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Published in:
Journal of Volcanology and Geothermal Research

DOI:
[10.1016/j.jvolgeores.2008.05.019](https://doi.org/10.1016/j.jvolgeores.2008.05.019)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2008

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Le Pennec, J. -L., Jaya, D., Samaniego, P., Ramon, P., Yanez, S. M., Egred, J., & van der Plicht, J. (2008). The AD 1300-1700 eruptive periods at Tungurahua volcano, Ecuador, revealed by historical narratives, stratigraphy and radiocarbon dating. *Journal of Volcanology and Geothermal Research*, 176(1), 70-81. <https://doi.org/10.1016/j.jvolgeores.2008.05.019>

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The AD 1300–1700 eruptive periods at Tungurahua volcano, Ecuador, revealed by historical narratives, stratigraphy and radiocarbon dating

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ARTICLE INFO

Article history:

Received 14 February 2008

Accepted 26 May 2008

Available online 6 June 2008

Keywords:

Tungurahua

Ecuador

radiocarbon dating

Integration Period

volcanic hazards

ABSTRACT

Tungurahua is a frequently active and hazardous volcano of the Ecuadorian Andes that has experienced pyroclastic flow-forming eruption in 1773, 1886, 1916–18 and 2006–08. Earlier eruptions in Late Pre-Hispanic and Early Colonial times have remained poorly known and are debated in the literature. To reconstruct the eruptive chronology in that time interval we examine relevant historical narratives recently found in Sevilla, Spain, and Rome, Italy, and we combine stratigraphic field constraints with 22 new radiocarbon age determinations. Results show that pyroclastic flow-forming eruptions and tephra falls took place repeatedly since ~700 ¹⁴C yr BP, when the Tungurahua region was already populated. Radiocarbon ages averaging around 625 yr BP reveal a period of notable eruptive activity in the 14th century (Late Integration cultural period). The associated andesitic eruptions produced ash and scoria falls of regional extent and left scoria flow deposits on the western flanks of the edifice. The fact that Tungurahua was known by the Puruhás Indians as a volcano at the time of the Spanish Conquest in 1533 perhaps refers to these eruptions. A group of ages ranging from 380 to 270 yr BP is attributed to younger periods of activity that also predates the 1773 event, and calibration results yield eruption dates from late 15th to late 17th centuries (i.e. Inca and Early Colonial Periods). The historical narratives mention an Early Colonial eruption between the Spanish Conquest and the end of the 16th century, followed by a distinct eruptive period in the 1640s. The descriptions are vague but point to destructive eruptions likely accompanied by pyroclastic flows. The dated tephras consist of andesitic scoria flow deposits and the contemporaneous fallout layers occur to the west. These findings reveal that the eruption recurrence rate at Tungurahua is at least one pyroclastic flow-forming event per century since the 13th century and the occurrence of such eruptions in 2006–08 is thus fully consistent with the rate inferred for the past seven centuries. In addition, historical chronicles suggest that a notch opened in the crater margin during the 1640 decade, as has occurred repeatedly in the past millennium at Tungurahua. Such small-volume collapse events represent a previously unrecognized source of hazards which deserve special attention for risk assessment purposes in the context of the currently ongoing eruption.

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1. Introduction

Reconstructing the recent geological history of volcanoes is an essential step for evaluating the eruption recurrence pattern at potentially hazardous edifices. This requires establishing a robust chronological framework of the eruptive events using appropriate methods (Simkin and Siebert, 1994). Local historical archives document more than 3000 years of activity (e.g. Etna in Italy, Branca and Del Carlo, 2004) but written records are too short in most volcanic

regions to adequately evaluate eruption return rates. Beyond historical times the radiocarbon method is widely used to date Holocene and Late Pleistocene volcanic events, which in turn is helpful for archeological and other studies (e.g., Lowe et al., 2000; Siebe et al., 2004; Friedrich et al., 2006 and references therein).

The Andes comprise many active volcanoes whose recent eruptive history remains poorly known. Reliable accounts exist since the 18th century but major Andean eruptions described in Spanish chronicles of the 16th and 17th centuries (a time interval hereafter referred to as the “Early Colonial Period”) are generally vague or ambiguous, leading to uncertain eruption dates and/or locations, as is apparent in the catalogue of active volcanoes (Simkin and Siebert, 1994). This is the case for several volcanoes in the Ecuadorian Andes including Tungurahua.

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Tungurahua is an andesitic stratovolcano (5023 m a.s.l.) situated in the southern part of the Northern Andean Volcanic Zone about 120 km south of Ecuador's capital, Quito (Fig. 1). Along with El Altar and Sangay volcanoes, Tungurahua defines the southern part of the Eastern volcanic range, which belongs to the “Cordillera Real” (Eastern Cordillera), about 35 km East of the western Cordillera (Hall et al., this volume).

The 3 km-high, steep-sided edifice rests upon a metamorphic basement of Paleozoic to Cretaceous age and is surrounded by three main rivers named Puela, Chambo and Pastaza, on its south, west and north base, respectively (Fig. 2).

The geology and structure of the volcano have been summarized in Hall et al. (1999), Molina et al. (2005) and Le Pennec et al. (2006) who showed that the edifice comprises three building stages, Tungurahua I, II and III, and at least two flank failure events. The young, presently active Tungurahua III edifice grew in the horseshoe-shaped amphitheater carved about 3000 years ago on the western flank of Tungurahua's stratocone (Fig. 3a and b). Recent geological and hazard studies have concluded that Tungurahua ranks among the most dangerous volcanoes of Ecuador as it threatens about 25,000 inhabitants living in the neighborhood (INECEL, 1989; Almeida and Ramón, 1991; Hall et al., 1999; Le Pennec et al., 2006). Based on historical documentation Almeida and Ramón (1991) showed that pyroclastic flow-forming eruptions took place in 1773, 1886 and 1916–1918, a list to which the 2006–08 events can be added. Previous studies (Hall et al., 1999; Le Pennec et al., 2006) have also revealed a period of strong eruptive activity from the ~7th to the 11th centuries (Early–Mid Integration Periods). In between, the activity before the Spanish Conquest, i.e. in the Late Integration (14th and 15th centuries) and Inca Periods (~1470–1533) remains essentially unknown, while the authenticity and exact date of Early Colonial eruptions (16th and 17th centuries) is debated in the literature.

