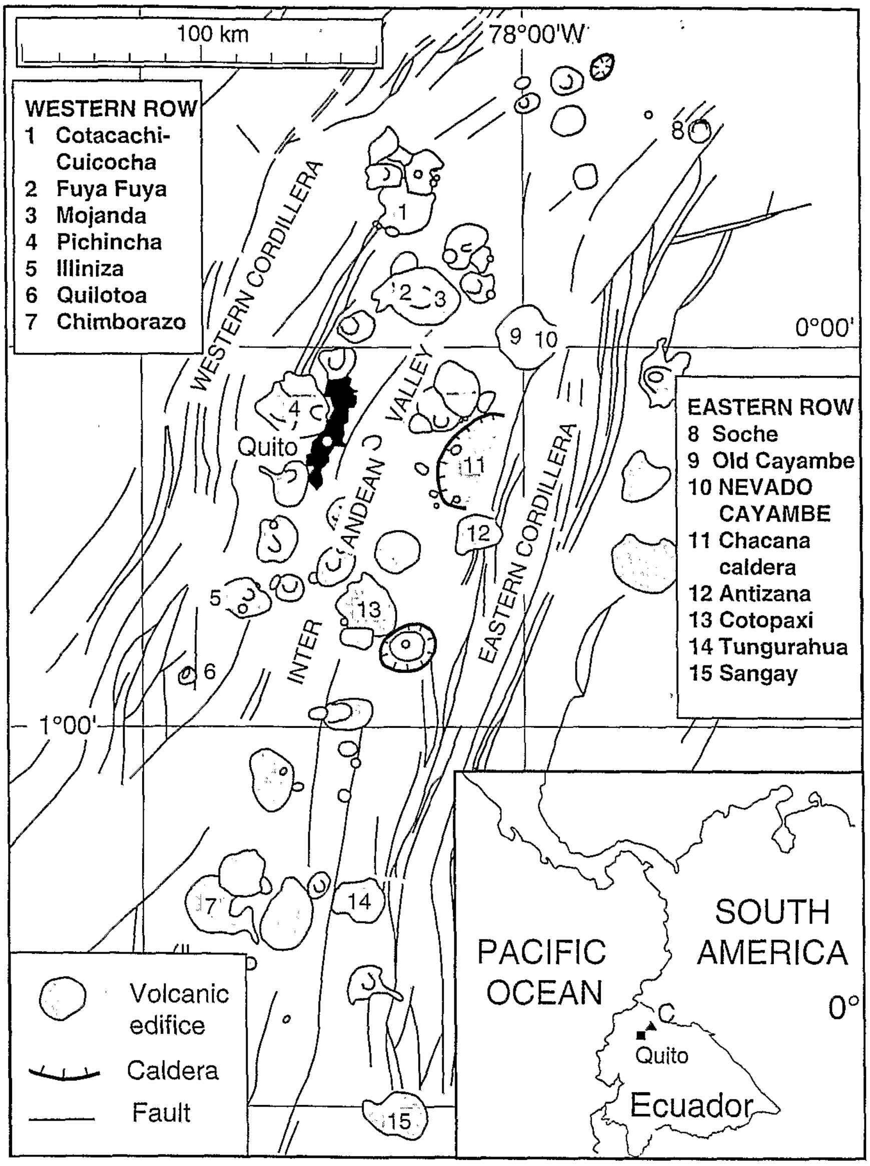

Fig. 1 Location of Cayambe Volcano in the Ecuadorian volcanic arc. Faults from Litherland and Egüez (1993)

(Fig. 2; Soulas et al. 1991; Ferrari and Tibaldi 1992). The complex is formed by three volcanic edifices (Fig. 2):

1. A western basal volcano, Old Cayambe, comprised mainly of lava flows. It is presently extinct and shows evidence of intense glacial erosion.
2. The less massive Nevado Cayambe, a composite edifice built over the eastern remnants of Old Cayambe. It followed a caldera-forming event that is suggested by a geomorphic structure and outward-dipping beds. This edifice was constructed mainly of lava flows, followed by ignimbrite eruptions that produced a large welded tuff, 60–80 m thick, in the La Chimba valley. This deposit is covered by large Late Pleistocene moraines. Later, Nevado Cayambe was capped by a complex of summit domes, the source of pyroclastic flows that descended the north–northeast side of the volcano and are the subject of this paper. The summit area is roughly elongate in an east–west direction, with its main summit at 5790 m and its eastern summit at 5487 m, both formed by domes. There is no observable crater. Large moraines extend down to 3700 m, especially on the north side; they overlie the Old Cayambe lava flows as well as those of Nevado Cayambe.
3. A 1-km-wide parasitic cone, called the "Cono de La Virgen" (3882 m) is found at the eastern foot of Nevado Cayambe. On the basis of its youthful appearance and lack of glacial deposits, this edifice is probably Holocene in age. A striking 200- to 300-m-thick series of lava flows (~ 3.8 km^3) was produced by this cone. The flows traveled eastward for 10 km, forming the Planada de la Virgen (Fig. 2).

