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Combining historical and ^{14}C data to assess pyroclastic density current hazards in Baños city near Tungurahua volcano (Ecuador)

Jean-Luc Le Pennec [a,*], Patricio Ramón [b], Claude Robin [a], Eduardo Almeida [c]

[a] Laboratoire Magmas et Volcans, Université Blaise Pascal - CNRS - IRD, OPGC, 5 rue Kessler, 63038 Clermont Ferrand, France
[b] Instituto Geofísico, Escuela Politécnica Nacional, Ap. 17-01-2759, Quito, Ecuador
[c] Geodinámica, Isabel la Católica y Galicia s/n. Edif. Torre Galicia, 203, Quito, Ecuador

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A B S T R A C T

Pyroclastic density currents (PDCs) from Tungurahua volcano, Ecuador, recurrently rush down the northern Vazcún valley and threaten the small tourist city of Baños located on its mouth. Estimating PDC hazards, i.e. PDC return rate and extent, is difficult in Baños and Vazcún because data from the literature are rare and debated, while geological exposures are few and vegetated. To improve our awareness of PDC hazards in the Baños area, we examined historical documents, conducted new geological research in the Vazcún valley, and obtained additional ^{14}C data. We highlight complex radiocarbon results that may lead to difficulties when interpreting the PDC chronology, and offer recommendations to improve sampling strategies for ^{14}C age determinations of PDC deposits. Overall, our results show that the 1640, 1773, and 1886 PDC-forming eruptions are recorded in the valley, while products of the 1918 and 2006 events were likely removed. Through considering recorded/unrecorded bias in the reconstruction of past PDC emplacement in Vazcún, we calculate a minimal average return rate of 18 PDC-forming events for pre-Columbian and historical eruptions since the devastating 3 ka BP eruption, which translates into a maximum average return rate of 150–200 years in the valley. However, the archives suggest that most PDCs did not affected the now-urbanized Baños area (e.g. 1918, 2006) and we estimate that the city is impacted on average every 350–500 years, a duration that is likely perceived as fairly long for people living in the area. The Baños case-study thus raises questions on how to communicate on uncertain threats and impacts, and how to improve alert messages in a town where economic incomes are essentially based on tourist activities. To better address these issues we plan in future works to focus on cognitive perception of risk and volcanic hazard judgment by populations of Baños and nearby rural communities.

1. Introduction

Pyroclastic Density Currents (PDCs) are hot volcanic gravity flows that represent the most deadly and destructive phenomena associated with volcanic activity and their impact on past and present human societies is the source of ample historical and volcanological researches (e.g. de Boer and Sanders, 2002; Cashman and Cronin, 2008; Riede, 2014, and references therein). While most famous catastrophes were caused by large PDCs (bulk deposit volume $V > 10^7$ m^3) as at Akrotiri (Santorini, Greece, Hardy, 1990) Pompeii (Vesuvius, Italy, Giacomelli et al., 2003), PDCs of smaller volumes ($V < 10^7$ m^3) can represent a significant threat to populations and infrastructures, as exemplified at Saint Pierre de La Martinique (Mt Pelée, West Indies, Lacroix, 1904) and more recently at Soufrière Hills (Montserrat, West Indies), and Merapi and Sinabung volcanoes (Indonesia). Therefore, evaluating the hazard associated with such small-volume PDCs is essential because their return rate is much higher than that of large-volume PDCs. This assessment is achievable through reconstructing recent PDC activity (recurrence and extent patterns) using geological (stratigraphy, geochronology), historical, and archaeological constraints (e.g. Sigurdsson et al., 1982). However, estimating the recurrence rate and the size of recent PDCs may reveal difficult, particularly at tropical volcanoes where intense erosion and fast vegetation growth tend to rapidly erase or hide the remnants of past PDC deposits. Such a

* Corresponding author.
E-mail address: jeanluc.lepennec@ird.fr (J.-L. Le Pennec).

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situation occurs in Baños, a small tourist town located at the northern base of the currently active Tungurahua volcano in central Ecuador. Earlier works have established that Tungurahua is a highly hazardous volcano in the country as it frequently threatens ~25,000 inhabitants from urban and rural communities (Almeida and Ramón, 1991; Hall et al., 1999; Tobin and Witeford, 2002; Lane et al., 2003; Ramón, 2010; Le Pennec et al., 2012). The city of Baños is situated in the Vazcún valley, which is initiated north of Tungurahua's crater, and hosts volcaniclastic successions in its lower area. Because of its proximity to Baños, the volcanology of the Vazcún valley has previously received some attention (Hall and Vera, 1985; Almeida and Ramón, 1991; INECEL, 1992; Hall et al., 1999; Mothes et al., 2004; Le Pennec et al., 2008; Stinton and Sheridan, 2008; Kelfoun et al., 2009; Hall et al., 2013), but data are still rare and a comprehensive view of recent PDC activity and deposition in the area is still lacking. To improve our volcanological understanding of PDCs chronology and distribution in Vazcún and Baños, we revisited the historical documentation and conducted new geological works based on litho-stratigraphic and geomorphologic studies as well as ^{14}C age determinations of organic remains from PDC deposits. The results allow us to make the first detailed appraisal of PDC hazard in and around this tourist tropical city.

2. Background

2.1. Tungurahua volcano

Tungurahua volcano (5023 m a.s.l.) is a 3-km-high, cone-shaped andesitic edifice located in the Eastern Cordillera of Ecuador (~120 km south of Quito), in the southern termination of the Northern Andean Volcanic Zone (Fig. 1a). The volcano, which witnessed three growth stages termed Tungurahua I, II, and III (Hall et al., 1999), is flanked by three rivers, Puela, Chambo and Pastaza, on its south, west and north base, respectively (Fig. 1b). The Pastaza River drains a fraction of the Ecuadorian highlands, flows along the northern base of Tungurahua, and runs to the Amazonian lowlands. The Vazcún valley, a U-shaped gorge of the Northern flank of the volcano that bisects old lavas and breccias of the Tungurahua I edifice (Hall et al., 1999), meets the Pastaza valley in an area where an old Pastaza meander formed a wide terrace that coincides with the present location of Baños city (Figs. 1b and 2). Pottery sherds found in PDC deposits dated at ~3 ka BP in nearby localities show that the area was largely inhabited when the last Plinian eruption took place. This event witnessed a major flank failure and a blast explosion that devastated the area (details in Le Pennec et al., 2013). The presence of pottery sherds in the blast layer confirms that the Pastaza valley has been for thousands of

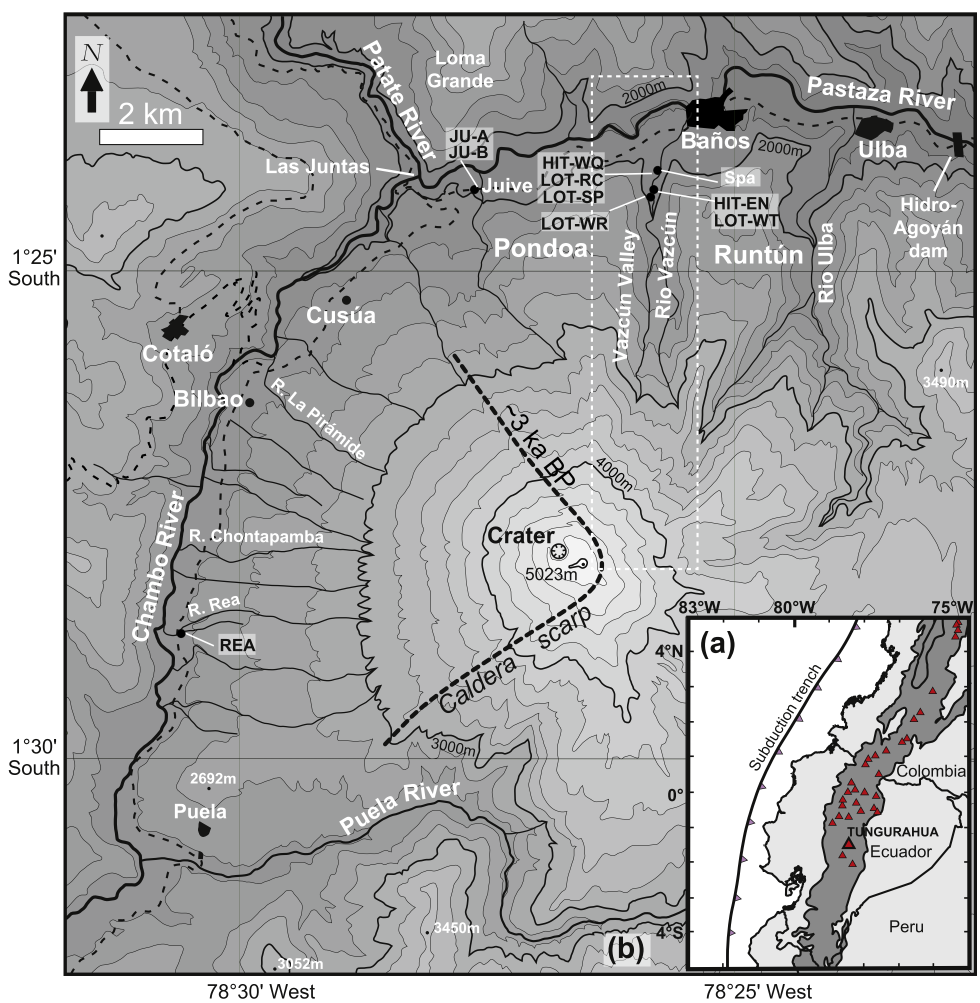

Fig. 1. (a) Inset map of Tungurahua volcano in the Ecuadorian volcanic arc, dark gray areas are Andean reliefs above 2000 m asl. Triangles are quaternary volcanic centers, with Tungurahua enlarged. (b) Topographic map of Tungurahua volcano with 200 m contour lines and place names cited in the text. The black dashed line is the trace of the 3 ka BP collapse scar. The studied Vazcún valley occurs in a white dashed box. The stratigraphic section sites and codes are reported in black uppercase letters (see Figs. 2, 4 and 5).

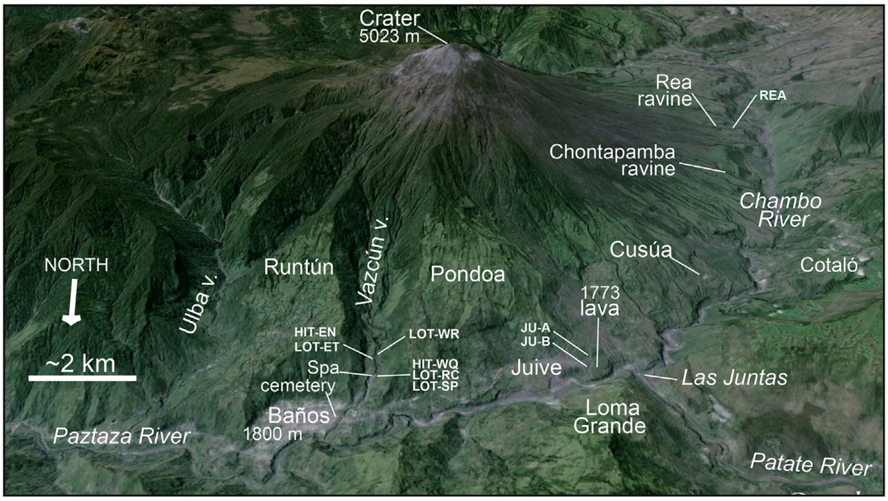

Fig. 2. Oblique Google Earth view (Landsat image) looking south towards Baños city and Vazcún valley. The main localities and geomorphological features discussed in the text are also reported. The stratigraphic section sites and codes are indicated with white uppercase letters (see Figs. 1, 4 and 5). The scale is approximate for the Pastaza – Baños – Vazcún area.

years a major route that connects the Interandean plateau to the Amazonian basin (Rostain, 2012). After this powerful event, the Pastaza meander terrace was inundated by a thick andesitic lava flow that descended from a lateral vent located on the northern flank of Tungurahua in the Pondoa Plateau, and travelled more than 30 km along the Pastaza valley (Hall et al., 1999; Bès de Berc et al., 2005). The city of Baños is built on this lava (Figs. 1b and 2). Since this 3 ka BP event, the young Tungurahua III has grown from frequent andesitic eruptions, and only three eye-catching whitish-yellowish dacitic pumice horizons occur in the monotonous scoriaceous successions (Almeida and Ramón, 1991; Hall et al., 1999; Le Pennec et al., 2006, 2008).