In this paper we present new evidence for eruptive activity at Tungurahua volcano from Late Integration to Early Colonial times. This is achieved by examining relevant historical narratives found in Sevilla, Spain, in Quito's documentation section of the General Archives of the Indies (“Archivo General de Indias”, AGI), and in Rome, Italy, in the “Archivum Romanum Societatis Iesu” (ARSI) (Egred, 1999, 2002; Moreno Yáñez, 2006). In addition, we combine field constraints with 22 new radiocarbon age determinations, which reveal that the volcano experienced repeated pyroclastic flow-forming eruptions and ash falls from Late Integration to Early Colonial times. It is known that the radiocarbon technique is not well suited to date events younger than a few centuries because of calibration problems (Trumbore, 2000). However, various case-studies have highlighted the usefulness of corroborating historical records with ^{14}C dating, as exemplified in paleoseismology (e.g., Sieh and Williams, 1990; Becker and Davenport, 2003) tsunami research (Suzuki et al., 2008; Bruins et al., 2008) and volcanology (Okuno et al., 1998; Friedrich et al., 2006; Robin et al., this volume).

Our radiocarbon data were obtained at the Center for Isotope Research, Groningen University, The Netherlands. Large samples were analyzed using the Proportional Gas Counting (PGC) technique and are indexed below with GrN prefix. Small samples were dated by Acceleration Mass Spectrometry (AMS) and are numbered below with GrA prefix. In this study all radiocarbon ages are quoted in BP (i.e. in ^{14}C years before 1950 AD), while calibrated dates are reported in cal AD, as recommended by van der Plicht and Hogg (2006). All other dates are quoted AD.

For practical reasons that apply particularly well to Tungurahua's eruptive behavior, we define in this paper an “eruptive period” as a time interval of several months to years that may comprise successive “eruptive phases” characterized by alternating eruption styles (e.g. strombolian, vulcanian, etc.), which typically last from hours to weeks.

Fig. 1. Location map of Tungurahua volcano in the volcanic arc of the Ecuadorian Andes. Dark grayed elements are Quaternary volcanic centers. The light gray area is the Interandean valley.

2. Previous historical and ^{14}C constraints

The Spanish conquest in Central Ecuador took place in 1533 and this year defines the beginning of the Historical Period in that region. Some documents (Cieza de León, 1553; Wolf, 1873, 1892) unambiguously describe a significant ash fall when the Conquistadores arrived in the Interandean Valley of Ecuador. The exact location of the Conquistadores at the moment of the ash fall is not clear, they were probably in the Western Cordillera somewhere in the Chimborazo area (Fig. 1). Cotopaxi and Tungurahua volcanoes are contenders for this ash fall episode because both lie upwind in the Eastern Cordillera region. Some chronicles have attributed the fallout event to a volcano in Quito's vicinity, with no further precision, while others assigned it to Cotopaxi (Velasco, 1789; Wolf, 1873, 1892) or to Tungurahua (González Suárez, 1892; Martínez, 1903). On the whole, the above documents bring little evidence to discriminate between these sources.

Another possible Tungurahua eruption was raised by La Condamine (1751) who met a 100 year-old man near Riobamba who remembered that the volcano erupted strongly around 1641. González Suárez (1892) also mentioned that before the 1773 eruption the volcano had remained quiet and no signs of activity were reported for the past 128 years, which implies possible activity around 1645. Martínez (1932) questioned the authenticity of the ca. 1640 event and argued that Velasco (1789), who made no mention of an eruption ca. 1640, could not have ignored the event while living in the region in the 18th century since such phenomena would not have been forgotten. Martínez (1932) concluded that if the 1533 event was somewhat doubtful, the ca. 1640 eruption was even less plausible.

Velasco (1789) also mentioned that the top of a volcano had collapsed and assigned the event to Cotopaxi, but geological work there offer no evidence of summit failure in Early Colonial times (P. Mothes, pers. comm., 2005).

Fig. 2. Topographic map of Tungurahua volcano (modified after Hall et al., 1999) with place names cited in the text. The heavy dashed line coincides with the topographic scarp formed during the ~3000 year-old collapse, as interpreted by Molina et al. (2005) and Le Pennec et al. (2006). Other dashed lines are roads. S1, S2, S3, S4 and S5 are localities of sections 1 to 5 in Fig. 4.

More recently during the INECEL (1989) hazard assessment program, scoria flow deposits on the lower western flank of Tungurahua were dated at 288 ± 110 and 290 ± 140 BP and both ages were assigned to the ca. 1640 date mentioned in historical archives. However, these ^{14}C ages with very large uncertainties translate to unreliable calendar age ranges and the deposits may as well be assigned to any other eruption between the 18th and 20th centuries. Based on stratigraphic analyses Almeida and Ramón (1991) correlated various scoria flow and pumice fall deposits to the ca. 1640 date. Yet, Hall et al. (1999) radiocarbon dated a deposit attributed by Almeida and Ramón (1991) to the ca. 1640 eruption and obtained an age older than 1000 BP. Because the postulated ca. 1640 eruption lacked both reliable eyewitness descriptions and stratigraphic confirmation, Hall et al. (1999) followed Egred (1989) to conclude that the authenticity of this eruption was doubtful and discarded it from their eruption list.

3. Evidence for eruptive activity from Late Integration to Early Colonial times

3.1. Historical narratives

The archives that describe the severe ash fall experienced by the Conquistadores in 1533 are undoubtedly related to a substantial eruption in the Interandean valley. Cieza de León (1553) pointed out

that the Conquistadores encountered a “furious flood full of large rock pieces” fed by a volcano when they arrived in the Interandean Valley. Consistently, Jiménez de la Espada (1878, reedited 1965) mentioned large mud and debris flows affecting Latacunga city (Fig. 1) and nearby villages as well as ash emissions. Documents recently examined in Quito’s documentation section of AGI unambiguously assign the ash fall and sediment flows described above to ice-clad Cotopaxi (Anonymous 1, undated document, AGI) and not to the still remote Tungurahua volcano.