Late Holocene volcanic products

Pyroclastic flows

Four pyroclastic flow sequences are found on the north–northeast flank of Nevado Cayambe. The older

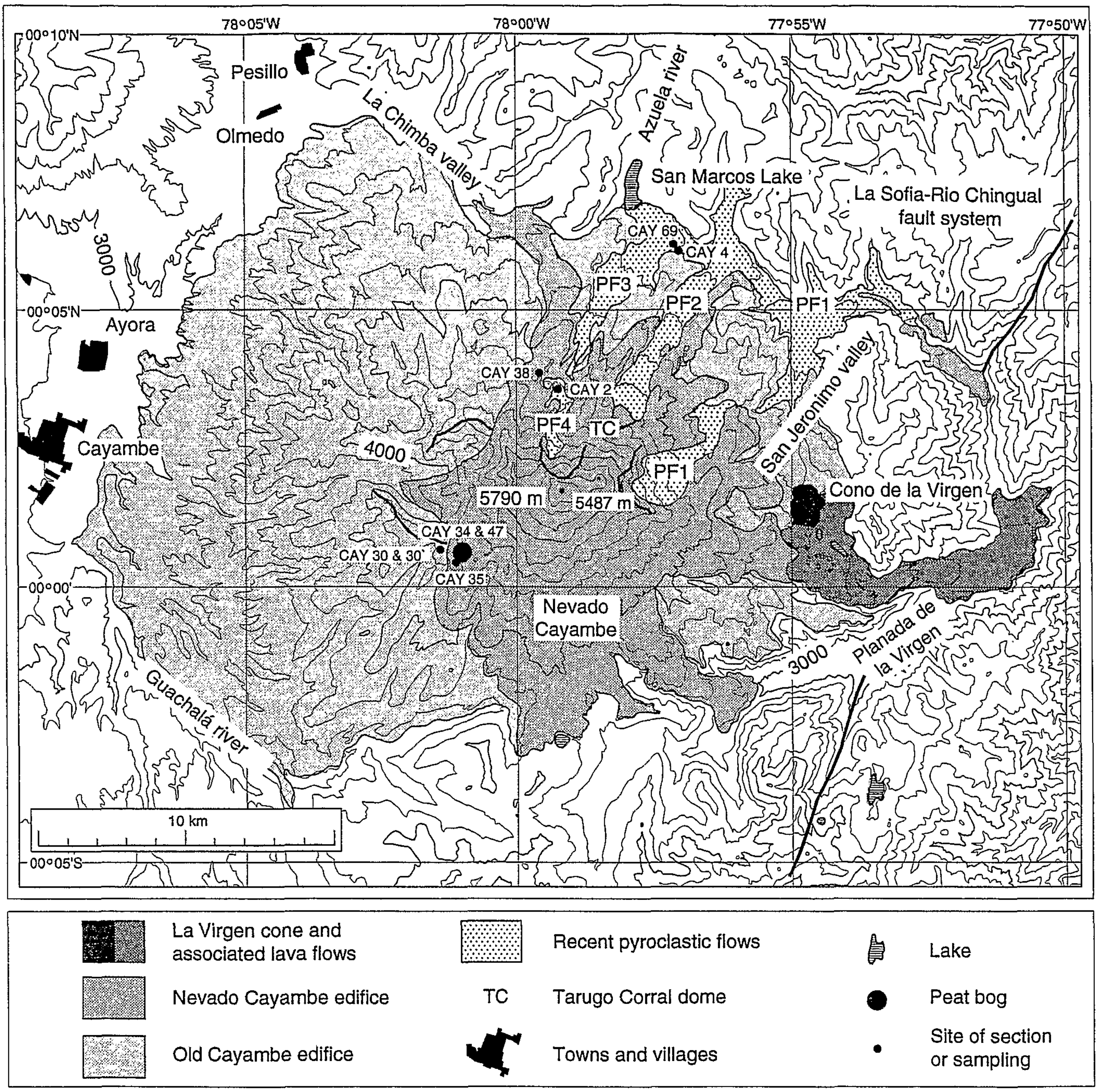

Fig. 2 Simplified map of Cayambe Volcano. Contour interval of 200 m. Recent pyroclastic flows (PF1–PF4) of Nevado Cayambe are highlighted, as well as sites where sections have been examined in detail

three (PF1–PF3) consist mainly of large block and ash flow deposits from dome collapses, whereas the youngest (PF4) consists of surge deposits comprised of ash and lapilli.