The examination of historical archives led two brothers, Augusto Martínez (1886, 1903, 1904) and Nicolás Martínez (1932), and later Almeida and Ramón (1991) to identify several eruptive periods, in AD 1640–45, AD 1773–81, 1885–88, and 1916–1925 (periods of enhanced fumarolic activity are also recorded in some reports). A. Martínez (1886, 1903, 1904) and N. Martínez (1932) precisely described the eruptive events and resulting deposits of the PDC-forming 1886 and 1918 phases, which hit Vazcún and adjacent Ulba valleys (Figs. 1b and 2). The volcano reawoke in 1999 with many eruptive phases of moderate intensity that affected nearby communities (Lane et al., 2003; Ramón, 2010; Le Pennec et al., 2012), and a violent subplinian phase took place in August 2006: scoria flows killed six and destroyed houses, roads and crops on the western side of the volcano, while PDCs descended the Vazcún valley and halted ~2 km upstream from Baños city, at about 2100 m asl (Stinton and Sheridan, 2008; Kelfoun et al., 2009; Ramón, 2010; Hall et al., 2013; Bernard et al., 2014).

2.2. Vazcún valley

On the northern side of Tungurahua, the straight Vazcún valley is carved to maximum depths of 300–600 m in the old edifice (Figs. 1b and 2). Waters of a small river, the Rio Vazcún, descend the gorge and locally mix with hot springs that were known by pre-Columbian inhabitants, and are now important for tourist activity in the city of Baños, notably in the El Salado Spa (located in Figs. 1b and 2). The upper part of the valley is a set of steeply inclined gullies incised in lavas of the upper cone, while the floor of the lower valley consists of volcaniclastic and epiclastic sequences emplaced since the last 3 ka BP Plinian and sector collapse event (Le Pennec et al., 2013). Erosion by waters of the Rio Vazcún and occasional lahars have cut these sequences, and the combined effect of sedimentation and reworking has resulted in the formation of distinct terraces that are well preserved in nowadays morphology (Hall et al., 1999; Mothes et al., 2004; Le Pennec et al., 2008; Stinton and Sheridan, 2008). A high terrace system comprises a thick sequence of PDC and tephra fall deposits, along with some lahar, debris flow, and fluviatile layers. In this higher terrace (HIT) system two main disconnected exposures occur; one in a quarry located on the west side of Rio Vazcún, about 50 m of the El Salado Spa (hereafter termed the "HIT-WQ", with WQ for "Western Quarry" section), and ~300–350 m upstream on the Eastern side, in a natural section of the Rio Vazcún (below "HIT-EN", with EN for "East-Natural" section). The lower terrace (LOT) occurs as discontinuous remnants of 10–20 m-thick deposits where fresh-looking exposures are observed in several places along the meandering Rio Vazcún bed. On the western side of the river, about 30 m west of the El Salado Spa, a complete exposure in the gully wall is termed here LOT-SP (with "SP" for "Spa"). About 300 upstream of the Spa, a transverse-to-valley-axis section occurs on the right (eastern) side of Rio Vazcún (hereafter "LOT-ET" with ET for "East-Transverse" section). A radial north-south exposure occurs along the left, western side of Rio Vazcún, ~450–500 m upstream of the Spa, and is termed in this note "LOT-WR" ("WR" for "West-Radial" section). These sections are located in Figs. 1b and 2.

3. Method

To obtain historical constraints on PDC activity in the Vazcún valley, we reexamined colonial narratives quoted in scattered contributions of the literature. We also appraised documents and paintings retrieved by J. Egred, formerly investigator at the Instituto Geofísico of Quito's National Polytechnic School (IG-EPN), who carried out extensive historical research in Spanish colonial archives at "Archivo General de Indias" (AGI, Sevilla) and compiled seismological and volcanological results in a series of internal reports in the context of an IG-EPN and IRD cooperation program. Egred (1999) referred to undated documents from AGI (AGI 1, 2 and 3 in our reference list) and provided reproductions of relevant paintings, one of which (described below) was later published in Samaniego et al. (2003). Other post-colonial records yielding constraints on the historical activity of Tungurahua volcano (Gonzáles Suárez, 1892; Stübel, 1897; A. Martínez, 1903, 1904; N. Martínez, 1932) are gathered in Almeida and Ramón (1991), Egred (1999) and Samaniego et al. (2003). In this work we selected those that help resolving the volcanology of the Vazcún valley, the Banõs area and the northern side of the volcano. Below we provide English translations by the authors of these critical documents [with authors' notes in bracket for clarity], while original citations in Spaniard are reported in Appendix A1–A5 in a Supplementary Electronic Material file (SEM 1). In this paper all dates from the historical documentation are quoted AD.

In addition, we investigated the structure, morphology and litho-stratigraphy of the depositional area in the Vazcún valley. The volcanic successions preserved on the flanks and near the base of Tungurahua volcano consist of deposits from tephra falls and PDCs, with concomitant reworked material of essentially laharic and fluviatile origins. The laharic layers are typically characterized by beige-toned, indurated fines-rich matrix and lack unbroken juvenile bombs, thus allowing distinction in the field from deposits of PDCs. Previous works at Tungurahua have pointed out the lithological, mineralogical and compositional monotony of Tungurahua III sequences (<3 ka BP), in which andesitic scoria fall and flow deposits with associated lavas are largely dominant (Almeida and Ramón, 1991; Hall et al., 1999; Le Pennec et al., 2006, 2008; Samaniego et al., 2011). This monotony is substantiated by published mineralogical and chemical analyses of juvenile products, which reveal sub-constant phenocryst assemblages and whole rock compositions (andesites with plagioclase and two pyroxenes, and some olivine in the low silica range; SiO_2 content in the range of 56–59 wt%; Hall et al., 1999; Samaniego et al., 2011). This stable andesitic composition renders mineralogical and chemical analyses of juvenile fractions ineffective to fix stratigraphic and correlation problems in the pyroclastic sequence, particularly in the Vazcún valley. On the other hand, three salient dacitic tephra occurrences (plagioclase and pyroxene, with some amphibole in the high silica range; SiO_2 content in the range of 61–66% wt%; Hall et al., 1999; Samaniego et al., 2011; Le Pennec et al., 2013) occur as key horizons dated around 3000 BP and 1300 BP, plus an historical one. In addition, these earlier works suggest no simple relation between magma composition (i.e. andesitic vs dacitic), eruption size, and PDC mobility or volume of deposits. Similarly, the incorporation of abundant accessory material by flowing PDCs translates into deposits with complex componentry signatures that are usually difficult to interpret in terms of stratigraphic and correlation patterns. Bernard et al. (2014) showed that about 50 wt.% of the 2006 PDC deposits belong to loose material incorporated by the PDCs on the upper cone, and the nature and amount of the different componentry classes exhibit ample variations downslope and laterally. Apart from the distinctive accessory silicic pumice clasts observed in PDC deposits younger than the major 1300 BP dacitic event, we considered that these limitations make componentry investigations inappropriate for stratigraphic and correlation purposes in Vazcún valley and surrounding areas.

We conducted a radiocarbon study of selected PDC deposits in Vazcún and nearby area. In general, the radiocarbon technique is not recommended to date events younger than a few centuries because of complex wiggle oscillations in the ^{14}C calibration curves. Nevertheless, recent studies indicate that ^{14}C dating can prove useful when combined with stratigraphic constraints and historical and archaeological records, notably in volcanology (e.g. Machida et al., 1996; Okuno et al., 1998; Lowe et al., 2000; Siebe, 2000; Gertisser and Keller, 2003; Siebe et al., 2004; Friedrich et al., 2006; Plunket et al., 2006; Hua, 2009). In this study, we gathered available ^{14}C data from the literature (Almeida and Ramón, 1991; INECEL, 1992; Hall et al., 1999; Mothes et al., 2004; Le Pennec et al., 2008; Stinton and Sheridan, 2008) and collected new wood and charcoal pieces trapped in PDC deposits of the Vazcún valley. Nine organic samples were submitted for ^{14}C age determinations to the Center for Isotope Research (CIO, Groningen University, The Netherlands). Large samples (trunk and branch pieces, twigs) were analyzed using the conventional Proportional Gas Counting technique (PGC) and results are hereafter indexed using lab codes with GrN- prefix (Table 1). Age determinations of smaller samples (usually collections of charcoal debris, whose length is in the range of a few millimeters to 1 or 2 cm) were obtained with Acceleration Mass Spectrometry and resulting AMS data are indexed below with GrA- prefix. In order to convert our ^{14}C results into calendar dates we used the CALIB7 program of Stuiver and Reimer (1993) and Stuiver et al. (2014) with Northern Hemisphere atmospheric data (IntCal13 curve of Reimer et al., 2013). The program yields date ranges with yearly precision, but our results in Table 1 are rounded off to nearest significant 5 years AD (10 years for data with 1 $\sigma \geq 50$ ^{14}C years), to account for possible offset due to the tropical location of Tungurahua volcano. Following the recommendations of van der Plicht and Hogg (2006) the ^{14}C data from this work and the literature are quoted BP (i.e. in ^{14}C years before 1950 AD), while calibration results are reported in calAD or calBC. As shown e.g. by Le Pennec et al. (2008) and our data below, and in spite of difficulties when interpreting some radiocarbon results (see discussion section), we consider from our experience at Tungurahua that the ^{14}C approach is currently an appropriate and decisive technique to settle most stratigraphic and correlation concerns at that volcano.

Table 1

Results of ^{14}C age determinations from this work and the literature, with converted calendar date ranges. The calibration is achieved using the CALIB7 program (Stuiver and Reimer, 1993; Stuiver et al., 2014) with the Northern Hemisphere atmospheric data of the Incal13 calibration curve (Reimer et al., 2013). The calendar results are given by the program with yearly resolution but are rounded off here to the nearest significant 5 years (nearest 10 years for data with 1 $\sigma \geq 50$ ^{14}C years). Small calendar age ranges with relative area <1% are not reported. a) Groningen laboratory codes are given as GrN- and GrA-for PGC and AMS determinations, respectively. b) Pretreatment methods: (A) consist in washing the samples with acid, (AAA) is the acid/alkali/acid triple treatment. c) UTM coordinates refer to the South America WGS84, UTM 17S, Ecuador Zone, accuracy about 40 m. The sampling sites for organic materials dated in this study and previous works are located in Figs. 1b and 2, and sampling sections are provided in Fig. 5. Abbreviation "n.p." is for "not provided" in original notes.