The first report of the Tungurahua region is mentioned in Cieza de León (1553) who wrote that Indian populations were living east of Riobamba in a mountain range called “Tinguragua”. Although the origin of the name Tungurahua is not well established, different sources suggest that the Indians of the Puruhás community, which lived in the Ambato–Riobamba region before the Conquest (Fig. 1), already considered Tungurahua as a volcano and not simply as a mountain (Moreno Yáñez, 2006). This raises the possibility of some activity before the Spanish Conquest.

A document called “Description of the communities in the Jurisdiction of the city of Villar Don Pardo [i.e. Riobamba], in the Purugayes province” (Anonymous 2, around 1605, cited in Torres de Mendoza, 1868) mentions the village of Baños near Tungurahua, and an ash fall that affected areas located west of the volcano as far as 350 km (“60 leguas”). In addition, the chronicle claims that before the Spaniards Tungurahua had a pyramidal shape with a very spiny,

Fig. 3. Views of the studied deposits in different places of the volcano. (a) Shaded relief map of the Tungurahua area with labeled localities (red circles) showing sites where pictures of the Figure were taken. OVT is Tungurahua Volcano Observatory in the Patate River valley. (b) A view of Tungurahua volcano from the OVT, ~15 km from the crater. The dashed line coincides with the Mandur Ravine which marks the northern limit of the ~3000 year-old collapse scarp, as interpreted by Molina et al. (2005) and Le Pennec et al. (2006). (c) Section of pyroclastic flow deposits in the Vazcún Valley showing places where charcoals have been collected for ^{14}C analysis. (d) Section in the Pingullo ravine showing the dated scoria flow deposits. (e) Natural section East of Cahuaji village exposing a massive deposit and a large dated tree log. Note some angular clasts in the lower part. This deposit occurs beneath prevailing winds and the absence of any overlying tephra fall layer on top of it points to a young age (max. few centuries). (f) A pottery sherd collected at Pailuco in a deposit dated at 240 ± 40 BP and displaying molded features of Colonial style.

needle-like summit which showed no evidence of “burning”, but it started “flaming up” at the beginning of the Conquest and “its fires and glows are spectacular phenomena that signify calamities”. A second explicit report found in the “Annual letter from 1642 to 1652 of the Province of the New Kingdom and Quito”, dated in Santa Fe (now Bogotá, Colombia) on October 23, 1652 (ARSI, 1652), mentions that a very high mountain called “Tunguragua” near the city of Riobamba caused such a desolation in the years 1644 and 1645 that many people in the vicinity wanted to move the site of their village. Further investigation in AGI has offered a description of the 1773 eruption (Anonymous 3, undated document, AGI) which reports that Tungurahua triggered “tremendous damages from a hole opened near the summit in the years 1640 and 1645, and the volcano remained unchanged for 128 years, although it produced smokes from time to

time”. Gonzáles Suárez (1892) was probably informed by this document.

Other chronicles claim that a village called Cacha near Riobamba city disappeared completely in 1640. Velasco (1789) has described the event noticing that it was a “major phenomenon associated with volcanoes” and it is therefore sensible to link this event to the confirmed ca. 1640 activity of Tungurahua. However, other historical sources are supportive of a non-volcanic landslide on hill flanks southwest of Riobamba similar to those that occurred in 2006.

3.2. Field and radiocarbon evidences

Gully walls and road cuts on and around the volcano expose volcanic and epiclastic sequences belonging dominantly to the activity

Fig. 4. Selected stratigraphic sections of the volcano's lower flanks that illustrate the position of the dated deposits in the upper part of the young Tungurahua depositional sequence. Sections are simplified for readability and localities are shown in Fig. 2. * Ages inferred from Hall et al. (1999) and other unpublished results.

of the Tungurahua III edifice. The successions mainly consist of scoria flow deposits rich in xenolithic fragments, alternating with fallout layers and their concomitant reworked materials. Monotonous facies and compositional characteristics make stratigraphic correlations of mostly disconnected outcrops difficult to achieve. However, the dacite pumice layers from ca. 1250 BP (Mid Integration Period) and January 1886 offer key horizons that help to investigate the eruptive history of the past millennium (Fig. 4). During a detailed geological study we have radiocarbon dated disconnected deposits that reveal repeated periods of activity after the 1250 BP eruption, in particular after ~700 BP (Table 1).

The outcrops occur in ravines on the lower flanks of the edifice, while others are dispersed around the volcano. Their main characteristics are summarized below from the north to the west and south of the edifice.

The Vazcún valley is a deep gorge cutting the northern flank of Tungurahua that widens near the city of Baños (Fig. 2). The depositional area down the valley comprises an old upper terrace of pre-Hispanic age (Mothes et al., 2004; Le Pennec et al., 2006) and a younger lower terrace. Historical archives describe the emplacement of pyroclastic flows or hot lahars near the old church of Baños in 1773 (Egred, 1999). Their deposits were identified in a section near the

Table 1

Results of radiocarbon age determinations and calendar age conversion analyses. The calibration is done using the CALIB5 program (Stuiver and Reimer, 1993; Stuiver et al., 2005) with the Northern Hemisphere atmospheric data of the Incal04 calibration curve (Reimer et al., 2004). Converted dates are given by the program with year resolution but are rounded off to the nearest significant 5 yr AD. 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 145 prov. S.A. 1956, Ecuador Zone 17N (84°W–78°W). The sampling sites are located on a map in Fig. 5