The oldest unit (PF1) is largely eroded. Only remnants of a 20- to 30-m-thick block and ash deposit persist in the lower San Jeronimo Valley, approximately 8 km from its source. The deposit, whose original volume is estimated at 0.4 km^3, formed by dome collapse from near the eastern summit (5487 m). Within this deposit, as well as in the younger deposits PF2–PF4, blocks are generally dense but can be vesicular and even pumiceous.

The PF2 and PF3 deposits are clearly younger than PF1, for they are less eroded and only partly covered by vegetation. The PF2 sequence consists of 15–20 units of interbedded block and ash flow, lahar, and ash flow deposits, whose original dimensions are estimated to have been 7–8 km long, 600–900 m wide, and 80–100 m thick (estimated volume: 0.5 km^3). A lahar deposit at the base of PF2 carries banded dacite blocks and is overlain by deposits of ash flows and block and ash flows, 1–10 m thick. The top layer consists of a pyro-

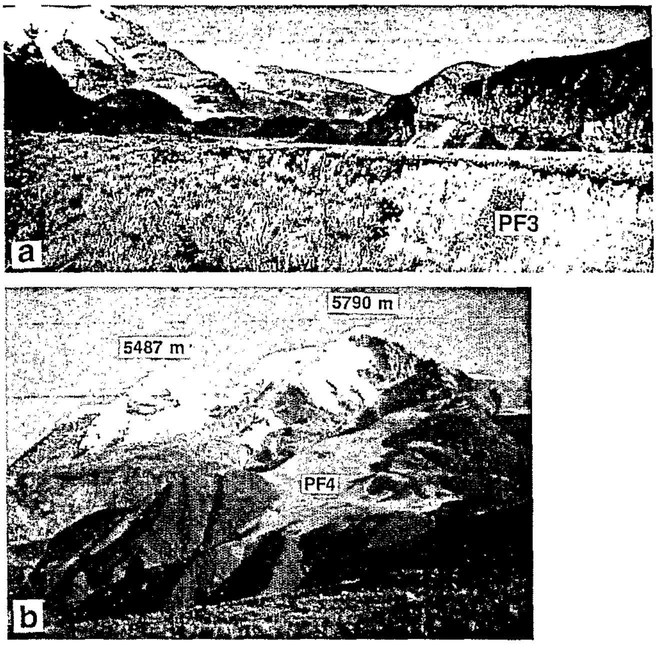

Fig. 3 Two views of Nevado Cayambe from the north, showing **a** the PF 3 deposit in a glacial valley and **b** the PF4 deposits

clastic flow deposit formed by dome collapse in which blocks up to 1 m in diameter constitute 80% of its volume. This unit reaches upslope to the 500-m-wide, morphologically young "Tarugo Corral" dome, located on the north–northeast side of the eastern summit.

Although as voluminous as PF2, the younger PF3 deposit (Fig. 3) corresponds to a single massive flow, 6 km long, 800 m wide, and 100 m thick. It contains decimeter-size, light-gray or dark-brown breadcrust bombs as well as banded blocks. This flow deposit, whose original volume was approximately 0.4 km^3, is best exposed at site CAY 4 and is apparently related to the partial collapse of a dome located north of the main 5790-m summit (Figs. 2, 3). The flow descended north–northeastward, down to 3400 m, where it dammed the Azuela River and formed San Marcos Lake.

The PF4 unit is located on the upper northern flanks of the main summit, above 4200 m elevation, and covers only 1.25 km^2 (Fig. 3). The deposits comprise a 10-m-thick sequence of surges that overlie approximately 40 cm of ash and lapilli-fall layers related to the eruption of PF3 (see Discussion), as well as a sequence of two paleosoils separated by an ash layer (sequence A, section CAY 2, Fig. 4). No soil exists on the surge deposits, which consist of dune-bedded layers of coarse ash, dense lapilli, and scarce blocks, some of which are banded. Charcoal from the upper paleosoil of sequence A gives an age of 360±70 years BP (Fig. 4; Table 1).

Units PF3 and PF4 apparently issued from the same vent. Nevertheless, the PF4 products erupted after the partial collapse of the dome that produced the PF3 block and ash-flow deposit. A thin paleosoil (stratigraphic section CAY 69, Fig. 4) between the PF3 and PF4 units clearly shows that they are different events, separated by a short period of quiescence. A semi-circular scar on the northern face of the main summit dome at 5200 m elevation may correspond to this event.

Fallout deposits

Stratigraphic sections have been studied on the volcano's upper flanks in order to characterize the fallout deposits related to the post-glacial activity (Fig. 4). For example, at site CAY 30, a 4-m-thick section shows numerous fallout beds separated by eight paleosoils, which generally consist of organic material containing ash. This section lies on morainal deposits of the last glacial event (i.e., 10000–11000 years BP; Clapperton et al. 1997).