Reference	Lab. Code[a] (pretreatment)[b]	Type of sample	Locality section	UTM[c] coordinates	^{14}C age, in years BP ($\pm 1\ \sigma$)[d]	$\delta^{13}C$ (‰)	Calendar age AD 1 σ (68.3%)	Relative area (%)	Calendar age AD 2 σ (94.5%)	Relative area (%)	Assignation
Stinton and Sheridan (2008)	(Authors' code, TUNG04-012CW) (n.p.)	Single charcoal piece	LOT-ET Lower PDC unit	785730 9844260	150 ± 90	−26.0	1665–1710 1715–1785 1795–1820 1830–1885 1910–1950	18 30 11 23 17	1525–1560 1630–1950	2 98	1640
This study	GrN-28970 (A)	small carbonized twigs	LOT-ET Lower PDC unit	785730 9844260	155 ± 15	−23.73	1675–1690 1730–1765 1770–1780 1800–1810 1925–1940	12 53 2 13 20	1665–1695 1725–1785 1795–1815 1915–1950	16 49 12 21	1640

(continued on next page)

Table 1 (*continued*)

Reference	Lab. Code[a] (pretreatment)[b]	Type of sample	Locality section	UTM[c] coordinates	^{14}C age, in years BP (±1 σ)[d]	δ^{13}C (‰)	Calendar age AD 1 σ (68.3%)	Relative area (%)	Calendar age AD 2 σ (94.5%)	Relative area (%)	Assign-ation
Mothes et al. (2004)	n.p. (n.p.)	Charcoal debris	Baños city, ~100 m N of the cemetery	786230 9845430	180 ± 40	n.p.	1660–1685 1730–1810 1925–1950	18 63 19	1650–1710 1715–1820 1830–1885 1910–1950	22 51 10 17	1773
This study	GrN-29567 (AAA)	One single partly charred branch, 7–8 tree-rings	LOT-WR	785660 9844180	190 ± 15	−24.13	1665–1680 1760–1785 1795–1800 1935–1950	28 35 11 26	1660–1685 1735–1805 1935–1950	23 57 20	1773
Le Pennec et al. (2008)	GrN- 27899 (AAA)	One branch segment	LOT-SP	785680 9844570	190 ± 30	−25.35	1660–1685 1735–1755 1760–1805 1935–1950	21 16 46 17	1645–1695 1725–1815 1915–1950	24 58 18	1773
Mothes et al. (2004)	n.p. (n.p.)	Charcoal debris	Baños city, ~100 m N of the cemetery	786230 9845430	190 ± 40	n.p.	1660–1685 1735–1805 1930–1950	20 63 17	1645–1700 1720–1820 1830–1880 1915–1950	24 52 7 17	1773
This study	GrN-30328 (A)	Small (2-cm in diam) carbonized twig	LOT-WR	785660 9844180	205 ± 15	−25.23	1660–1670 1780–1800 1945–1950	23 59 18	1650–1680 1760–1805 1935–1950	29 55 16	1773
This study	GrN-27900 (A)	Charcoal piece	LOT-ET Lower PDC unit	785730 9844260	230 ± 20	−25.48	1650–1665 1785–1795	61 39	1640–1670 1775–1800 1940–1950	57 38 5	1640
Le Pennec et al. (2008)	GrN-29338 (AAA)	Thin carbonized branches with leaves	LOT-RC Lower PDC unit	785670 9844500	270 ± 25	−25.70	1525–1550 1630–1660	29 71	1520–1595 1620–1670 1780–1800	39 57 4	1640
Le Pennec et al. (2008)	GrN-27851 (A)	One carbonized branch	LOT-RC Lower PDC unit	785670 9844500	300 ± 30	−25.01	1520–1575 1585–1590 1625–1650	69 5 26	1490–1605 1610–1655	73 27	1640
This study	GrN-27901 (A)	Piece of charcoal	LOT-ET Upper PDC unit	785730 9844260	335 ± 25	−23.99	1490–1530 1550–1605 1610–1635	32 50 19	1480–1640	100	1773
Stinton and Sheridan (2008)	(Authors' code TUNG04-009F) (n.p.)	Piece of charcoal (n.p.)	LOT-WR	785660 9844180	380 ± 40	−18.2	1445–1520 1590–1620	74 26	1440–1530 1540–1635	58 42	1773
This study	GrN-28969 (A)	Small carbonized twig	LOT-ET Lower PDC unit	785730 9844260	390 ± 40	−26.76	1445–1515 1595–1620	80 20	1435–1530 1550–1635	64 36	1640
This study	GrN-28712 (A)	A single carbonized branch	LOT-ET Lower PDC unit	785730 9844260	420 ± 20	−24.80	1440–1465	100	1435–1490	100	1640
This study	GrN-29483 (A)	A single carbonized branch	LOT-ET Lower PDC unit	785730 9844260	460 ± 20	−24.81	1430–1445	100	1420–1455	100	1640
INECEL (1992)	(Author code TU90-9) (n.p.)	Charcoal	Vazcun Near Rio Salado	855700 (aprox.) 9845000 (aprox.)	943 ± 78	n.p.	1020–1170	100	970–1260	100	~1100 BP
Mothes et al. (2004)	n.p. (n.p.)	Charcoal	HIT-WQ Uppermost PDC unit	785670 9844600	1130 ± 40	n.p.	880–990	100	770–990	100	~1100 BP
Mothes et al. (2004)	n.p. (n.p.)	Charcoal	HIT-WQ Dacite pumice PDC unit	785670 9844600	1370 ± 40	n.p.	630–680	100	600–720 740–770	95 5	~1300 BP
Mothes et al. (2004)	n.p. (n.p.)	Charcoal	Baños city, barrio Inés Maria, near edge of Pastaza River	786240 9845800	1450 ± 40	n.p.	580–650	100	540–660	100	~1300 BP
This study	GrA-23510 (A)	Small charcoal debris	Western flank, road cut in La Pyramide ravine	778460 9840910	4040 ± 50	−25.02	2630–2480	100	2860–2810 2750–2720 2700–2460	8 2 90	1773

Finally, our historical, stratigraphic, geomorphologic and calibrated ^{14}C results are merged with previous findings of the literature to get a comprehensive view of historical and pre-Columbian PDC activity in the Vazcún valley. For clarity, we define in this article an "eruptive period" as a volcanic event that lasts several months to years. It may comprise successive "eruptive phases" that correspond, in a single eruptive period, to duration of heightened eruptive activity that typically last from hours to weeks, without prolonged interruptions in the activity.

4. Constraints from historical data

In this section, we summarize the selected historical evidence of PDC emplacement in the Vazcún valley and isolate key descriptions of events and resulting products, to be combined with field and ^{14}C data.

4.1. The 1640–45 eruptive period

Examination of Early Colonial archives has revealed that a substantial eruption, whose authenticity was previously questioned (Egred, 1999; Hall et al., 1999), took place around 1640–1645 (Almeida and Ramón, 1991; Le Pennec et al., 2008). There is no clear historical evidence of PDC emplacement during the event, but recent stratigraphic and radiocarbon data indicate that some andesitic scoria flow deposits on the western side of the volcano and in the Vazcún valley most likely correlate to the 1640–45 eruptive period (Le Pennec et al., 2008).

4.2. The 1773–82 eruptive period

The occurrence of an eruption at Tungurahua was reported by J. Saona (undated document of the 18th century) who mentioned the following events (for original quoting in Spanish see Appendix A1 in SEM 1). "*Year 1773. On 23 of April, the famous Tungurahua blown up, made very grave damages in all its surroundings, vomiting very large amounts of fire, burning water, and rocks of large and diverse size. But the village of Baños … didn't lose a single soul …*" The narrative suggests a strong explosive event with serious destruction, and without any fatalities. In his seminal historical compilation F. González Suárez (1892) offered further descriptions of the eruption process (Appendix A2 in SEM *1). … "Five years after the eruption of Cotopaxi (4 April 1768) Tungurahua did another equally harmful and sudden one. On 23 of April 1773, around five in the afternoon, it was heard suddenly a dull and frightful roaring sound from the volcano, and later started to overflow from the crater a mighty current of glowing lava that, descending deep inside the valley, fall into the channel of the river* [Pastaza River] *and, forming a bench of scoria and rocks stopped the course of the waters: dense columns of smoke rose from the crater and obscured the air*; *after started to fall a rain of small scoria*, *of pieces of pumice stones so light that they swam in the water*, *and of ash or fine dust*, *that covered the fields and killed the plants in them"* … *"The inhabitants of the small village of Baños*, *located on the lower sides of the volcano*, *surprised by the sudden outburst*, *went out fleeing hastily and climbed to the summits of nearby hills*, *to escape the spate of lava*, *which started discharging from the crater*" … In his book N. Martínez (1932) cited R. Vieira, a chronicler in Baños who commented on the 1773 eruption as follow (Appendix A3 in SEM 1): "*The second eruption happened on Friday 23 April 1773 … with the alluvium that descended everything was destroyed and razed*, *and the only area of salvation that stood in the sea of fire was the small church of Baños … the source of hot water stopped sprouting.*" These descriptions yield evidence of abundant tephra deposition on the northern side of the volcano (A1, A2), with a flow that went down the Pastaza River (A2), and probably PDCs or hot lahars that affected Baños, at least down to the old church (A3). In addition, the description of scoria and floating "*pumice stones*" ("*piedra pómez*" in A2) suggests the co-existence of juvenile andesitic and dacitic compositions, respectively, in the eruptive products (we show below that these "*pumice stones*" are more probably low-density andesitic scoria fragments, and not dacitic pumice clasts).

A spectacular painting hosted in AGI and reproduced in Egred (1999) and Samaniego et al. (2003) shows Tungurahua volcano erupting on 23 April 1773 (Fig. 3a). Although naïve in style, the painting clearly portrays the river junction of Chambo, Patate and Pastaza rivers (Las Juntas located in Figs. 1b and 2), as well as two active vents in the snowy summit area. Flame-like patterns are depicted on the western flank (PDC-west in Fig. 3a), and on the northwestern flank, where a dark tongue with rugged morphology is visible (indexed "Lava" in Fig. 3a). According to the original caption (stylized inset in Fig. 3a) this tongue is a "*tajamar de piedra y cascajo producido por la erupción*" [bench of rocks and scoria produced by the eruption], which represents a lava flow that dammed the Pastaza River. In 1873, i.e. 100 years after the 1773 event and 13 years before the 1886 eruption, this lava flow front has been depicted by Stübel (1897) in an accurate line drawing showing the northern flank of the volcano, with the Vazcún valley and the smoothed, gently inclined Juive surface (Fig. 3b). This andesitic lava in Juive is a key to understand the stratigraphy of the Vazcún valley deposits.

From the above documentation, among other uncited reports, we infer three essential points. First, the lava that went "*deep inside the valley*" and dammed the Pastaza River (A2) is clearly the one painted as a dark blocky bench in Juive on the northeastern side of the volcano (Fig. 3a). On the lower gently inclined Juive area, the andesitic lava must have flowed quite slowly before reaching the Pastaza River, and it is unlikely that it could have threatened the rare inhabitants in that cultivated area. Secondly, the report of people escaping from the "*spate of lava*" (A2) in Baños obviously relates to a hurried evacuation during PDC emplacement in the Vazcún valley, and not to the advance of a lava flow. Thirdly, the records of the 1773 event strongly suggest that the activity started in February 1773 and lasted with several eruptive phases till around 1781–82 (Almeida and Ramón, 1991; Egred, 1999; Samaniego et al., 2003). However, available reports yield evidence of PDC-forming activity only during the short-lived 23 April 1773 paroxysm.

4.3. The 1885–88 eruptive period

The January 1886 eruption is well documented in accounts of A. Martínez (1886, 1903, 1904). On 14 February 1886, from a site located 11 km NW of the crater, Martínez described the eruptive deposits as follow (Appendix A4 in SEM 1): *"I could realize the fabulous quantity of fragmental lava* [PDC deposits] *thrown out by the volcano and accumulated in the Juivis area* [Juive, Figs. 1b, 2 and 3]. *And while these accumulations are large*, *those of Cusua and Chontapamba are even larger* [Figs. 1b and 2] … *The previously pleasant and smiling aspect of the landscape … has changed in an absolute way. The fields uncovered by the fragmental lava* [PDC deposits] *are blanketed by ash and sand* [tephra fall layer of small lapilli] *of a quasi-white color, and they occur like after an intense snowfall"*. These descriptions yield evidence of PDC and fallout deposits in Juive and on the western side of the volcano, while the "*snowfall*" tint of the fallout deposit in proximal localities support a dacitic composition for the juvenile fraction (at Tungurahua all coarse-to fine-grained pyroclastic falls of andesitic composition produce dark, grayish to blackish tephra layers, even tens of kilometers away from the source, e.g. Le Pennec et al., 2012). On the other hand, large (probably hot) lahars and debris flows were reported in both Vazcún and Ulba valleys (Figs. 1b and 2), but from available archives it is not made clear whether these lahars were syn-eruptive mass flows of PDC material mixed with snow and ice melts, or post-eruptive debris flows.