Lab. code ^a	Type of sample (pretreatment) ^b	Locality	UTM ^c coordinates	¹⁴ C age, in years BP ($\pm 1\sigma$) ^d	$\delta^{13}\text{C}$ (‰)	Calendar age AD 1σ (68.3%)	Relative area (%)	Calendar age AD 2σ (94.5%)	Relative area (%)
GrN-27905	Small charcoal fragments (A)	Upper southern wall of Rea ravine	777280 9836766	55 $\pm$ 60	–25.38			1680–1950	100
GrN-27899	One wood branch (A)	Vazcún valley, inner terrace, west side of El Salado River, near pool	785970 9844660	190 $\pm$ 30	–25.35	1660–1685 1735–1755 1760–1805 1935–1950	21 16 46 17	1645–1695 1725–1815 1915–1950	24 57 19
GrA-28978	Small charcoal pieces (AAA)	Pailuco road in Palitahua area.	778692 9831482	240 $\pm$ 40	–24.64	1530–1540 1635–1680 1765–1775 1775–1800 1940–1950	5 55 3 29 8	1520–1595 1615–1685 1730–1810 1925–1950	15 43 33 9
GrN-29338	Thin carbonized branches with preserved leaves (AAA)	Vazcún valley, inner terrace, west side of El Salado River, near pool	785970 9844660	270 $\pm$ 25	–25.70	1525–1545 1545–1550 1630–1665	25 4 71	1520–1580 1580–1595 1620–1670 1780–1800	37 2 57 4
GrN-27851	Piece of a tree log (A)	Vazcún valley, inner terrace near pool (spa)	785945 9844892	300 $\pm$ 30	–25.01	1520–1575 1580–1590 1625–1650	67 6 27	1485–1605 1610–1655	73 27
GrN-28030	Tree log (wood), 8–10 cm from rim (A)	West side of Chambo river near Yuibug	776306 9834190	320 $\pm$ 15	–23.92	1520–1530 1535–1580 1580–1595 1620–1635	13 57 11 19	1495–1510 1510–1605 1615–1645	3 77 20
GrN-29482	Part of carbonized tree log (AAA)	Pingullo ravine, upper layer above scoria fall layer	778058 9840356	320 $\pm$ 35	–25.66	1515–1600 1615–1645	78 22	1475–1650	100
GrN-28431	Part of carbonized tree log (AAA)	Pingullo ravine, upper layer above scoria fall layer	778058 9840356	330 $\pm$ 30	–25.64	1495–1505 1510–1530 1540–1605 1615–1630	6 17 59 18	1475–1645	100
GrN-28429	Part of a carbonized tree log (AAA)	Confesionario Ravine, scoria flow deposit below A.D. 1886 pumice fall layer.	777400 9835946	360 $\pm$ 30	–23.22	1465–1525 1570–1585 1590–1625	58 7 35	1450–1530 1540–1635	50 50
GrA-28975	Part of a small carbonized branch (AA)	Mandur Ravine, right on top of an older lava flow.	781357 9843760	365 $\pm$ 35	–25.75	1455–1525 1575–1585 1590–1625	64 5 31	1445–1530 1540–1635	52 48
GrN-29481	Part of a carbonized tree log (AAA)	Confesionario Ravine, scoria flow deposit below A.D. 1886 pumice fall layer.	777400 9835946	365 $\pm$ 35	–23.26	1450–1500 1505–1515 1600–1620	72 8 20	1445–1525 1570–1630	70 30
GrA-28974	Small piece of charcoal (A)	Mandur Ravine, scoria flow right on top of a series of older lava flows	781357 9843760	430 $\pm$ 35	–25.39	1430–1475	100	1415–1520 1595–1620	93 7
GrA-31242	One piece of charcoal (AAA)	Grayish scoria flow, upper Rea ravine, south wall	777280 9836766	485 $\pm$ 30	–25.79	1415–1445	100	1405–1450	100
GrN-28968	Portion of a carbonized branch (A)	Mandur Ravine, right on top of an older lava flow	781357 9843760	540 $\pm$ 40	–25.22	1325–1345 1390–1430	28 72	1305–1365 1385–1445	39 61
GrA-24093	Small charcoal pieces (A)	Road cut near Nabuso Bajo	774627 9823740	560 $\pm$ 40	–25.70	1315–1355 1390–1420	52 48	1300–1370 1380–1435	54 46
GrN-27486	Charcoal fragments (A)	Motilonas ravine, upper block and ash flow deposit	778026 9839566	590 $\pm$ 50	–24.11	1305–1365 1385–1410	72 28	1290–1425	100
GrN-27487	Charcoal fragments (A)	Motilonas ravine, upper block and ash flow deposit	778026 9839566	610 $\pm$ 50	–25.04	1300–1370 1380–1400	80 20	1280–1415	100
GrN-28430	Collection of carbonized twigs (AAA)	Pingullo ravine (see section 2 in Fig. 4)	778058 9840356	610 $\pm$ 20	–22.84	1325–1340 1390–1410	19 81	1320–1350 1385–1420	33 67
GrN-28733	Crushed charcoal, probably a single fragment (A)	Quebrada seca ravine, tributary of Rea ravine, in block and ash flow deposit	779430 9836356	645 $\pm$ 25	–22.13	1290–1310 1360–1390	40 60	1280–1325 1345–1395	43 57
GrN-29336	One carbonized branch 5 cm diameter (AAA)	Scoria flow deposits, la Pyramide Ravine (see Fig. 3)	778550 9841282	650 $\pm$ 30	–23.19	1285–1315 1355–1390	44 56	1280–1330 1340–1395	46 54
GrA-28579	Charcoal fragments (A)	Chacauco terrace	778692 9841816	685 $\pm$ 30	–25.67	1275–1300 1365–1385	73 27	1265–1315 1355–1390	67 33
GrN-28894	Carbonized branches (A)	Lower scoria flow deposit, Pingullo ravine	778058 9840356	765 $\pm$ 25	–22.69	1225–1235 1240–1250 1250–1280	6 12 82	1220–1280	100

Baños cemetery by Mothes et al. (2004) who AMS-dated charcoal pieces at 195 ± 40 and 185 ± 40 BP. Near the El Salado Spa (Fig. 2), a road cut in the lower terrace exposes two main pyroclastic flow deposits separated by reworked gravel layers (Fig. 3c, and section 1 in Fig. 4).