On the southwest flank of Nevado Cayambe, 4 km from the summit and at 4300 m elevation, an active peat bog occupies a small depression in a glacial valley, which has been a good tephra trap since the last glaciation. A composite 4.5-m-thick section was studied in two excavations (sites 34 and 47; Fig. 2), which provide a good record of the Late Holocene fallout history of Nevado Cayambe (Fig. 5). Here, 23 ashfall layers or sets of associated ashfalls belonging to the same eruption alternate with peat layers. Most of them include dacitic lapilli whose petrography is similar to that of the dacitic blocks in units PF1–PF4. Correlations between the fallout layers of the six sections presented in Fig. 4 and the beds observed in the peat bog are discussed below.

Summary of petrological characteristics

Based on 14 whole-rock chemical analyses given in Samaniego (1996), the Holocene rocks of Nevado Cayambe are medium-K silicic andesite and dacite. These analyses form a part of a detailed petrological study of the overall Cayambe volcanic complex, in preparation, and are available on request. All blocks from PF1 are homogeneous gray dacite, whereas light- or dark-gray blocks or bombs, as well as banded blocks, are present in PF2–PF4. This suggests magma heterogeneity or mixing, which is demonstrated by a compositional range varying from silicic andesite to dacite in the same flow or within the same banded sample (SiO_2=60.5–65.2%; analyses normalized to 100%, LOI free).

Blocks from units PF1–PF4 and lapilli from the fallout deposits in the peat bog are medium grained, porphyritic, and typically contain plagioclase (20–25%), hornblende (<7%), ortho- and clinopyroxene (<10%), magnetite (<2%), rare biotite (<1%), and quartz. In all rocks, unzoned or poorly zoned plagioclase occurs (An_{31-56}), but strong normal or reverse zoning is common in plagioclase of PF 2, 3, and 4 (An_{64-39}; An_{63-41}; An_{35-71} as examples), as well as com-