4.4. The 1916–25 eruptive period

N. Martínez (1932) provided detailed descriptions of the products left by the 5 April 1918 paroxysm, and focused on still hot PDC deposits he visited near Baños four days after the eruption. Here we select some citations to show the importance of PDC deposits in the Vazcún valley (Appendix A5 in SEM 1). "… *The most grandiose phenomenon of that eruption was that of the gigantic "Glowing clouds" … However the largest "Glowing clouds" descended along the Vadcún* [Vazcún] *valley, to the entry of Baños, an unsurprising and undoubted fact, as many ravines that have their origin in the crater converge toward it. … There, the deposited material was entirely similar to that of the ravine I described earlier, but immensely larger, as in some places where the valley narrows, it thickens to more than 30 m, as I could check later, and leveled all the bottom, which presented the aspect of a road.*" … "*The vegetation, in steep places of the margins, had been burned up to elevations that exceeded 100 m, and also were included some plantations and small houses of the farmers. Fortunately for Baños, the eruption lasted a short time, and consequently the "Glowing clouds" did not reach till the valley depression where there is an entry to the village, as they stopped at about 100 m from that place, because if they progressed more it was certain that they would have penetrated to the populated area, and thus from Baños we would have kept only the memory, converting it to a new*

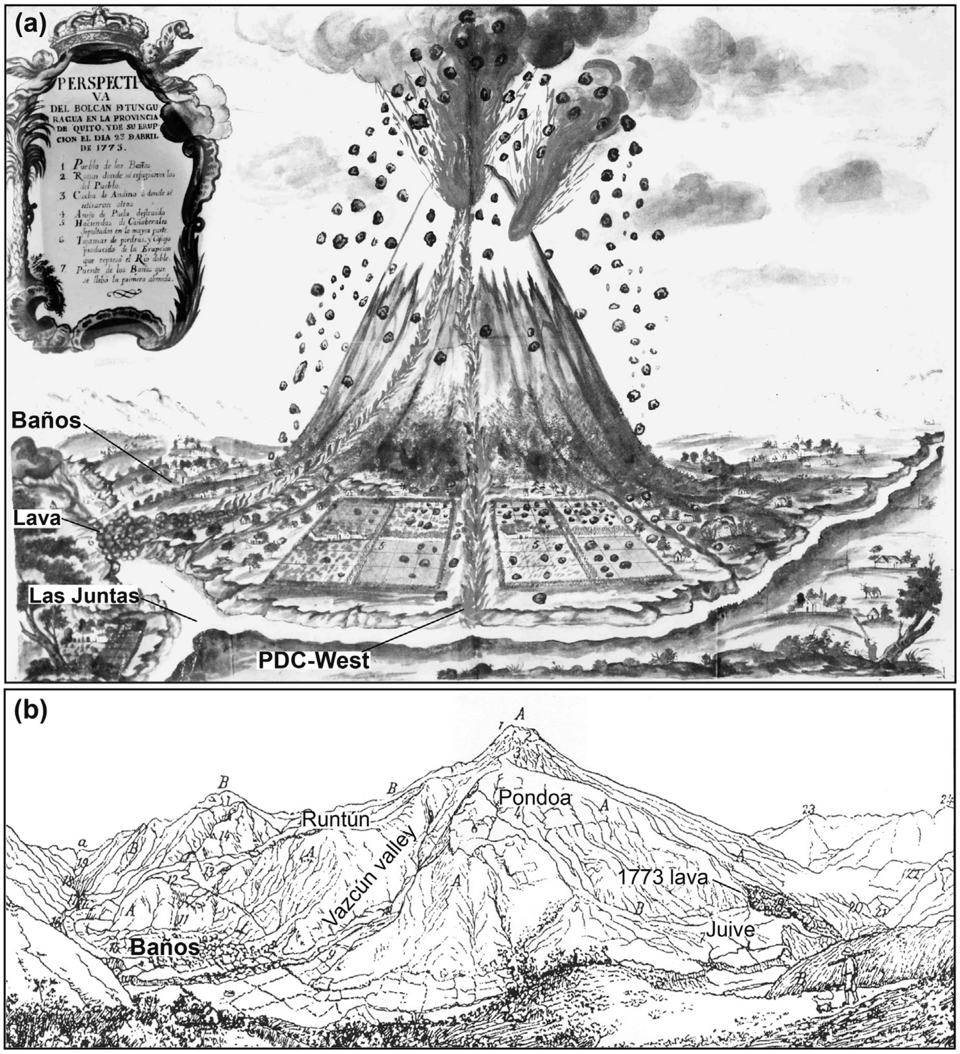

Fig. 3. (a) Painting showing Tungurahua volcano erupting in April 1773 (from AGI 3, and Samaniego et al., 2003) with annotations added for clarity by the authors. It depicts the junction of the Chambo, Patate and Pastaza Rivers (annotated "Las Juntas"), with a PDC descending the western side of the volcano ("PDC-West"). The 1773 lava flow ("Lava") is portrayed as a dark and rugged area on the lower northwestern side of the volcano, in Juive, close to Baños village ("Baños"). (b) Line drawing of the northern side of Tungurahua volcano, as depicted by Stübel in 1873 (i.e. 13 years before the 1886 eruption). The Baños area and Vazcún valley are clearly shown, and the 100-years-old 1773 lava is represented as a dark rugged bench over the smooth, gently inclined Juive area.

Pompeii or in a Saint Pierre de La Martinique" … These accounts, among others, bear clear witness of PDC emplacement in the Vazcún gorge, with valley-ponded deposits and lateral effects on valley sides (hot co-PDC clouds, with possible associated surge layers). The distance reached by the PDC is not made clear, as the location of the "*entry*" of Baños in 1918 is not described in the document. Beside the 5 April 1918 event, there is no evidence of PDC emplacement in Vazcún during other eruptive phases of the 1916–25 eruptive period.

4.5. The 1999-ongoing eruptive period

After height decades of quiescence the volcano reawaken in 1999 and witnessed a series of eruptive phases of low to moderate intensity that spanned from late 1999 to early 2006. These phases were characterized by an open-system behavior and included strombolian explosions, lava fountains, ash emissions, but without PDC formation. After increased eruptive intensity in the first semester of 2006, the activity peaked with a first modest PDC-forming eruption on 14 July 2006, though the Vazcún valley was not affected. One month later on August 16–17, a stronger sub-plinian eruption took place and produced a >15 km-high column, feeding copious scoria flows that travelled in many gullies of the southern and western flanks of the edifice. The PDCs also descended the Vazcún valley and halted ~2.5 km south of Baños city center (details on eruptive chronology and products e.g. in Arellano et al., 2008; Kelfoun et al., 2009; Ramón, 2010; Samaniego et al., 2011; Eychenne et al., 2013; Hall et al., 2013; Bernard et al., 2014). Although smaller in size, other PDC-forming phases have occurred after the 2006 paroxysm, notably from 2010 to 2014. In addition, many substantial lahars took place in the course of the 1999-ongoing period, with fatalities in 2008 in the Vazcún valley.

5. Constraints from geological and ^{14}C results

5.1. Juive and Rea valleys

A geological inspection of the Juive area indicates that a single prominent, dark-toned andesitic lava occurs there with a fresh-looking ragged surface morphology (Fig. 2). The sedimentary sequence upon the lava has been previously documented by Almeida and Ramón (1991, section JU-A in Fig. 4a), while recent excavations have exposed the sedimentary cover on the north-eastern side of the lava (Fig. 4b and section JU-B in Fig. 4a). This latter section consists of a basal massive lava overlain by a 2–2.5 m-thick sequence of texturally immature andesitic scoriaceous blocks. This is covered by a 1.5–1.7-m-thick stratified succession of whitish layers, which are extremely rich in 2–4 cm-large subrounded pumice clasts. The section is capped by a thin undisturbed and well sorted layer of dark-toned scoria lapilli, up to 3–5 cm in diameter. On the western flank of the volcano, an eye-catching pumice lapilli layer is exposed at shallow depth (a few decimeters) beneath the

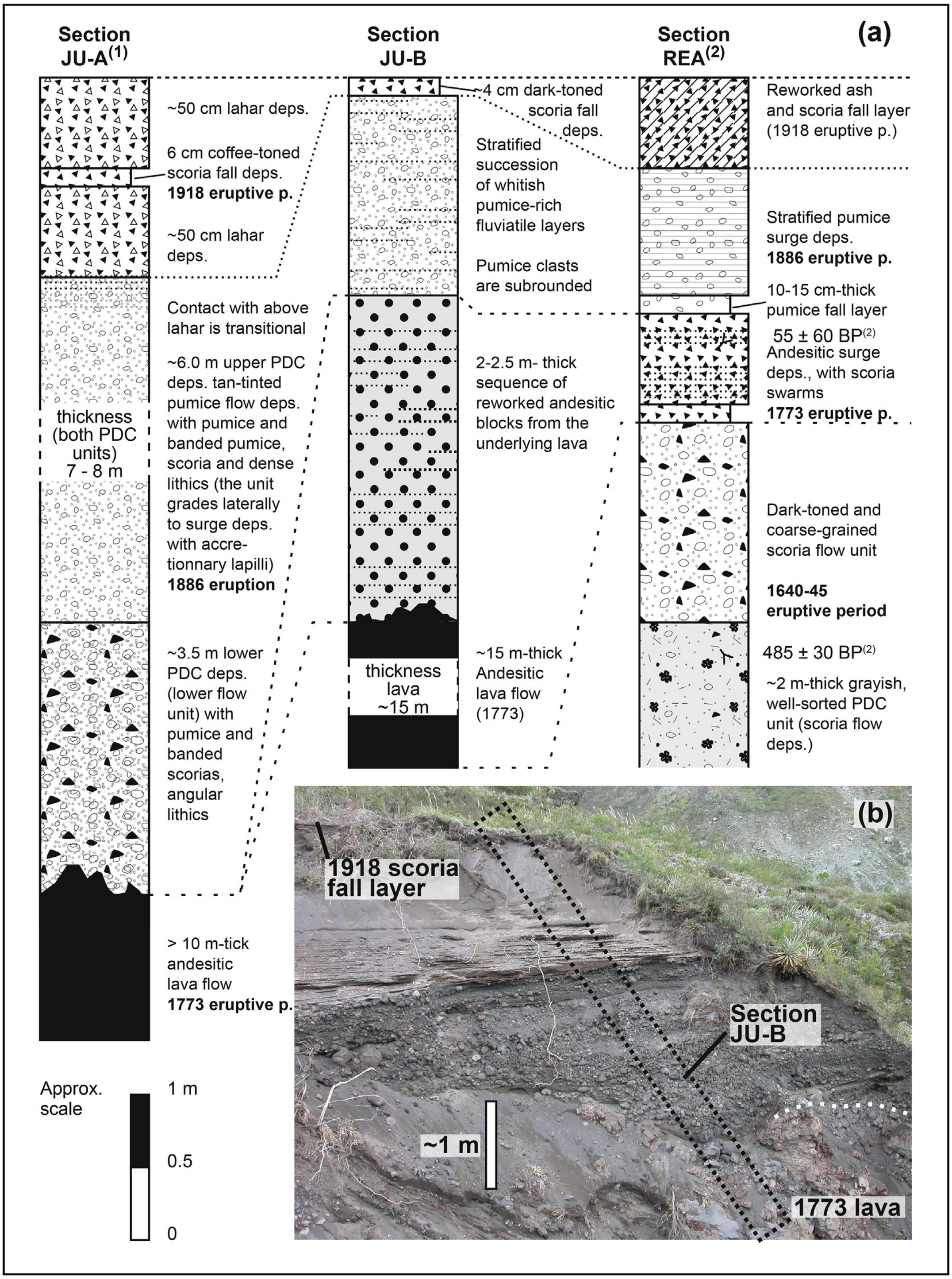

Fig. 4. (a) Three stratigraphic sections showing correlation of the whitish silicic products from the 1885–88 eruptive period. JU-A[(1)] is modified from Almeida and Ramón (1991), and section REA[(2)] is an enlarged segment of a section by Le Pennec et al. (2008). The section JU-B is established from the exposure shown in (b) (see location in Figs. 1 and 2). Dashed lines are correlation patterns to show the main eruptive periods evidenced in the Juive area and Rea ravine on the western flank. In our interpretation the pumice-rich PDC deposits in JU-A are isochronous to the pumice fall layer in section REA[(2)]; they postdate andesitic products of the 1773–81 eruptive period, and predate the andesitic scoria fall horizon of the 1916–25 eruptive period.

present-day soil in the somber andesitic succession of late Tungurahua III activity. The layer consists of light-toned, crystal-poor pumice clasts with glassy sub-fibrous and sugar-like textures, and also contains different types of accessory fragments, including some reddish oxidized lithics. Previous works show that the pumice bear some plagioclase and pyroxene, and whole rock analyses point to silicic andesite to dacitic compositions (Almeida and Ramón, 1991; INECEL, 1992; Hall et al., 1999; Samaniego et al., 2011, and our unpublished data). In the Rea ravine (located in Figs. 1b and 2), the pumice layer is associated with gully-confined pumice flow and surge deposits, and recent datings of underlying scoria flow deposits point to an historical age for the pumice layer (section REA in Fig. 4a, Le Pennec et al., 2008).