A conventional PGC age of 190 ± 30 BP (GrN-27899, Table 1) obtained from a tree branch fragment collected in the upper layer supports the 1773 eruption (see also the calibration section below). The underlying scoria flow deposit also contains charcoal near its base and a sample of undifferentiated carbonized branches yielded an age of 300 ± 30 BP (GrN-27851, Table 1 and Fig. 4 section 1) while a set of thin charred twigs that still had carbonized leaves attached was dated at 270 ± 25 BP (GrN-29338). This lower scoria flow deposit is poorly sorted and comprises a coarse-grained fraction (10–60 cm in length) composed of angular to sub-angular xenolithic clasts, of which many are oxidized, as well as a few dark andesitic cauliflower bombs with chilled margins (58.3 wt.% SiO_2). The matrix is made up of similar elements in the sand-size range and the amount of fine ash is relatively small. Lapilli-sized sub-rounded pumice clasts are also found as incorporated material.

Deep in the Mandur ravine (Fig. 2), a scoria flow unit with dark andesitic bombs rests on top of a series of thin andesite lava flows. Carbonized wood pieces were PGC-dated at 540 ± 40 BP (GrN-28968) while smaller charcoal pieces were AMS-dated at 430 ± 35 (GrA-28974) and 365 ± 35 BP (GrA-28975) (Table 1, Fig. 5). In the La Piramide

gully, 25–30 m thick scoria flow deposits have been exposed in the course of the ongoing eruption and a carbonized branch sampled near the road has given an age of 650 ± 35 BP (GrN-29336). Similar scoria flow deposits with more distal facies characteristics are exposed on the Chacauco terrace, in front of the La Piramide gully on the other side of the Rio Chambo canyon, and have been AMS-dated on charcoal to 685 ± 35 (GrA-28974). Along with stratigraphic position and morphological context, these close age determinations support that the Chacauco deposits are correlated to the dated scoria flow deposits of the La Piramide gully (Fig. 5).

A more extended succession is exposed in the Pingullo ravine (Figs. 2 and 3d, and section 2 in Fig. 4). Carbonized branches in a scoria flow layer in the lower part of the section were dated at 765 ± 25 BP (GrN-28894). This layer is covered by light-toned ash beds, above which a series of grayish scoria flow deposits are lying. Carbonized twigs in these units yielded an age of 610 ± 20 BP (GrN-28430). A prominent khaki-colored debris flow layer with dispersed angular blocks rests discordantly on these old pyroclastic deposits. The debris flow layer is in turn covered by a 5 cm-thick scoria fall horizon and a dark-toned scoria flow deposit, in which pieces of a carbonized trunk yielded ages of 320 ± 35 (GrN-29482) and 330 ± 30 BP (GrN-28431) (Table 1, Fig. 5).

Nearby road cuts show that the succession is capped by a layer of scoria and ash probably deposited during the 1773 eruption, and by

Fig. 5. Sites where charcoal and wood samples have been collected for radiocarbon age determination, with results indicated. * Weighted average values of two ^{14}C data (see Table 1). The dashed line coincides with the scarp formed during the ~3000 year-old flank failure event.

the distinctive 1886 pumice horizon. More to the south, near the top of the Motilones ravine succession, a scoria flow tongue beneath the 1886 pumice layer has been dated at 590 ± 50 (GrN-27486) and 610 ± 50 BP (GrN-27487) (Table 1, section 4 in Fig. 4).

On the southern wall of the ~70 m-deep Rea ravine the 1886 pumice is recognized below the incipient present-day soil that is mixed with scoria clasts of the 1918 eruption. Below, a 20–30 cm-thick massive andesitic ash layer is dated at 55 ± 60 (GrN-27905) and the sub-continuous scoria bed at its base is assigned to the 1773 eruption.

Two prominent scoria flow units are observed underneath. The upper one is a coarse-grained, poorly sorted deposit with cauliflower bombs and many 20–40 cm-large oxidized xenoclasts. The lower unit is a grayish, moderately sorted deposit that has been AMS-dated at 430 ± 35 BP (GrA-28974). Large charcoal pieces in similar scoria flow deposits exposed in the upper part of the nearby Confesionario gully yielded ages of 360 ± 30 (GrN-28429) and 380 ± 25 BP (GrN-29481) (Table 1, Fig. 5), consistent with the age of the overlying 1886 pumice (section 5 in Fig. 4).

About 1 km south-southwest of the Confesionario ravine, the Cahuaji area forms a flat-topped sedimentary fan that is only slightly

incised by erosion. It is bounded to the east by a prominent cliff carved by the Rio Chambo which exposes a massive grayish, 15–25 m-thick volcanoclastic deposit (Fig. 3e). This latter is poorly to non-consolidated and contains few 10–40 cm-large angular volcanic blocks, as well as dispersed intensely vesiculated scoria clasts (56–57 wt.% SiO_2) in the ashy matrix. Rare non-carbonized wood fragments are also found and a piece sampled inside a large log yielded a radiocarbon age of 320 ± 15 BP (GrN-28030) (Table 1, Fig. 3e).

Hillsides located south of the volcano are draped with volcanoclastic material composed mainly of ash and disseminated scoria and pumice clasts. Along road cuts at Pailuco locality, near Palitahua village (Figs. 2 and 5), scattered pumice lapilli close to the very top of the exposure identify the 1886 dacitic eruption. Below, a 2–3 m-thick, poorly stratified ash layer with dispersed scoria clasts is exposed and small charcoal pieces collected in the middle part of the section yielded an AMS age of 240 ± 40 BP (Table 1, Fig. 5). At the same stratigraphic level, the deposit contains pottery sherds of variable size and appearance and their age is discussed below. Similar deposits chiefly composed of andesitic ash with disseminated scoria clasts are also exposed along road cuts more to the south near Nabuso village

Fig. 6. Density probability functions for the calibrated radiocarbon ages obtained in this study plotted using the CALIB program of Stuiver and Reimer (1993), 2005 version (Stuiver et al., 2005), and the atmospheric data of Reimer et al. (2004). Small and large ticks limit 1 and 2σ date ranges, respectively. * The approximate periods of apparent low (grayed time intervals) and high levels of activity are inferred by combining historical narratives with stratigraphic and radiocarbon constraints as summarized in the discussion section.

Fig. 7. Distribution of our age determinations on the radiocarbon time scale (in BP), with 1σ uncertainties indicated. The clustering of PGC ages in two groups between 200 and 700 BP (i.e., the “old group” is from 540 to 650 BP and the “young group” is from 380 to 270 BP) points to at least two eruptive periods with pyroclastic flow-forming events.

