Journal of Volcanology and Geothermal Research 176 (2008) 70–81

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

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 ^{14}C 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.

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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doi:10.1016/j.jvolgeores.2008.05.019

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.

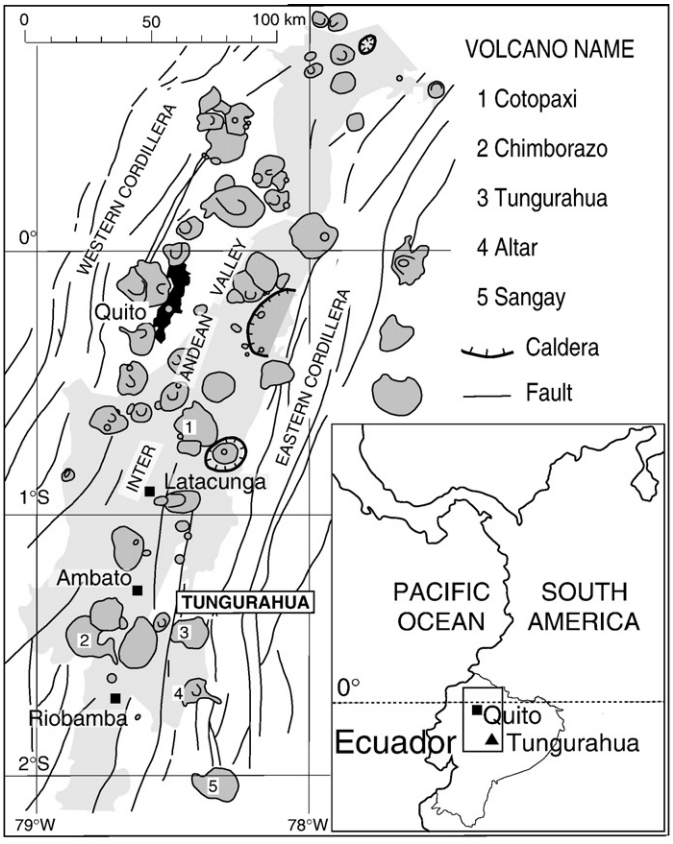

Fig. 1. Location map of Tungurahua volcano in the volcanic arc of the Ecuadorian Andes. Dark grayed elements are Quaternary volcanic centers. The light gray area is the Interandean valley.

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 Yánez, 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.

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 (Gonzáles 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. Gonzáles 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).