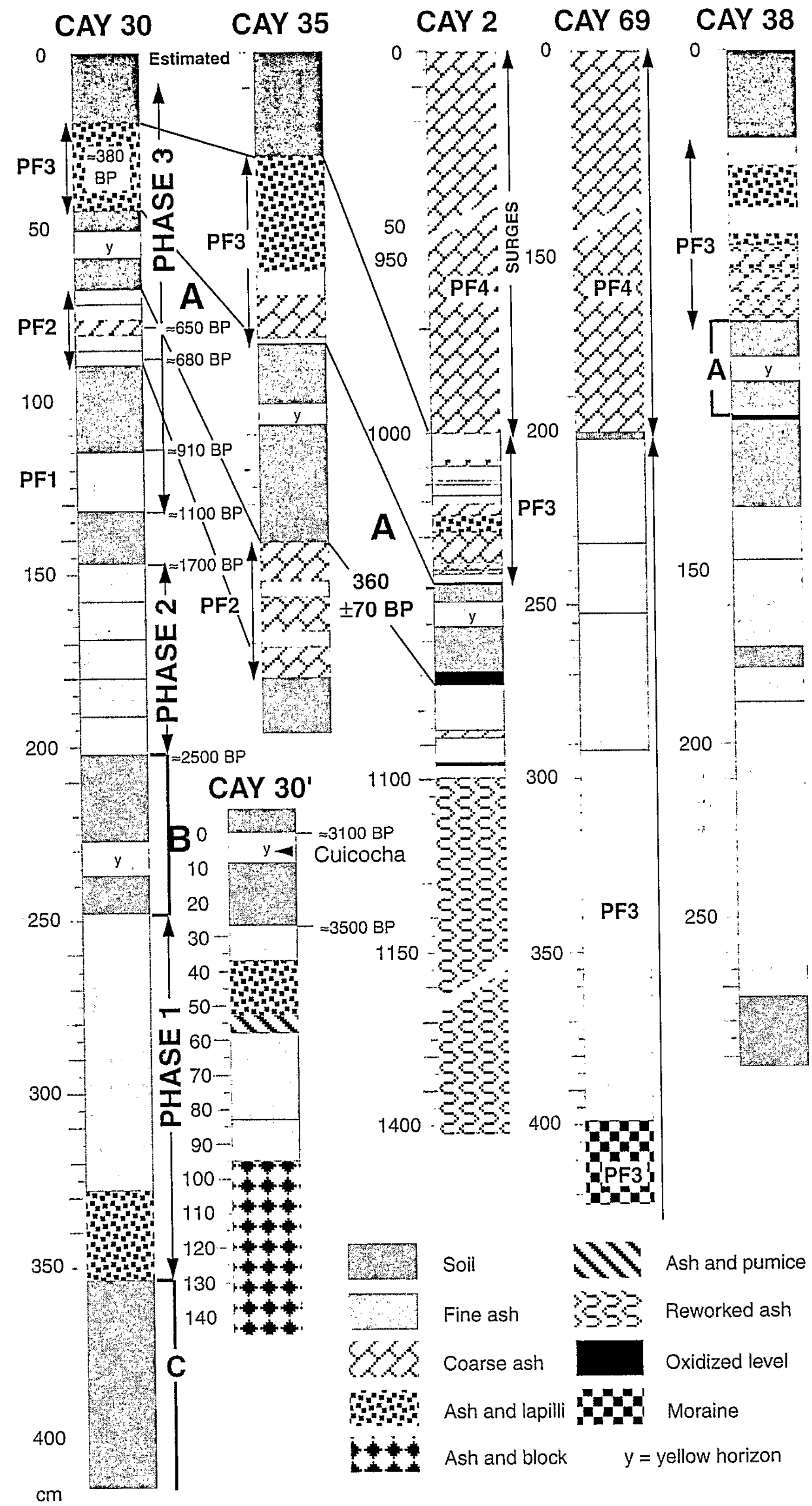

Fig. 4 Cross sections through fallout deposits related to the post-glacial activity of Nevado Cayambe (see locations in Fig. 2). The reported ages for the CAY 30 section are deduced from Fig. 5

plex zoning. Reverse zoning also occurs in orthopyroxene of the lighter-colored bands (En_{63-67}), and a compositional gap exists between this orthopyroxene and that of the dark bands (En_{73-74}). Clinopyroxene has compositions ranging from $Wo_{44}En_{43}Fs_{13}$ to $Wo_{43}En_{47}Fs_{10}$. Scarce olivine (Fo_{75}) occurs in the PF3 blocks.

The chemical variability of these magmas is shown by the varied mineralogy of the PF2–PF4 units as well as by the two compositional ranges observed in the vit-

Table 1

No. (Groningen no.)	Age (BP)	Cal BC/AD age range =68.3% (1 sigma) confidence level	Cal BC/AD age range =95.4% (2 sigma) confidence level
CAY 2G (GrN-21805)	360±70	1544 cal AD–1636 cal AD 1470 cal AD–1532 cal AD	1436 cal AD –1660 cal AD
CAY 47E (GrN-22109)	400±40	1598 cal AD–1618 cal AD 1446 cal AD–1508 cal AD	1554 cal AD–1632 cal AD 1436 cal AD–1526 cal AD
CAY 47I (GrN-22110)	700±40	1358 cal AD–1382 cal AD 1281 cal AD–1306 cal AD	1338 cal AD–1394 cal AD 1257 cal AD–1320 cal AD
CAY 47M (GrN-22111)	1100±30	952 cal AD–994 cal AD 892 cal AD–920 cal AD	890 cal AD–1004 cal AD
CAY 34O (GrN-21704)	2040±40	68 cal BC–18 cal AD 96 cal BC–80 cal BC	120 cal BC–66 cal AD 158 cal BC–138 cal BC
CAY 34I (GrN-21703)	2580±40	626 cal BC–598 cal BC 808 cal BC–762 cal BC	682 cal BC–544 cal BC 814 cal BC–758 cal BC
CAY 34A (GrN-21702)	3880±30	2306 cal BC–2295 cal BC 2360 cal BC–2312 cal BC 2402 cal BC–2370 cal BC 2452 cal BC–2430 cal BC	2224 cal BC–2208 cal BC 2458 cal BC–2280 cal BC

Type of material, geographic coordinates, and altitude of the sample:

CAY 2G	Soil and ± charred plants	00°03′35″N–77°59′15″W; 4240 m
CAY 47E, I, M	Peat	00°00′37″N–78°01′02″W; 4300 m
CAY 34O, I, A	Peat	00°00′37″N–78°01′02″W; 4300 m

ric phases of the banded samples. In PF2, for example, the vitric phases of the light and dark bands have compositions of 70–76% SiO_2 and 63–71% SiO_2, respectively. In addition, a compositional range of 71–77% SiO_2 exists in vitric phases of apparently homogeneous samples.

Discussion: eruptive phases

To determine the age of the volcanic events, six peat samples from sites 34 and 47 were dated by the ^{14}C method. Based on these six ages (Table 1), an inferred time scale was established, which assumes that the rate of peat accumulation was constant between dated samples and that the volcanic events were instantaneous and did not interfere significantly with vegetation growth. Each dated peat sample was obtained at the contact with the overlying ashfall layer. The calculated peat accumulations in the bog are: 7.7±0.15 cm/100 years from the present to 2040 years BP, 4.5±0.7 cm/100 years from 2040 to 2580 years BP, and 2.7±0.15 cm/100 years from 2580 to 3880 years BP. The variation is apparently due to compaction, as suggested by the presence of more densely packed layers with depth. The extrapolated ages for the volcanic events take into account these variations in peat accumulation and are given in Fig. 5.