(Fig. 5). Many pottery sherds are found 1–1.5 m below the present-day surface and small pieces of associated charcoal have been AMS-dated at 560 ± 40 BP (GrA-24093).

3.3. Calibration of radiocarbon data

In order to convert our ^{14}C age determinations into calendar dates we have used the CALIB5 program of Stuiver and Reimer (1993) and Stuiver et al. (2005) with Northern Hemisphere atmospheric data (Intcal04 curve of Reimer et al., 2004). The program yields dates with year precision but our results are rounded to the nearest significant 5 AD (Table 1). The density probability functions for all radiocarbon determinations obtained in this work are displayed in Fig. 6.

The plot confirms that the sample dated at 190 ± 30 BP matches the 1773 eruption date at both $1-2\sigma$ confidence levels. Conversely, the oldest sample collected in the deepest scoria flow deposit of the Pingullo ravine (765 ± 25 BP) point to an eruption in the 13th century, i.e. in the Mid Integration Period (Table 1, Fig. 6). Between these extremes, the ^{14}C ages are distributed all along the radiocarbon timescale from 685 to 240 BP (Fig. 7).

However, the age of the large samples analyzed using PGC techniques show two incipient clusters (GrN laboratory numbers noted in bold text in Fig. 6 and solid bars in Fig. 7) with an “old group” of data between 650 and 540 BP and a “young group” between 380 and 270 BP. In contrast results obtained on small, probably less representative AMS samples appear more scattered (GrA numbers in Fig. 6 and open bars in Fig. 7). The calibrated dates equally cluster around two main periods, either in the 14th century or from mid-15th to mid-17th centuries (Table 1, Fig. 6).

Our collection of wood and charcoal pieces encompass samples of uneven size and quality, leading to variable precision in age determination, as illustrated by the age distribution of PGC and AMS determinations on the ^{14}C timescale (Fig. 7). In fact, some PGC ages may be difficult to interpret if they correspond to wood that died years or decades before incorporation in the pyroclastic flow deposits. The large samples GrN-28429, 28431, 29481, 29482 yielded ages in the range 320–380 BP and may reflect this process. Similarly, some AMS samples mix small fragments representing elements of unknown position in branches or tree trunks, which in turn may be significantly older than the eruption date. On the other hand, two selected charcoal and wood pieces offered more favorable calibration conditions. Sample GrN-29338 dated at 270 ± 25 BP consisted of thin charred twigs with attached leaves and is considered as the most reliable sample for calibration purpose because the presence of attached leaves implies that the bush was still alive at the moment of the eruption. Also, by comparison with current plants of the same genus now living on the volcano, the growth duration of the twigs, which were 2–5 mm in diameter, should have been less than 2–3 yr. Another sample (GrN-28030) collected from about 8–10 cm inside a large non-carbonized tree log in the Cahuaji area (Fig. 3e), yielded an age of 320 ± 15 BP, also suitable for detailed calibration analysis. Given these good conditions, we calibrated these ^{14}C determinations at a high resolution using the

“single year” calibration curve UWSY98 of Stuiver et al. (1998) as they have 1σ values <30 yr and both ages are younger than the limit where the single year curve merges into the smoother Intcal04 curve (Reimer et al., 2004). Results are given in Table 2, neglecting very short time intervals ($<2-3$ yr) with relative areas $<1\%$. The density probability function for sample GrN-29338 is illustrated in Fig. 8a and the resulting calibrated date ranges are plotted in Fig. 8b against their calculated relative area values (2σ confidence level).

Results for sample GrN-29338 at 270 ± 25 BP provide a good match for the 1640 decade with relative areas higher than 45% at both $1-2\sigma$ confidence levels, corresponding to date ranges cal AD 1640–1658 and 1632–1666, respectively. The relative areas in the 16th century are also high with 33% at the 2σ level for the period cal AD 1523–1560 and 20% at the 1σ level in the date range cal AD 1528–1542. Results for sample GrN-28030 dated at 320 ± 15 BP also yield calendar intervals mostly in the Early colonial Period (Table 2). Although growth rings are not clear in tropical tree sections and not necessarily annual, the distance of 8–

Table 2

Results of the calendar age conversion analysis for samples GrN-29338 and GrN-28030 using the CALIB5 program (Stuiver and Reimer, 1993) and the single year UWSY98 calibration curve (Stuiver et al., 1998). Time intervals with relative area values $>10\%$ are indicated in bold text while those with relative area values $<1\%$ are omitted (duration shorter than 2–3 yr) and their sum represents less than 4% of the total area

Sample number and ^{14}C age BP $\pm 1\sigma$	Calendar age AD 1σ (68.3%)	Relative area (%)	Calendar age AD 2σ (94.5 %)	Relative area (%)
GrN-29338 270 ± 25	1528–1542	20.7	1523–1560	32.9
	1545–1545	1.0	1561–1567	2.3
	1546–1553	11.3	1568–1575	3.4
	1554–1556	2.6	1588–1592	1.5
	1572–1573	1.3	1632–1666	45.1
	1635–1638	5.8	1781–1797	8.7
	1638–1640	1.8		
	1640–1658	45.2		
	1659–1661	3.2		
	1787–1788	1.9		
	1792–1793	1.4		
	1794–1796	2.0		
	1517–1517	1.3	1494–1507	4.1
	1521–1522	1.0	1512–1518	3.7
	1523–1531	11.2	1520–1602	70.6
GrN-28030 320 ± 15	1533–1536	5.3	1617–1642	20.4
	1539–1547	11.2		
	1549–1551	2.9		
	1552–1560	10.1		
	1561–1567	9.1		
	1568–1575	11.0		
	1577–1580	4.0		
	1582–1584	2.3		
	1585–1586	2.6		
	1588–1592	4.7		
	1593–1596	3.0		
	1618–1621	4.4		
	1622–1625	3.1		
	1627–1630	3.2		
	1632–1635	4.0		
	1637–1640	4.4

Fig. 8. (a) High resolution calibration of sample GrN-29338 using the CALIB program, 2005 version (Stuiver and Reimer, 1993; Stuiver et al., 2005) and the UWSY98 single year curve of Stuiver et al. (1998). The Gaussian radiocarbon age determination is shown with its 1σ (dark gray) and 2σ (light gray) uncertainties. These color codes also apply to the density probability function on the calibrated axis. (b) Relative area results (in %) obtained from the calibration analysis at the 2σ confidence level. High relative area values appear from 1520 to 1560 and from 1630 to 1670, while smaller values correlate to short time intervals between 1560 and 1600. Relative area values smaller than 1% (typically corresponding to calibrated intervals <2 – 3 yr) are not shown.