5.2. Vazcún valley

5.2.1. Higher terrace – western quarry section (HIT-WQ)

The sequence of the quarry (section HIT-WQ in Fig. 5) has been studied earlier by Mothes et al. (2004, their photo 3 and Fig. 1), who documented a succession of scoria flow, pumice flow and tephra fall deposits, along with lahar and mudflow deposits. The uppermost scoria flow deposit was previously correlated to the 1916–25 eruptive period of Tungurahua volcano (Hall et al., 1999), but AMS-dating of it at 1130 ± 40 BP revealed that the whole succession there is pre-Columbian in age (Mothes et al., 2004, Table 1). A similar deposit dated at 943 ± 78 BP (INECEL, 1992) in the same area is likely correlated to that upper scoria flow horizon, and both ages give a weighted mean of 1091 ± 36 BP (quoted below as 1100 BP). Mothes et al. (2004) also AMS-dated an eye-catching whitish dacitic pumice flow deposit with banded juvenile bombs at 1370 ± 40 BP, consistent with the age of the overlying scoria flow deposit, and correlated it to a similar pumice-rich horizon in the western area of Baños that they AMS-dated at 1450 ± 40 BP (Table 1). These conspicuous dacitic pumice (61–65% SiO_2 according to Hall et al., 1999) bear plagioclase and pyroxene phenocrysts, and the deposits have been previously dated in a quarry near Las Juntas (Figs. 1b and 2) at 1175 ± 41 BP (INECEL, 1992), and at 1230 ± 30 BP and 1210 ± 200 BP (P1 layer in Hall et al., 1999) and the five ^{14}C ages yield a weighted mean of 1294 ± 18 BP. The event is thus referred below to as the dacitic 1300 BP eruptive period. Further details on depositional features, lithology, mineralogy and chemical composition of the 1300 BP pumice products are provided in the above-cited works.

5.2.2. Higher terrace – eastern natural section (HIT-EN)

Upstream in the Vazcún, the HIT-EN section (Fig. 2) exposes more than 30 m of pyroclastic and epiclastic deposits (section HIT-EN in Figs. 5 and 6a). The sequence essentially consists of dark-toned to pinkish lithic-rich PDC deposits with interbedded scoria fall layers, as well as laharic and fluviatile horizons. The section clearly pertains to the higher terrace system (the vertical contact with the lower terrace system is shown as a white dashed line in Fig. 6a), but the age of the pyroclastic units in it remains uncertain, as no organic material has been found in them. Stinton and Sheridan (2008) proposed ages of 2000 BP, 1800 BP, and 1450 BP for the main lowermost PDC layers, but provided no ^{14}C data to support these assignations. In this study we considered the absence in the HIT-EN section of the conspicuous dacitic 1300 BP layer, and noted the lack of incorporated accessory pumice clasts in the andesitic PDC deposits, which all suggest that the whole sequence belongs to eruptive periods that predate the major dacitic 1300 BP event (Almeida and Ramón, 1991; INECEL, 1992; Hall et al., 1999; Le Pennec et al., 2006).

5.3. Vazcún valley – lower terrace (LOT)

The inner terrace remained previously undated, but recent works indicate that the two PDC deposits exposed in cliffs below the western quarry are historical in age. An 8–10 m-thick section (LOT-SP in Fig. 5) located very near the Spa exposes a single PDC deposit that has been PGC-dated at 190 ± 30 BP (Le Pennec et al., 2008). Simple physical continuity indicates that this section exposes a thick gully-confined deposit which correlates laterally, about 50 m to the south, to the upper unit of the well-exposed road cut described below.

5.3.1. Road cut section (LOT-RC)

The base of the succession (section LOT-RC in Fig. 5, see photos in Le Pennec et al., 2008) consists of fluviatile deposits with coarse-grained lava cobbles. This is overlain by a lens of reworked pumice-rich deposits with rounded clasts. This light-tinted lens is in turn covered by a 7–8 m-thick dark-toned scoria flow deposit that host a few juvenile andesitic bombs as well as many accessory fragments (including sub-rounded pumice clasts) incorporated by the PDC during flow. This lower PDC deposit has been PGC-dated at 270 ± 25 BP and 300 ± 30 BP (Table 1). The PDC deposit is overlain by 5–15 cm-thick stratified layers of fluviatile sands and gravels. Above, the upper PDC layer is similar to the lower one, i.e. 7–8 m of faintly stratified scoria flow deposits with a juvenile fraction composed of andesitic bombs and scoria fragments and abundant accessory material including oxidized lithic blocks and some accessory rounded pumice clasts. The relatively crystal-poor bombs bear the typical mineralogical assemblage of Tungurahua andesites (plagioclase and two pyroxenes).

5.3.2. East Transverse section (LOT-ET)

The ET section, about 300 m upstream of the Spa, exposes a sequence (section LOT-ET in Figs. 5 and 6b) that is in all aspects similar to the above LOT-RC section. The lower layer, whose base is covered by screes, is a 7–8 m-thick PDC deposit with no clear stratification, though diffuse elongated swarms of coarse-grained clasts are observed (Fig. 6b). The deposit hosts rare juvenile andesitic bombs and abundant accessory material, a fraction of which is oxidized. The coarsest angular to subangular lithic clasts have sizes in the range of 20–60 cm. The matrix is composed of sand- and ash-sized grains with some juvenile scoria fragments and scattered sub-rounded pumice clasts. The crystal content, the mineralogy, and the overall texture of the juvenile andesitic clasts are in all aspects similar to those observed in PDC deposits in the LOT-RC section. In addition, partly-to-completely carbonized wood pieces occur in the deposit (Table 1). A trunk segment collected in the lower part of the exposure gave a PGC-age of 155 ± 15 BP (GrN-28970), while carbonized twigs and a charcoal piece yielded PGC-ages of 390 ± 40 BP (GrN-28969) and 230 ± 20 BP (GrN-27900), respectively. In the upper part of this lower unit we collected two charred wood pieces that were PGC-dated at 460 ± 20 BP and 420 ± 20 BP (GrN-29483 and GrN-28712 respectively, Table 1). At the same level, Stinton and Sheridan (2008) reported an age of 150 ± 90 BP for a charcoal remain. This lower PDC layer is covered by 10–20 cm of fluviatile beds of texturally sub-mature sands and gravels.

The upper PDC layer rests upon the gravel beds and is ~7 m thick, while the top shows small-scale erosional incisions (Figs. 5 and 6b). This PDC deposit is similar to the lower one with juvenile bombs and scoria fragments, and a mixture of accessory material of varied size, color, and texture, including some sub-rounded pumice clasts. About 1 m above the base of the deposit, a charred branch fragment yielded a PGC-age of 335 ± 25 BP (GrN-27901).

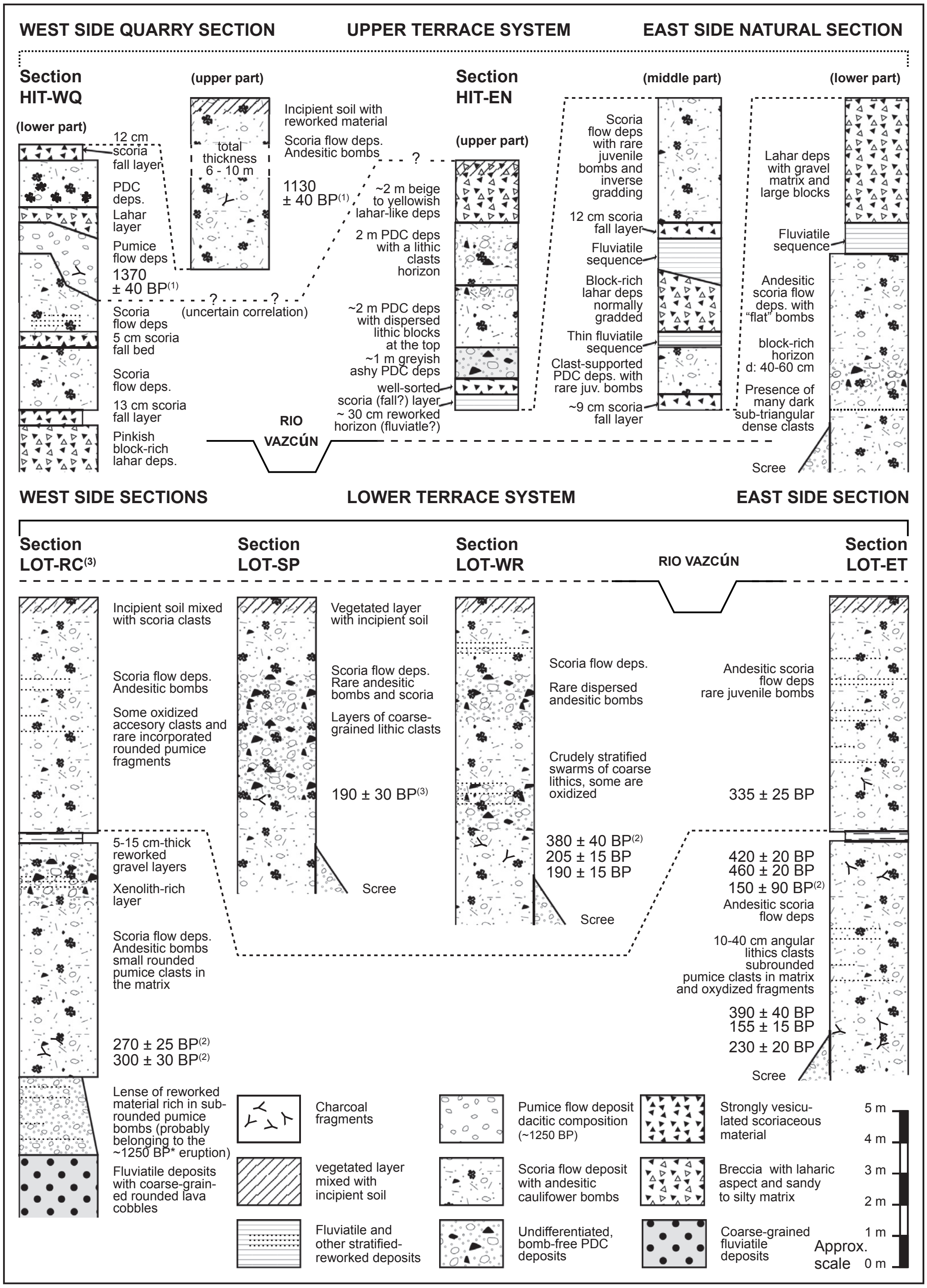

Fig. 5. Selected stratigraphic sections in the Vazcún valley to illustrate the position of dated and undated deposits from Higher and Lower terrace systems. Section localities are shown in Figs. 1b and 2. The relative location of Rio Vazcún is also indicated. Radiocarbon data from [(1)] Mothes et al. (2004) and [(2)] Stinton and Sheridan (2008). [(3)]Radiocarbon data in section LOT-SP, and section LOT-RC are from Le Pennec et al. (2008).

The top of the deposit coincides with the present-day vegetated horizon.