Based on the coarseness and petrography of the lapilli, the tephra horizons at ~910, 680–650, and 400–380 years BP in the bog are considered to be the fallout equivalents of the PF1, PF2, and PF3 pyroclastic flows, respectively. The PF4 surges, whose underlying soil is dated at 360±70 years BP (section CAY 2, Fig. 4; sample CAY 2G, Table 1), appears to be represented in the peat bog only by a 10-cm horizon of scattered ash within the peat. The scarcity of ash is probably due to the vent's location on the upper north flank and the fact that the PF4 surges were clearly directed down a steep valley on the north side. This unit is separated from the underlying coarse lapilli layer of PF3 by a very thin peat bed (Fig. 5).

Two sets of ash layers high in the peat section give inferred ages of approximately 220 and 290 years BP. The upper layer is attributed to the 1785–1786 eruption described by Ascásubi (1802). He reported that this eruption, which apparently occurred high on the snow-capped southeast flank of Nevado Cayambe, produced a 13-mm-thick ashfall layer at the town of Cayambe in February 1785, additional ash emissions in July 1785, and finally a lava flow (or mud flow) in March 1786. According to Ascásubi, the vent was still fuming in 1802.

The deposit at 290 years BP consists of very fine ash. Its source may be Guagua Pichincha Volcano, close to Quito, which experienced its largest historical eruption in 1660 AD, a date that agrees well with the inferred age. Only this ash and a 2-cm-thick ash layer at approximately 3150 years BP seem to be related to other volcanoes, the other layers in the bog being too coarse grained to have had a distant origin. The 3150-years-BP ash is likely to correspond to the large eruptions of Cuicocha (50 km northwest of Cayambe) dated at 2990±300 and 3100±150 years BP (Hillebrandt 1989). Other fallout deposits identified elsewhere in the Interandean Valley, attributed by Hall and Mothes (1994) to