10 cm between the margin of the log and the sampling site might well represent a duration of 10–40 yr before the tree's death, assuming a ring growth-rate of 1–4 mm per yr, respectively. In this case, the growth date range of the wood sample is at the 2σ level most likely in the range of cal AD 1520–1602 or 1617–1642 (relative areas of 70% and 20%, respectively), which would finally give a tree's death date in the range of ~1530–1680.

4. Discussion

4.1. Eruptive chronology since ~700 BP

The distribution of our age determinations on the radiocarbon timescale has revealed two clusters of the PGC ages, in contrast to more scattered AMS results (Fig. 7). We infer that these two PGC groups reflect periods of relatively high activity with pyroclastic flow-forming eruptions (Fig. 6).

The old PGC group has an age around 625 ± 13 BP (weighted average of five PGC data) corresponding in calibrated terms to the 14th century (Late Integration Period, Fig. 6). The fact that Puruhás Indians considered Tungurahua as a volcano may refer to eruptive activity at that time. The young group comprises PGC data between 380 and 270 BP, which yield calendar intervals from mid-15th to late-17th centuries (i.e. between the ends of the Late Integration and Early Colonial Periods, Table 1, Fig. 6).

The stratigraphic relation between both groups is exposed in the Pingullo ravine (section 2 in Fig. 4) where an apparent repose period is suggested by the time gap separating the lower scoria flow unit dated at 610 ± 20 BP from the upper one dated at 320 ± 35 and 330 ± 30 BP (Table 1). This is consistent with the notable discordance and the debris flow layer observed between the dated pyroclastic deposits.

On the other hand, these large calendar intervals imply that each PGC group may encompass several eruptive periods separated by years to decades of quiescence. For example, the group between 380 and 270 BP comprises at least two eruptive periods inferred from historical archives. The chronicle written around 1605 states that some activity took place after the Spanish Conquest in 1533 and before the beginning of the 17th century while later accounts confirm the occurrence of a distinct eruptive period in the 1640 decade, thus validating the reports of La Condamine (1751) and González Suárez (1892). These narratives may describe mild strombolian–vulcanian activity without pyroclastic flows but allusions to “calamities” in the second part of the 16th century, and to the fact that “people wanted to move the site of their village” in the 1640 decade, point to severe impacts on human activities. By comparison with more recent eruptions, it suggests that these Early Colonial events were of some importance (at least VEI 2, probably VEI 3) and most likely accompanied by pyroclastic flows. It is not possible, however, to distinguish the deposits of each Early Colonial eruptive period in the field because of similar facies and compositional characteristics, and limited ^{14}C age resolution.

4.2. Deposits on the lower flanks of the volcano

The scoria flow deposits correlated to the ~625 BP eruption(s) are identified in a narrow area of the volcano in La Piramide ravine and Chacauco terrace, in Pingullo and Motilones gullies and in a tributary of the Rea ravine. By comparison with younger eruptions, this distribution and associated depositional and compositional characteristics point to a “typical” andesitic Tungurahua eruption, i.e. a VEI 3 event comprising scoria flows and violent strombolian to vulcanian–subplinian eruption columns.

The evidence for pyroclastic flow activity in Early Colonial times seems well established in the Vascún Valley where charcoals yield dates in the range cal AD 1520–1670, consistent with the overlying 1773 layer (Fig. 3c, section 1 in Fig. 4). Similar deposits dated around 300–380 BP in the Pingullo, Rea, and Confesionario ravines (Fig. 5) also point to emplacement dates from mid-16th to mid-17th centuries (Fig. 6), but we preferably correlate them to Early Colonial eruptions because these PGC ages were obtained on portions of carbonized trunks.

The three radiocarbon ages obtained for a single scoria flow unit in the deepest levels of the Mandur ravine succession span from 540 to 365 BP (Figs. 2 and 5) and can be assigned either to the eruptive period (s) around 625 BP (the fact that the 540 BP age is a PGC result favors this interpretation), or to an Early Colonial age, as suggested by AMS data. Based upon the dating uncertainties the assignation can not be resolved.

4.3. Deposits SW and S of the volcano

The relatively thick and massive deposits of the Cahuaji area dated at 320 ± 15 BP occur disconnected from contemporaneous scoria flow deposits and their origin is less clear. The deposits contain intensely vesiculated scoria (56–57 wt.% SiO_2), but lack cauliflower bombs and the organic remains are not carbonized. These deposits may result either from a relatively cold scoria flow or perhaps the distal part of a flow, or from a mass flow related to a dam-break after a pyroclastic flow-forming eruption.

The origin of the dated massive ash and scoria layers at Pailuco, near Palitahua village, and Nabuso (Fig. 5) is also uncertain. The AMS-dated charcoals collected at Pailuco occur at levels where some ceramic sherds show greenish painting and glaze coating (Fig. 3f), which are features undisputedly attributed to a Colonial origin (Idrovo Urigüen, 1990, 2000). Also, one sherd (Fig. 3f) represents the base of a container that exhibits a molded mark (probably the letter f) indicative of Colonial times (Porras, 1987). These sherds and charcoal

occur in the andesitic horizon well below the 1886 dacite pumice, i.e. about 1–2 m below the present-day surface. Such depths lead us to assign these dated levels to an Early Colonial eruption instead of 1773. Similarly, the AMS age of charcoals collected in the andesitic ash and scoria deposits at Nabuso (Fig. 5) is contemporaneous with the activity identified in the 14th century (Late Integration Period). A grayish, fine-grained andesitic ash fall horizon that underlies the debris flow deposit left after the 1698 Ambato earthquake (Fig. 1) has been attributed to Tungurahua volcano by Vásconez (2006). These ash layers were likely deposited during the eruptive periods identified above.