5.3.3. West Radial section (LOT-WR)

About 50–100 m upstream of LOT-ET in the Rio Vazcún, the LOT-WR section (see Figs. 5 and 6c) is cut in a single PDC deposit, in which dark-toned bombs suggest a juvenile andesitic composition (Hall et al., 1999; Samaniego et al., 2011). The PDC deposit shows faint stratifications revealed by elongated swarms of coarse-grained material (Fig. 6c). About 2–3 m above the Rio Vazcún bed, we collected a partly carbonized branch piece, ~6-cm in diameter, with tree rings still visible, and obtained a PGC-age of 190 ± 15 BP (GrN-29567, Table 1), while a charred twig was dated at 205 ± 15 BP (GrN-30328). In the same place (Fig. 6c), Stinton and Sheridan (2008) reported a charcoal age of 380 ± 40 BP (Table 1). Upstream and close to the LOT-WR section we identified a pumice-rich deposit with both oxidized and dark-toned accessory lithic elements. Although not well exposed, this light-toned deposit is

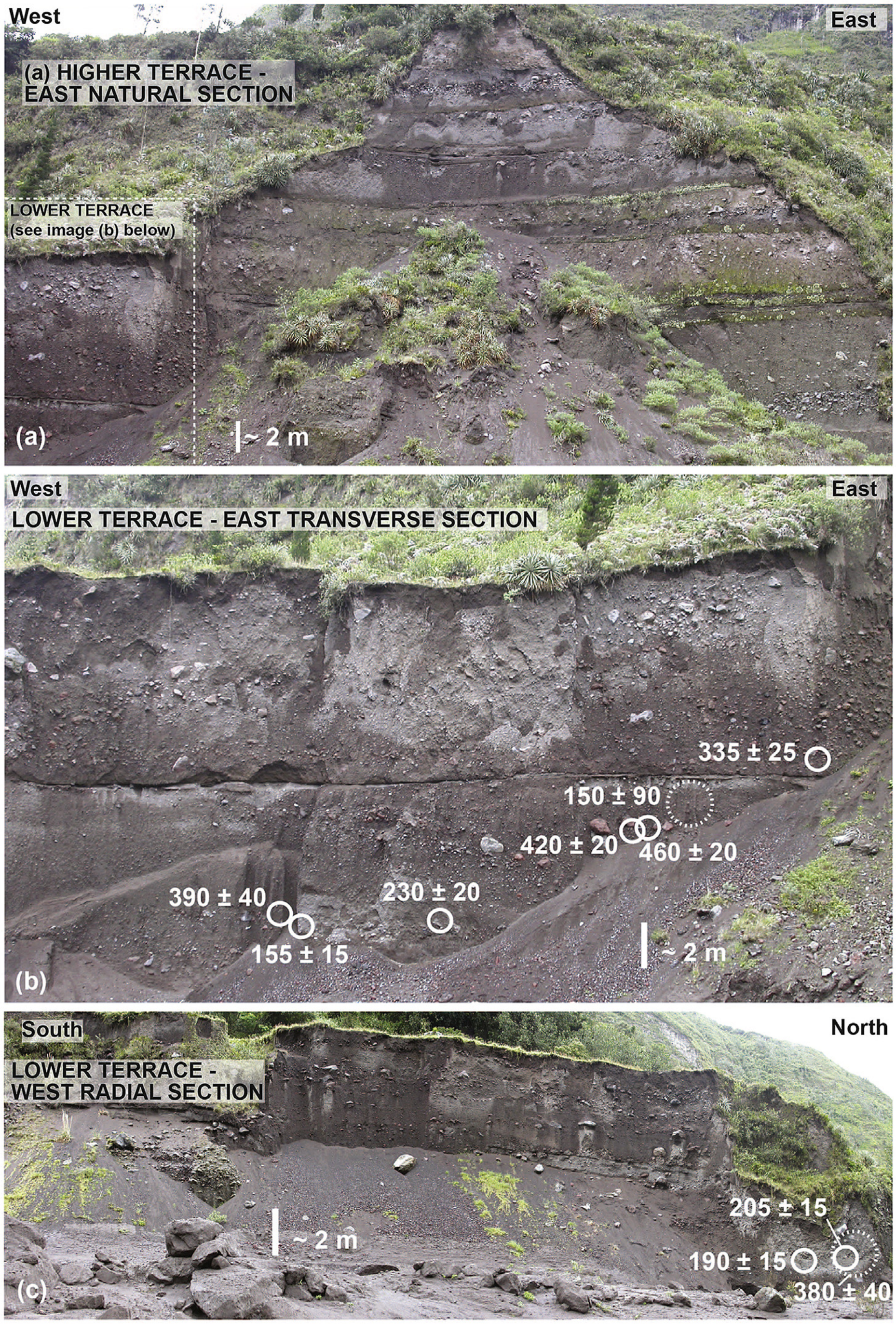

Fig. 6. Selected views of the studied deposits in natural exposures of the Vazcún valley (see sections in Fig. 4). The open circles show the emplacement of organic remains with 14C age determinations indicated (dashed circles are charcoal sampling locations by Stinton and Sheridan, 2008). (a) Higher Terrace — East Natural section (HIT-EN), the dashed box is the lower terrace shown in (b). (b) Higher Terrace — East Transverse section (HIT-ET). (c) Lower Terrace — West Radial section (LOT-WR).

seemingly reclined along a subvertical contact against the andesitic PDC deposit of the LOT-WR section described above, and it thus corresponds to pumice plastering inside a preexisting U-shaped channel, implying it is younger than nearby LOT-WR scoria flow deposits, as also inferred by Stinton and Sheridan (2008).

6. Discussion

Before reconstructing the recent PDC activity in the Vazcún valley, we need to consider some issues raised by the ^{14}C results.

6.1. Interpreting the ^{14}C age determinations

A number of processes can account for inaccuracies and scatterings of ^{14}C age determinations obtained in this and earlier studies. Below, we pinpoint some factors that may account for such difficulties in the case of Tungurahua and other tropical volcanoes, without addressing additional complications owed to calibration concerns.

a) Within a single organic remain, a $^{14}C/^{12}C$ heterogeneity may arise from simple fractionation of carbon isotopes in different vegetation tissues, although the impact on the ^{14}C determination is supposed to be negligible after $\Delta^{13}C$ corrections (Southon, 2011). b) As is plausible at volcanoes in tropical regions, alteration of the ratio $^{14}C/^{12}C$ may result from contamination by roots and humic acids that propagate from overlying soils (e.g. Tonneijck et al., 2006) to deeper horizons where permeable wood in charcoal pieces occur. These processes may lead to apparent rejuvenated ^{14}C determinations (Harkness et al., 1994), notably when routine analytical protocols are applied. However, progress in optical and chemical decontamination and pretreatment tend to limit these effects (e.g. Table 1). (c) Similarly, before being incorporated in PDCs, plant debris that spend a long time in river beds may be contaminated by ^{14}C from young carbon dissolved in running waters, which constantly equilibrate with atmospheric ratios when hydrothermal contributions are absent, while any wood-charcoal piece in the deposits may get impregnated by rain waters that also convey young carbon (Mook, 2000). d) Conversely, magmatic gases are typically depleted in ^{14}C and are another possible source of $^{14}C/^{12}C$ modification. Such magmatic carbon may percolate through diffuse degassing in the ground, or may be disseminated into the atmosphere by fumarolic activity, thus affecting the $^{14}C/^{12}C$ signature of nearby vegetation. The influence of such magmatic carbon on ^{14}C determinations is significant e.g. in the Azores (Pasquier-Cardin et al., 1999), but charcoal beneath lava flows located at a short distance from a fumarolic field in Hawaii suggests little or no effect on the $^{14}C/^{12}C$ ratio (Dzurisin et al., 1995). At Tungurahua, small charcoal debris (collection of thin needles of some millimeters in length) collected against an andesitic bomb on the western side of the volcano yielded an AMS age of 4040 ± 50 BP (GrA-23510, Table 1), although excellent exposure and clear stratigraphic context indisputably assigned the hosting deposit to PDCs of the 1773–82 eruptive period. We speculate that bomb degassing may have affected the $^{14}C/^{12}C$ ratio in the plant debris, leading to an apparent old age. e) In some fine-grained ashy deposits the presence of small charcoal pieces leads to consider those as plant debris incorporated in volcanic surge flows. However, such carbonized pieces may as well result from fires (they were common in Ecuador in Holocene times, particularly since the colonial period, Niemann and Behling, 2007), while the hosting layers may simply result from aeolian ash reworking. f) An additional and severe problem arises with the "old-wood effect" that is well-known in archaeology but poorly documented in volcanology. Assessing such effect requires multiple ^{14}C dating of a single horizon, as is the case in our study (Fig. 6), and different situation may occur (see Fig. 7). For illustration, we consider a young gully-confined PDC of age *D* correctly dated with an organic remain (sample T in Fig. 7) that was alive at the time of PDC emplacement. However, the young PDC may incorporate dead wood that accumulated for a long time in a river bed, as is common at tropical volcanoes (sample *z* in Fig. 7). The ^{14}C age of the potentially carbonized wood will be therefore older than that of the deposit, i.e. than the age *D* of the PDC-forming eruption. The PDC may also incorporate material from sidewalls of U-shaped valleys in which it flows, where older wood-charcoal-hosting PDC and/or lahar deposits are present. If dated with such incorporated material, the young PDC deposit will thus be erroneously assigned to previous eruptive or erosional periods (e.g. samples *i*, *j* and *x* in Fig. 7). Recent works at Tungurahua reveal that typical PDCs, e.g. the 2006 scoria flows, incorporated about 50 wt.% of non-juvenile material (Bernard et al., 2014), we thus infer that such "old wood effects" are likely a major source of PDC misdating at many volcanoes in the tropics. g) Analytical requirements on sample size (for PGC vs. AMS dating) from a multi-piece organic sample may lead to mix wood-charcoal of different ages, resulting in ^{14}C determinations that ponder the ages of different wood-charcoal fractions (e.g. samples *k* and *y* in Fig. 7). h) Age resolution and accuracy also depends on sample nature, size and quality. For example it is known that multiple PGC analyses (devoted to large samples) tend to yield more clustered ages determinations than AMS techniques (adapted to small samples), and this is verified with ^{14}C data obtained at Tungurahua (cf. Le Pennec et al., 2008; their Fig. 7). i) Finally, as is common in many radiocarbon studies, aberrant and non-interpretable ^{14}C ages can occur, but a justification to discard such anomalous data may be difficult to find.

The above concerns should be kept in mind when discussing ^{14}C results from PDC deposits and the difficulty faced when interpreting young (<500 BP) ^{14}C determinations for volcanological applications raises the necessity to develop rigorous sampling and preparation strategies prior to ^{14}C analyses, as in archaeological sciences (e.g. Bird et al., 2002; Friedrich et al., 2006). This is achievable through careful sample selection (mixtures of charcoal fragments should be avoided while remains that show evidence of having been alive at the time of eruption are ideal materials, twigs should yield better results than thicker trunk pieces etc.), multiple dating of a single layer when possible (e.g. to reveal possible "old wood effects"), appropriate sample pretreatment (to remove chemical contaminants) etc., while reporting of ^{14}C data with international standards is also essential to facilitate interpretations.