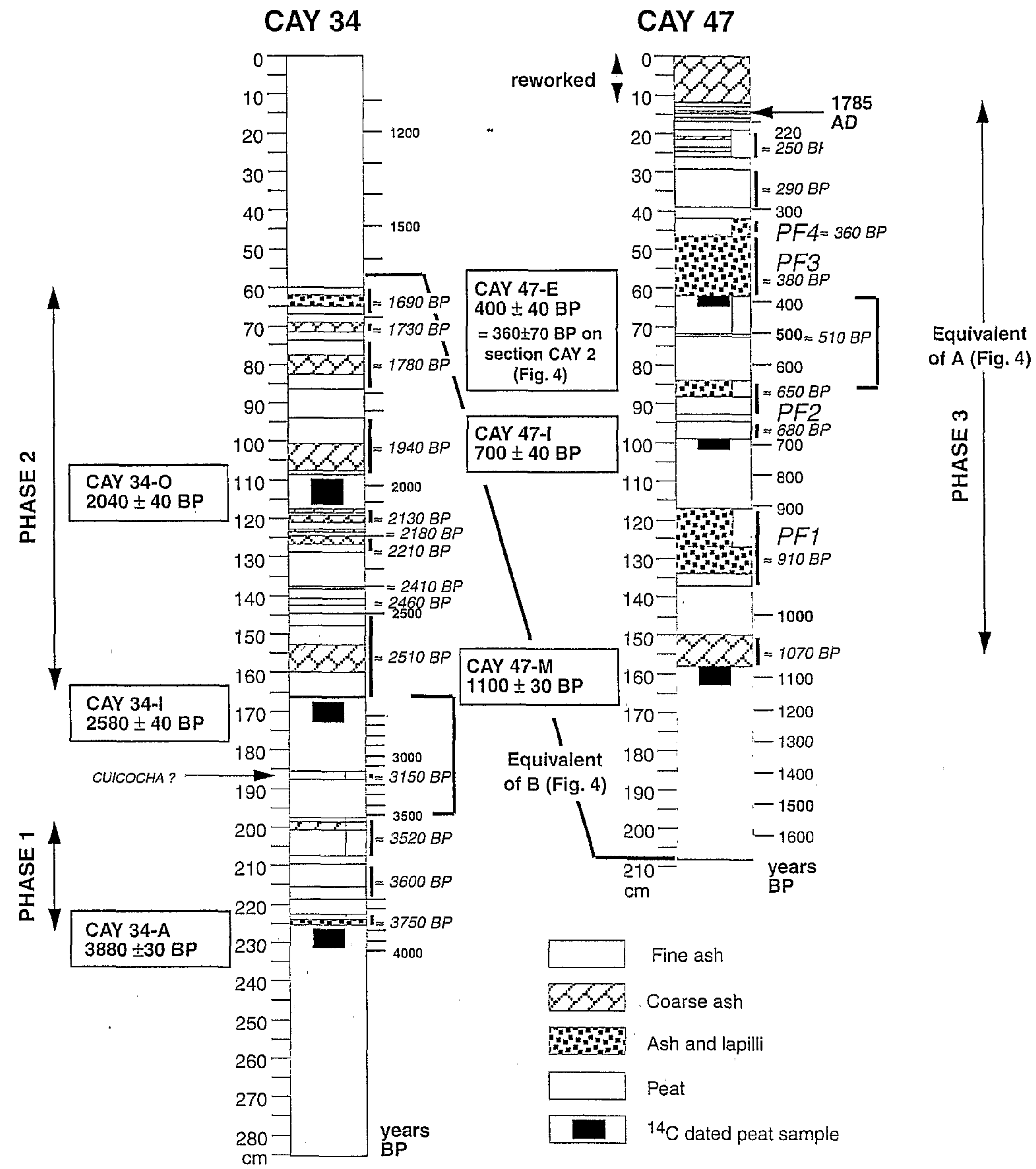

Fig. 5 Cross section through the peat bog at sites 34 and 47

Plinian eruptions from Quilotoa (140 km southwest of Cayambe, dated at 840±50 and 785±50 years BP) and Pululahua (55 km west of Cayambe, 2305±65 years BP), were not observed in the peat bog. Papale and Rosi (1993) showed that ash from the eruption of Pululahua is not widely distributed.

The inferred ashfall ages from the peat bog section are presented in a chronodiagram that recognizes three main eruptive phases of activity during the past 4000 years (Fig. 6). The first phase, of 300 years duration, occurred after a repose period of at least 2000 years and comprises three volcanic events at approximately 3750, 3600, and 3520 years BP. The second eruptive phase began at approximately 2510 years BP with an intense eruption (Fig. 5) and continued for approximately 800 years, with at least ten eruptive events, the most notable being at approximately 2460, 2210, 2130, 1940, 1780, 1730, and 1690 years BP. The latest period is composed of five important events, dated at approximately 1070, 910, 680–650, 380, and 250 years BP.

The PF3 and PF4 deposits are readily recognizable in the field from their stratigraphic relations. PF3 is almost everywhere underlain by two thick paleosoils (sequence A), which are separated by a yellow ash layer (y; Fig. 4). The upper of these paleosoils has been dated at 360±70 years BP (section CAY 2, Fig. 4; Table 1), whereas the peat underlying PF3 in the peat bog has

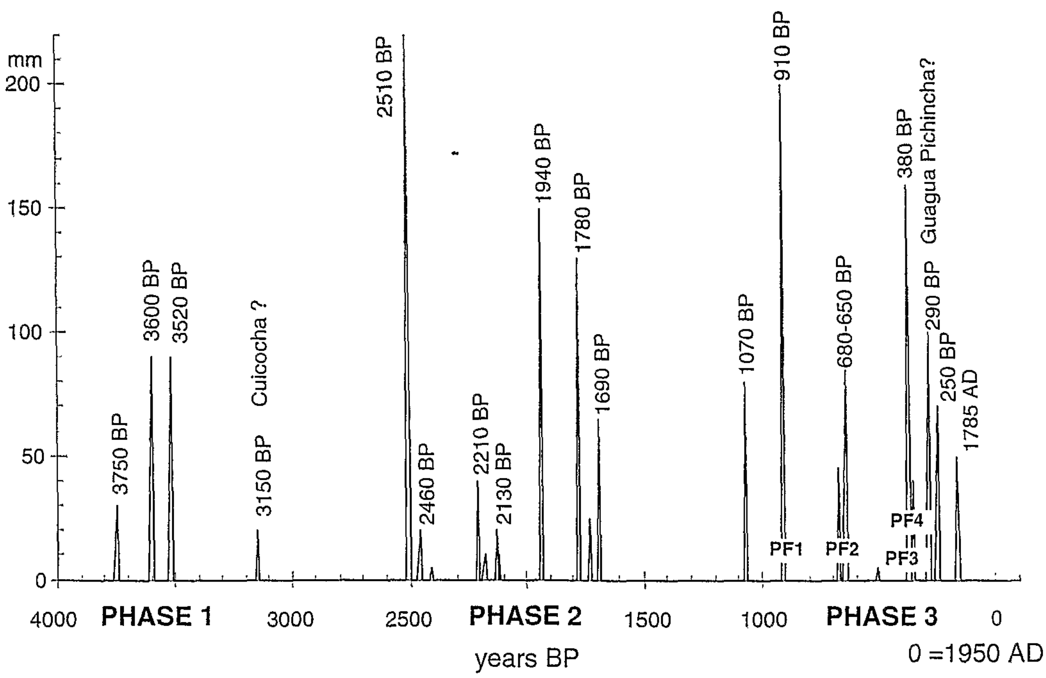

Fig. 6 Chronodiagram of the Nevado Cayambe events recorded in the peat bog during the past 4000 years.