4.4. Frequency, size and style of the eruptions

Previous works have estimated a recurrence rate for pyroclastic flow-forming eruptions at Tungurahua since the Spanish Conquest at one event per 1 to 1.5 century (INECEL, 1989; Almeida and Ramón, 1991; Hall et al., 1999). Our constraints on the eruptive chronology since the 13th century imply that the volcano experienced *at least* seven pyroclastic flow-forming periods (including the 1999-ongoing period) in the past seven centuries, i.e. at least 1 event per century.

The deposits of the 14th to 17th centuries resemble those emplaced during the well-documented eruptions of 1918 (Martínez, 1932) and 2006 (Samaniego et al., 2007), which suggest comparable eruptive dynamics. The scoria flows have limited runout distances of 5–7 km and their deposits comprise ravine-ponded breccias associated to finer-grained overbank surge layers, recalling the granular flows described at other andesitic volcanoes (e.g., Arenal in Costa Rica, Avarado and Soto, 2002; Colima in Mexico, Saucedo et al., 2002; Ngauruhoe in New Zealand, Lube et al., 2007). The interbedded scoria fall layers are composed of highly vesiculated scoria clasts with rare xenolithic elements. We infer that the eruption dynamics of the Late Integration to Early Colonial periods were dominated by violent strombolian to vulcanian–subplinian styles with VEI 2 to 3.

The amount of dense non-oxidized and oxidized xenoclasts in the scoria flow deposits reveal that the flows incorporated material in the conduit or during transport (gully walls, bed rocks), but it may also result from erosion or collapse of the crater margins during eruption. These events could have occurred in the 1640s and correspond to the narrative, which claims that the volcano erupted in 1773 “from a hole opened near the summit in the years 1640 and 1645”. Consistently, lavas and ballistic tephra erupted since the 17th century (1773, 1886, 1918 and 2006–08) chiefly accumulated on the northwest margin of the crater and probably filled an indentation opened before the 1773 eruption as concluded by Egred (1999). The report of Velasco (1789), which mentioned that the top of a volcano had collapsed, may refer to the ca. 1640 eruptions, thus explaining that the volcano no longer had the spiny, needle-shaped summit reported in the chronicles prior to the 16th century. Moreover, recent works (Le Pennec et al., 2006) reveal that small-volume collapse of the crater margin has occurred repeatedly in the past millennium at Tungurahua and the youngest events have dominantly affected the west–northwestern area of the crater (e.g. in ~1350 BP, ~1250 BP, 1640 decade, 1886); the resulting deposits have been identified in the Chambo and Patate river valleys at the base of the edifice. Such crater wall collapse and associated pyroclastic flows may also result from processes described by Alvarado and Soto (2002) at Arenal volcano, Costa Rica.

Small-scale collapse events of the summit area represent a previously unrecognized source of hazards at Tungurahua. Several villages (e.g., Chacauco, Fig. 1) and crucial economic infrastructures (e.g. the main road and bridge at Las Juntas, Fig. 1) sit in areas previously covered by small-volume debris avalanche deposits. Such gravitational instabilities are promoted by intense fumarolic alteration and fracturing, and by the steep-sided morphology of the upper part of the cone (Fig. 3b). About two years after the onset of the 1999-ongoing eruptive period, new active fumaroles appeared along

a ~1 km-long fracture on the northern flank of the volcano above Baños city, at about 4000 m a.s.l. These superficial manifestations highlight the importance of carefully monitoring any morphological change and deformation of the summit area.

5. Conclusion

The eruptive activity of Tungurahua volcano in the Late Integration and Early Colonial periods has remained poorly known and debated. In this study we have combined appropriate historical narratives with stratigraphic constraints and 22 new ^{14}C age determinations to infer the chronology and nature of the activity in that period of time.

A group of ^{14}C ages averaging around 625 BP reveals a period of eruptive activity in the 14th century (Late Integration Period). These andesitic eruptions produced ash and scoria falls of regional distribution and left scoria flow deposits on the western flanks of the edifice. The fact that Tungurahua was known by Puruhás Indians as a volcano at the time of the Spanish Conquest perhaps refers to these eruptions.

A group of ages ranging from 380 to 270 BP is correlated to younger eruptions that also predates the 1773 event. Historical narratives mention Early Colonial activity between the Spanish Conquest in 1533 and the end of the 16th century, followed by a distinct eruptive period in the 1640 decade. The descriptions are vague, but point to damaging eruptions likely accompanied by pyroclastic flows. The dated remains were collected in andesitic scoria flow deposits on the northern to southwestern parts of the volcano and the ash fall layers also occur predominantly westward.

Our findings have implications for risk assessment at Tungurahua. First, the reconstructed eruptive chronology yields a recurrence rate of *at least* one pyroclastic flow-forming event per century back to the 13th century. Hence, the occurrence of pyroclastic flow eruptions in July–August 2006 and February 2008 is fully consistent with the rate inferred for the past seven centuries. Secondly, historical chronicles suggest that a notch formed in the crater margin during the 1640 decade, as has occurred repeatedly in the past millennium at Tungurahua. Such small-volume crater wall-collapse events represent a previously unrecognized source of hazards which deserves special attention in the context of the ongoing eruption.

Acknowledgements

This work has been carried out during a cooperation program between the French Institut de Recherche pour le Développement (IRD) and the Instituto Geofísico of Quito's National Polytechnic school (IG-EPN), Ecuador. Discussions with J.P. Eissen, C. Robin, M.L. Hall, P. Mothes were appreciated. G. de Saulieu offered an expertise of the ceramic sherds collected in this study and helped with bibliographical sources. This paper has been reviewed by S. Cronin, J.L. Macías and J. Johnson. An early version has been revised by C. Gardner, H. Delgado Granados, M.L. Hall, J.-C. Thouret, while P. Lanos examined the ^{14}C calibration section. Financial support by IRD and European Community project “Communities Affected by Tungurahua: Mitigating the Risks of Living Near an Active Volcano” (ECHO/TPS/219/2003/04002).

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