6.2. Age of the pumice in Juive and Rea ravines

We assign the lava in the Juive area (sections JU-A and B in Fig. 4a) to the 1773–82 eruptive period, as shown in the 1773 painting and confirmed in Stübel's line drawing described earlier (Fig. 3), and there are no other young lava contenders in that area. The above andesitic and texturally immature blocks in section JU-B (Fig. 4) are interpreted as incipiently reworked products of the 1773 blocky scoria carapace of the lava, and were emplaced while the eastern side of the lava was progressively re-incised by waters and mudflows of the Juive ravine. The conspicuous overlying pumice-rich layers mark a sudden sedimentary event involving essentially pumice material that is typical at Tungurahua of dacitic to silicic-andesite compositions (Almeida and Ramón, 1991; INECEL, 1992; Hall et al., 1999; Samaniego et al., 2011). We interpret these light-toned pumice-rich layers as reworked products of nearby pumice flow deposits (section JU-A in Fig. 4a) studied by Almeida and Ramón (1991), and in turn ascribe these to the "*fragmental lava*" of "*Juivi*" [Juive] reported by A. Martínez after the January 1886 eruption (appendix A4 in SEM 1). Similarly, we correlate the whitish pumice fall layer in Rea ravine (section REA in Fig. 4a) to the pumice flow deposits of Juive (both are silicic andesites – dacites with ~61–65 Wt% SiO_2, Hall et al., 1999; Samaniego et al., 2011), and we equally allocate it to the 1886 eruption. This is consistent with the "*quasi-white color*" of the tephra fall layer described by A. Martínez as "*after an intense snowfall*" (Appendix A4 in SEM 1), and with available ^{14}C data from underlying deposits (section REA in Fig. 4a). This correlation concurs with that of Almeida and Ramón (1991) and differs from that of Hall et al. (1999), who attributed their upper pumice fall layer *P2* to the 1773 eruptive period. This might be owed to the mention of "*pieces of pumice stones so light that they swam in the water*" reported after the April 1773 event (González Suárez, 1892; Appendix A2), though strongly vesiculated andesitic scoria clasts (described as "*pomez*" i.e. "*pumice*" in the narrative) may as well float on water. This correlation is essential because the 1886 dacitic pumice deposits are key horizons to resolve the volcanic stratigraphy in the Vazcún valley and beyond.

6.3. Reconstructed PDC activity in Vazcún valley

Gathering previous historical, volcanological and radiometric data and considering the above issues about ^{14}C uncertainties and

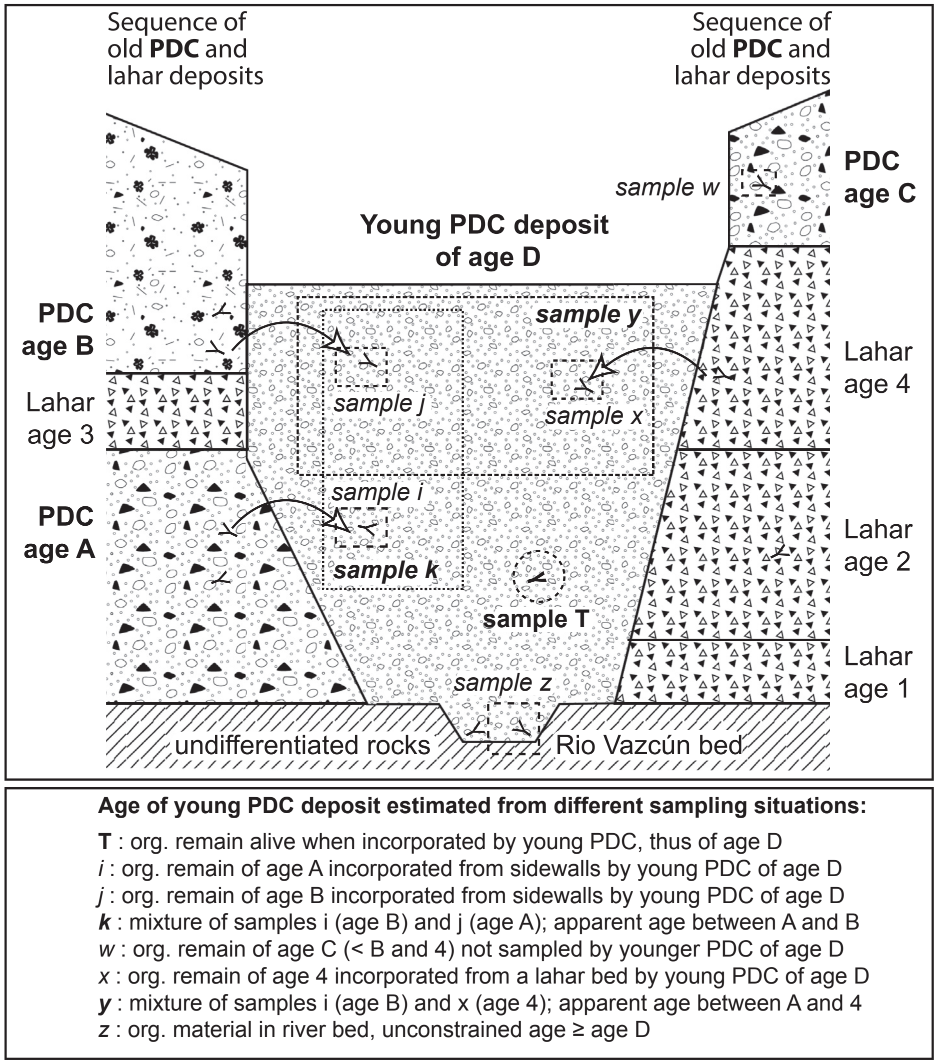

Fig. 7. Schematic cartoon showing possible conditions for "old wood effects" that may complicate the interpretation of recent ^{14}C age determinations of PDC deposits, regardless of any other chemical ^{14}C–^{12}C contamination processes. The cartoon depicts an idealized section of a valley-confined PDC deposit of age D to be dated with organic remains from different sources (current vegetation and organic remains incorporated in previous PDC and lahar deposits) and ages (ages A to D for PDC deposits and ages 1 to 4 for lahar deposits). Resultant misdating situations are summarized below the cartoon and in the main text.

pumice correlations allow us to offer new constraints on recent PDC activity in the Vazcún valley. First, we assume that the best ^{14}C age determinations rely on clear evidence that the organic material was alive at the time of incorporation in the PDC avalanche during the eruption (as also presumed by Friedrich et al., 2006; in their accurate dating of the Minoan eruption). Moreover, high-resolution data (i.e. 1 σ < 30 ^{14}C years) are required to obtain narrowed calibrated date ranges. In our ^{14}C dataset (Table 1, Fig. 8) the only sample that meets both requirements (a thin twig of *Photinia* that still had charred leaves attached) is GrN-29338 dated at 270 ± 25 BP, from the lower scoria flow unit in LOT-RC (Fig. 5). Using the high-precision UWSY98 calibration curve, it was assigned to the 1640–45 eruptive period (Fig. 8 and Le Pennec et al., 2008). This is consistent with the age of the upper scoria flow unit dated at 190 ± 30 BP in nearby LOT-SP section (Fig. 5), which best correlates to the 1773–82 eruptive period at both 1 and 2 σ confidence levels, as also supported by calibration results of similar ^{14}C ages for samples collected in Baños (Table 1, Fig. 8 and Mothes et al., 2004; Le Pennec et al., 2008). Evidence for two distinct eruptive periods in the LOT-RC section is further indicated by fluviatile gravel layers between both scoria flow units (Fig. 5). The sedimentary record of an erosion phase on top of the lower scoria flow unit implies that the gravel layers were emplaced some time (at least several weeks?) after deposition of the underlying hot PDC deposit. After incipient erosion of the cooling PDC unit the incision process concentrated in narrow gullies carved in hot loose materials, and thus the fluviatile sedimentation on top of the remaining PDC terrace was no longer maintained. Such long durations between PDC emplacement and resumption of erosion (at least several weeks) has been reported by N. Martínez (1932) for the 1918 event and witnessed by some of us at Tungurahua after all PDC-forming phases since 2006. From this erosional pattern and because historical archives suggest a single PDC-forming phase during the 1773–82 eruptive period, we infer that the two salient PDC units in the LOT-RC system belong to two different eruptive periods, and not from two distinct phases during a single eruptive period. Consequently, we assign the two PDC deposits in LOT-RC to the eruptive periods in 1640–45 and 1773–82. Accordingly, the presence of many accessory pumice clasts in both scoria flow units points to incorporation from the older dacitic 1300 BP products identified in nearby HIT-WQ quarry, as previous stratigraphic

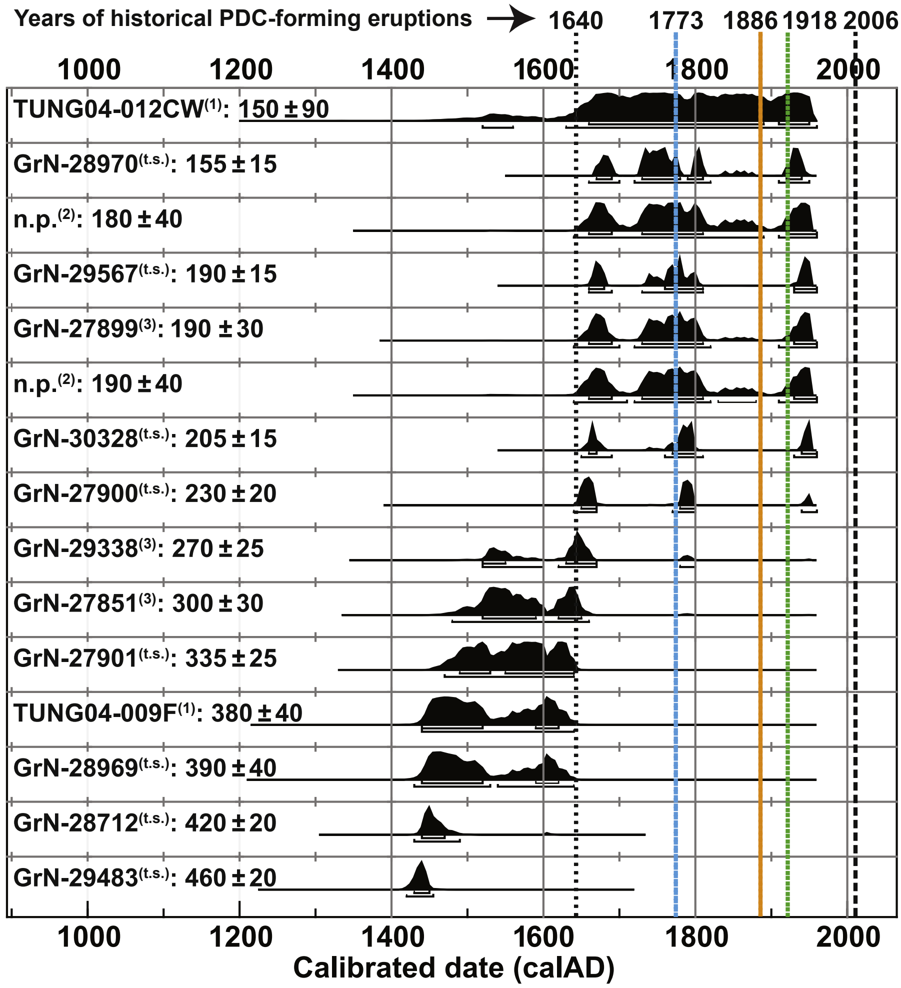

Fig. 8. Density probability functions of young (<500 BP) radiocarbon determinations of samples collected in the Vazcún valley and Baños area in this and previous works. References: [(1)]Stinton and Sheridan (2008), [(2)]Mothes et al. (2004), [(3)]Le Pennec et al. (2008), [(t.s.)]as shown in the Fig. for This Study. See Table 1 for sample and calibration details.

works suggest no other candidates (Almeida and Ramón, 1991; INECEL, 1992; Hall et al., 1999; Le Pennec et al., 2006).

On the same western side of the Rio Vazcún, the LOT-WR section exposes similar PDC deposits, but the fluviatile gravel layer is absent (Fig. 6c). Calibrated ^{14}C ages of 190 ± 15 BP and 205 ± 15 BP support the 1773–82 eruptive period at 2 σ level (Table 1, Fig. 8), while the 380 ± 40 BP determination of Stinton and Sheridan (2008) may correspond to an "old wood effect" due to the incorporation of organic material from older deposits, e.g. those of the 1640–45 event identified downstream. Multisource componentry assemblages in the PDC deposits are too complex and offer no clear evidence of recycling from an old PDC layer to a younger one. An assignation to the 1773–82 event is fully consistent with the pumice-rich deposits plastered against the LOT-WR section that we correlate to the Juive and Rea pumice layers, and thus to the dacitic 1886 event described by A. Martínez (1886, 1903 see A4). The pumice products flowed into a U-shaped gully carved in the 1773 scoria flow unit, and despite the 1886 event was fairly large (likely VEI 4), the material in Vazcún was almost entirely removed by erosion in the following century.