ago, since little tephra is observed overlying the moraine of section CAY 30′.

given an age of 400±40 years BP (Fig. 5). A very thin (~1 cm) peat separates the PF3 and PF4 deposits, implying a short time interval between PF3 and PF4, in agreement with the idea that both were generated at the same vent. Furthermore, the thickness of PF3 is generally greater and more uniform than that of PF4, which was directed mainly northward and, as a consequence, is absent in sections 30 and 35. Sections on the upper northern slopes of the volcano also show a continuous sequence of ash and lapilli (section CAY 69) that correspond to the successive PF3 and PF4 events.

Correlations among the older fallout beds are more difficult. The ash and lapilli beds directly underlying the A paleosoil sequence likely represent ashfalls associated with PF2. Moreover, a 16-cm-thick layer may represent the PF1 event in both the CAY 30 and CAY 47 sections. In CAY 30 it underlies a paleosoil at 90–115 cm depth (Fig. 4), and in CAY 47 it lies below the peat at 100–117 cm depth (Fig. 5); the peat and paleosoil correspond to approximately 200 years of repose. In the lower part of section CAY 30, detailed correlations are more speculative. Probably the eruptive events of phases 2 and 1 produced the tephra that comprise the thick ash and lapilli deposits observed at 147–202 and 248–354 cm depths, respectively. These ashfall sequences are separated by a 60-cm-thick paleosoil or peat (sequence B) at CAY 30 and 34, suggesting quiescence from approximately 2500 to 3500 years BP. At the base of both sections, a thick paleosoil (C) is essentially ash free and implies that the volcano was quiet from approximately 4000 to 6200 years BP and probably until approximately 10000 years

Conclusion

Nevado Cayambe is much more active than previously believed. Its activity during the past 4000 years has been mainly characterized by lava dome extrusions, dome collapses, and pyroclastic flows. The numerous ash and lapilli layers in the peat bog (CAY 34 and 47) document at least 21 eruptive events during the past 4000 years, grouped into three main eruptive periods of activity of 300, 800, and 900 years duration. The last period, corresponding to four recent pyroclastic flow units observed on the north–northeast flank, probably has not ended, as implied by the 1785-1786 eruption.

The recent pyroclastic flows descended into uninhabited areas, and tephra fell mainly on the upper slopes of Nevado Cayambe. Given the summit topography, products of future eruptions will probably have a similar distribution and will not generate significant hazards for the inhabited areas west of the volcano. Nevertheless, a large eruption near the summit would melt ice and snow, resulting in mudflows, some of which would certainly move toward the town of Cayambe and adjacent inhabited areas, creating a serious hazard for more than 30000 people. Mud flows would be directed eastward, threatening the Trans-Ecuadorian pipeline and the Interoceanic Highway.

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References

Ascásubi JJ (1802) Letter to Baron von Humboldt. In: "von Humboldt A, Briefe aus Amerika, 1799-1804", herausgegeben von Ulrike Moheit, Akademic Verlag, Berlin, 1993, pp 174–176

Clapperton CM, Hall ML, Mothes P, Hole MJ, Still JW, Helmens KF, Kuhry P, Gemmell AMD (1997) A younger Dryas icecap in the Equatorial Andes. Quaternary Res 47:13–28

Ferrari L, Tibaldi A (1992). Recent and active tectonics of the northeastern Ecuadorian Andes. J Geodynamics 15 (1/2):39–58

Hall ML, Mothes P (1994) Tefroestratigrafía holocénica de los volcanes principales del Valle Interandino, Ecuador. Estudios Geogr 6:47–67

Hillebrandt C (1989) Estudio geovulcanológico del complejo volcánico Cuicocha-Cotacachi y sus aplicaciones. Provincia de Imbabura. Thesis, Escuela Politécnica Nacional, Quito, 167 pp

Litherland M, Egüez A (1993). Mapa geológico de la República del Ecuador, 1/1000000. British Geological Survey (Keyworth, Nottingham) y CODIGEM (Quito, Ecuador), Quito

Papale P, Rosi M (1993) A case of no-wind plinian fallout at Pululagua caldera (Ecuador): implications for models of clast dispersal. Bull Volcanol 55:523–535

Samaniego P (1996) Estudio vulcanológico y petrológico de la historia reciente del volcán Cayambe. Thesis, Escuela Politécnica Nacional, Quito, 143 pp

Soulas J, Egüez A, Yepes H, Pérez H (1991) Tectónica activa y riesgo sísmico en los Andes ecuatorianos y el extremo sur de Colombia. Boletín Geol Ecuatoriano 2 (1):3–11