As in the LOT-RC section, the LOT-ET section on the East side of Rio Vazcún consists of two scoria flow units separated by reworked gravel layers (Figs. 5 and 6b) and we similarly infer two distinct eruptive periods. However, the ^{14}C and calibration results are more difficult to interpret here. Most organic samples from the lower PDC unit yield calibrated date ranges (Table 1, Fig. 8) that are consistent with the 1640–45 period, with exceptions of samples GrN-28712 (420 ± 20 BP) and GrN-29483 (460 ± 20 BP), which give dates in the 15th Century (old wood effect?) and GrN-28970 (155 ± 15 BP) that may have experienced a young carbon contamination. In this interpretation, the upper PDC layer would correlate to the 1773–82 eruptive period, and the age at 335 ± 30 BP would correspond to an old wood effect, e.g. through incorporation of older organic remains from the 1640–45 deposits located below and nearby, as in the case of the LOT-WR section. Similarly, we attribute the abundant accessory pumice clasts scattered in both scoria flow units of the LOT-ET section to the dacitic 1300 BP deposits.

Therefore, the lower terrace (LOT system) consists of disconnected remnants of the 1640–45 products buried beneath younger channelized and overbanked deposits of the 1773–82 eruptive period. The 1773 PDCs leveled the valley bottom to produce a single flat-topped structural unit, and the surface of its present-day remnants defines the lower terrace system. Such flat-topped morphologies are typical features of small-volume valley-confined PDC products at many andesitic volcanoes (e.g. Colima in Mexico and Merapi in Indonesia, Saucedo et al. 2004; Charbonnier and Gertisser, 2008). As pointed out by N. Martínez (1932; appendix A5) the 1918 PDCs in Vazcún also tended to form flat-topped "*road-like*" deposits, but the above findings imply that the 1918 scoria flow deposits, which were not identified in our study, were likely entirely removed by erosion, or perhaps their remains are not exposed.

These discussions about ^{14}C data of PDC deposits, depositional record of reworking, erosional unconformities and timescales lead us to identify at least four eruptive periods in the HIT-WQ section (Fig. 5), including the large dacitic 1300 BP event that is calibrated at 660–770 calAD (Table 2). Similarly, from facies examination of the undated HIT-EN section (Figs. 5 and 6a) we estimate that at least four eruptive periods have pyroclastic archives emplaced prior to the 1300 BP event. Starting with the 3 ka BP blast event and considering that the uppermost scoria flow deposits in HIT-EN may correlate to the lowermost andesitic PDC sequence in HIT-WQ (Table 2), we calculate that at least 8 PDC-forming periods took place in Vazcún between ~1100 calBC (date of the blast event) and ~880–1020 calAD (calibrated 2σ range for the weighted ^{14}C age of 1091 ± 36 BP of the uppermost PDC unit in HIT-WQ).

(~600–700 years) and the oldest PDC unit in LOT (1640–45). Stinton and Sheridan (2008) argued that the lack of pyroclastic records between these dates reflected a volcanic repose period, but studies on the western side of the edifice indicated that Tungurahua volcano experienced at least two PDC-forming eruptions in that time interval, at about 630 BP and 760 BP (Le Pennec et al., 2008). In addition, exposure scarcity or complete reworking of past PDC products (e.g. as those of 1918 and 2006) may explain the apparent absence of PDC remains in Vazcún from that time interval.

7. Conclusion

Our study points to at least 8 pre-Columbian and 3 historical eruptive periods recorded in exposures of the lower Vazcún valley and Baños area (Table 2), which translates into a minimal average PDC recurrence rate of ~250–300 years. However, our data suggest an historical ratio of recorded/unrecorded PDC sedimentation in Vazcún of about 0.6, as 1918 and 2006 products are unpreserved or concealed. Applying this correction ratio to the pre-Columbian eruptive record yields a total of 18 eruptive PDC-forming periods

Table 2

Synthetic PDC activity in the Vazcún valley and Baños area, as reconstructed in this note from our study and previous works. (a) The left column is a count of past PDC-forming eruptive periods based on historical archives for Hispanic times, and on records of erosional unconformities and laharic/fluviatile sediments on top of PDC units for pre-Columbian times. The star* denotes unknown correlation of the uppermost unit in HIT-EN with the lowermost unit in HIT-WQ; both deposits are counted here as a single eruptive period # 5. (b) Dates (*d*) in italics are from historical archives (since Spaniards arrived in 1533) and calibrated date ranges (*d.r.*) in italics are obtained from ^{14}C age determinations (*A*) for pre-Columbian times. (c) In order to determine PDC return rates since 3 ka BP in Vazcún and Baños areas the fourth column summarizes features of the sedimentary record from past eruptive periods. (d) Impact data compiled in the last column (confirmed from historical narratives or supposed from apparent volume and height of pre-Columbian deposit in the Higher Terrace system) are used to estimate the recurrence rate of PDCs that affected Baños city. See text for more details.

# of eruptive periods[a]	Date (*d*),calibrated date ranges(*d.r.*) and ^{14}C age (*A*) of the eruptive periods[b]	Magma composition	Depositional record in Vazcún-Baños areas[c]	Impacts in Baños[d]
13	*d:1999-ongoing*	Andesitic	PDCs: no known record Lahars: yes	PDCs: No impacts as yet. Lahars: limited impact, but two victims in 2008.
12	*d: 1916–25*	Andesitic	PDCs: no known record Lahars: no known record	PDCs: very little impact. Lahars: small to moderate.
Erosional unconformity on top of event 11 sequence				
11 *(P2)*	*d: 1885–88*	Dacitic onset, Andesitic later	Mixed ice-melts and pumice flows and lahars: yes	PDCs: no known impact. Lahars: moderate.
Erosional unconformity on top of event 10 sequence (surface of Lower Terrace system)				
10	*d: 1773–81*	Andesitic	PDCs: One scoria flow unit	PDCs: moderate impact, no victims. Lahars: probable impact
Fluviatile deposits on top of event 9 sequence				
9	*d: 1640–45*	Andesitic	PDCs: One scoria flow unit	PDCs: probable impact. Lahars: probable impact.
Lahar deposits on top of event 8 sequence				
8	*d.r.: 880–1020 calAD* *A*: ~1100 BP (1091 ± 36 BP)	Andesitic	One scoria flow unit recorded, with scorial	Highly probable impacts from PDC and lahars, possible victims
Erosional unconformity on top of event 7 sequence				
7	*Undated* 1100BP < *A*< 1300 BP	Andesitic	PDCs: one scoria flow units Falls: no	Probable impacts from PDCs and lahars
Lahar deposits on top of event 6 sequence				
6 (*P1*)	*d.r.: 660–770 calAD* *A*:~1300 BP (1294 ± 18 BP)	Dacitic Andesitic Later	PDC: One pumice flow unit Lahar: yes	Severe impacts from PDCs and lahars, possible victims
*Lahar deposits on top of event 5 sequence in HIT-EN**				
*Erosional unconformity on top of event 5′ sequence in HIT-WQ**				
5*	*Undated* 3000 BP < A < 1300 BP	Andesitic	PDCs: Three scoria flow units Falls: one scoria fall	Very likely, overflow of Vazcún valley
Fluviatile deposits on top of event 4 sequence				
4	*Undated* 3000 BP < A < 1300 BP	Andesitic	PDCs: one scoria flow unit Falls: one basal scoria fall	likely, overflow of Vazcún valley
Lahar and fluviatile deposits on top of event 3 sequence				
3	*Undated* 3000 BP < A < 1300 BP	Andesitic	PDCs: one scoria flow unit Falls: one basal scoria fall	unlikely, bottom fill of Vazcún valley
Lahar and fluviatile deposits on top of event 2 sequence				
2	*Undated* 3000 BP < A < 1300 BP	Andesitic	PDCs: two scoria flow units with dense triangular clasts	unlikely, bottom fill of Vazcún valley
No known record in the probably long time interval between events 1 and 2				
1	*d: ca. 1100 calBC A*: ca. 3000 BP (2935 ± 16 BP)	Dacitic onset (brief) andesitic later	PDCs: one blast unit Falls: one plinian scoria fall on top of blast unit	**Complete devastation.** **Fatalities very likely.**

In the Vazcún valley the clear morphological distinction between lower (LOT) and higher (HIT) terrace systems suggests two episodes of PDC activity since 3 ka BP, separated by a long-lasting depositional gap between the youngest PDC unit in HIT in Vazcún since ~1100 calBC, consistent with previous estimates at the scale of the whole Tungurahua III edifice (19 periods according to Le Pennec et al., 2006, 2008), which means a maximum average PDC return rate of 150–200 years. On the other hand, the historical record indicates that many PDCs did not impact the now-urbanized Baños area (e.g. 1918, 2006, Table 2) and we assume that this situation applies to pre-Columbian times, e.g. perhaps only the 3 or 4 youngest PDC units in HIT affected the Baños area, as previous ones had first to fill in the valley bottom (Table 2). As a result, we estimate that one third to half of the PDC-forming events affected the area of Baños, and thus the average impacting PDC return rate is on the order of 350–500 years, a duration that might seem long for people living in the area. This return rate concurs with the relatively large (and thus less frequent) eruption size required to supply a pyroclastic volume that can fill the lower Vazcún gorge and overflow towards the urbanized zone. Nonetheless, our volcanological analysis does not fully account for possible highly mobile detached surge flows that may have impacted the lower Vazcún area without leaving clear geological records, and such hazardous detached flows are known to occur at many andesitic volcanoes worldwide (e.g. at Merapi in Indonesia, Bourdier and Abdurachman, 2001; and Unzen in Japan, Fujii and Nakada, 1999).

The recurrence and magnitude of the PDCs emplaced in the Vazcún valley also depend on geometry and conformation of the summit crater (Mothes et al., 2004). The crater hosts an internal active pit whose location, size (depth) and shape change considerably during each eruptive period. Accordingly, the location and the level of infill of the pit have strong control on the pattern of PDCs initiation and overflow, and thus on PDCs distribution on the volcanic cone. In the past hundred years, the lowest rim of the crater has been located on its western side, implying that most PDCs and lavas were channelized towards gullies of the western flank of the edifice (e.g. 2014–10, 2006, 1918, 1886, 1773, and 1640 etc.). Conversely, a topographic high located on the northern side of the crater has acted as a rampart which maintained the Vazcún valley and Baños area relatively protected during many PDC-forming events, and only the strongest eruptions were able to produce hazardous PDCs (Mothes et al., 2004). In parallel, collapse of the western unstable crater rim has occurred repeatedly in the past millennium, with formation of dangerous small-volume debris avalanches down to the base of the volcano (Le Pennec et al., 2008). This configuration may change in the future as the Tungurahua III cone grows, and crumbling of the steep-sided, altered and fragile northern crater rim is an option which would change drastically the frequency and path of future PDCs on the northern side of the cone. While this worst-case scenario cannot be excluded from our hazard analysis, we recommend considering such a situation with caution, as it is not expected to occur in the near future.

These findings have implications for risk assessment, alert level definition and crises management because future descent of PDCs in the Vazcún valley does not necessarily imply that the city of Baños will be affected. The Ecuadorian authorities had to face this situation when Tungurahua reawoke in 1999, prompting complete evacuation of Baños city. The absence of early PDCs led the population to move back to Baños and learn how to live with an active volcano (Tobin and Whiteford, 2002; Lane et al., 2003; Ramón, 2010). The scoria flows that went down in 2006 and halted ~2 km upstream of Baños suggested that PDCs are not as dangerous as previously thought (historical archives never reported any fatalities from PDCs in Vazcún and Baños) and it is now fairly clear that many people in the city would not escape in case of a new evacuation alert. These concerns, beyond the effort made by the IG-EPN to operate properly all volcano monitoring devices and alert systems, point out the need to investigate the cognitive perception of PDC hazards and the psychosocial judgment of volcanic risks in the population of Baños. We currently focus our research at Tungurahua on these issues, in order to develop new communication strategies for higher crisis management effectiveness.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2015.06.052.

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