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Late Holocene history of Chaitén Volcano: New evidence for a 17th century eruption

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ABSTRACT. Prior to May 2008, it was thought that the last eruption of Chaitén Volcano occurred more than 5,000 years ago, a rather long quiescent period for a volcano in such an active arc segment. However, increasingly more Holocene eruptions are being identified. This article presents both geological and historical evidence for late Holocene eruptive activity in the 17th century (AD 1625-1658), which included an explosive rhyolitic eruption that produced pumice ash fallout east of the volcano and caused channel aggradation in the Chaitén River. The extents of tephra fall and channel aggradation were similar to those of May 2008. Fine ash, pumice and obsidian fragments in the pre-2008 deposits are unequivocally derived from Chaitén Volcano. This finding has important implications for hazards assessment in the area and suggests the eruptive frequency and magnitude should be more thoroughly studied.

Keywords: Historical eruption, Ash fallout, Channel aggradation, Chaitén Volcano.

RESUMEN. Historia holoceno tardía del volcán Chaitén: nueva evidencia de una erupción en el siglo XVII. Antes de la erupción de mayo de 2008, se pensaba que la última erupción del volcán Chaitén había ocurrido hace más de 5.000 años, lo que sugería un muy largo período de reposo en un segmento de arco volcánico tan activo. Sin embargo, cada vez más erupciones holocenas han sido identificadas. Este artículo presenta evidencia geológica e histórica de actividad eruptiva en el siglo XVII (AD 1625-1658) que incluye una erupción explosiva riolítica que generó un depósito de caída al oriente del volcán y produjo agradación del cauce del río Chaitén. Ambos efectos son similares a lo observado en la erupción de mayo 2008. La ceniza fina y los fragmentos de obsidiana y pómez en el depósito pre-2008 fuero inequívocamente derivados del volcán Chaitén. Este hallazgo tiene importantes consecuencias para la evaluación del peligro volcánico en el área y sugiere que tanto la frecuencia eruptiva como la magnitud de los eventos deben ser rigurosamente estudiadas.

Palabras clave: Erupción histórica, Caída de ceniza, Agradación de canal, Volcán Chaitén.

1. Introduction

Chaitén Volcano is a small rhyolite volcano in southern Chile (Fig. 1). Prior to the onset of its May 2008 eruption, it was thought that Chaitén Volcano had been dormant for thousands of years (Lara, 2009; Carn *et al*., 2009). In fact, Naranjo and Stern (2004) suggested that the former dome (the youngest geological unit before the emplacement of the 2008-2009 dome complex) was older than *ca.* 5.6 ka and was perhaps associated with an early Holocene explosive eruption dated at *ca.* 9.4 ka. This apparent long quiescent period is suspicious in the Southern Andes where a high eruptive flux has been reported (*e.g*., up to 0.9 km^3/ky in Puyehue-Cordón Caulle Volcanic Complex at 40ºS; Singer *et al*., 2008) with at least 3-4 significant eruptions (VEI>3) each century (Siebert *et al*., 2010; Dzierma and Wehrmann, 2012). Historical eyewitness reports of unrest or eruption of Chaitén Volcano were also absent, which is not surprising because human settlement in the Chaitén Bay area did not begin until 1921. Accordingly, Chaitén Volcano was ranked 40/95 in the national threat score (considering 95 geologically active volcanoes; Lara *et al*., 2006a; modified by Lara *et al*., 2011; methodology based on Ewert, 2007) and, therefore, not considered as a high-priority volcano for monitoring before 2008.

However, recent studies (*e.g*., Watt *et al.*, 2009; Watt *et al.,* 2013, this volume; Amigo *et al.*, 2013, this volume) have identified evidence of several explosive eruptions of Chaitén Volcano in the Holocene. Moreover, we present evidence suggesting eruptive activity only a few centuries ago. The aim of this article is to present geological evidence of an historical eruption that produced a thin rhyolitic tephra layer downwind and caused aggradation along the Chaitén River system. This evidence is consistent with information gleaned from historical documents.

2. Pre-2008 eruptive record

The geologic record of Chaitén Volcano's past eruptions had been obscured by dense temperate rain forest vegetation and limited fresh exposures along rivers prior to the 2008 eruption and eruption-related channel erosion. Lack of exposure precluded

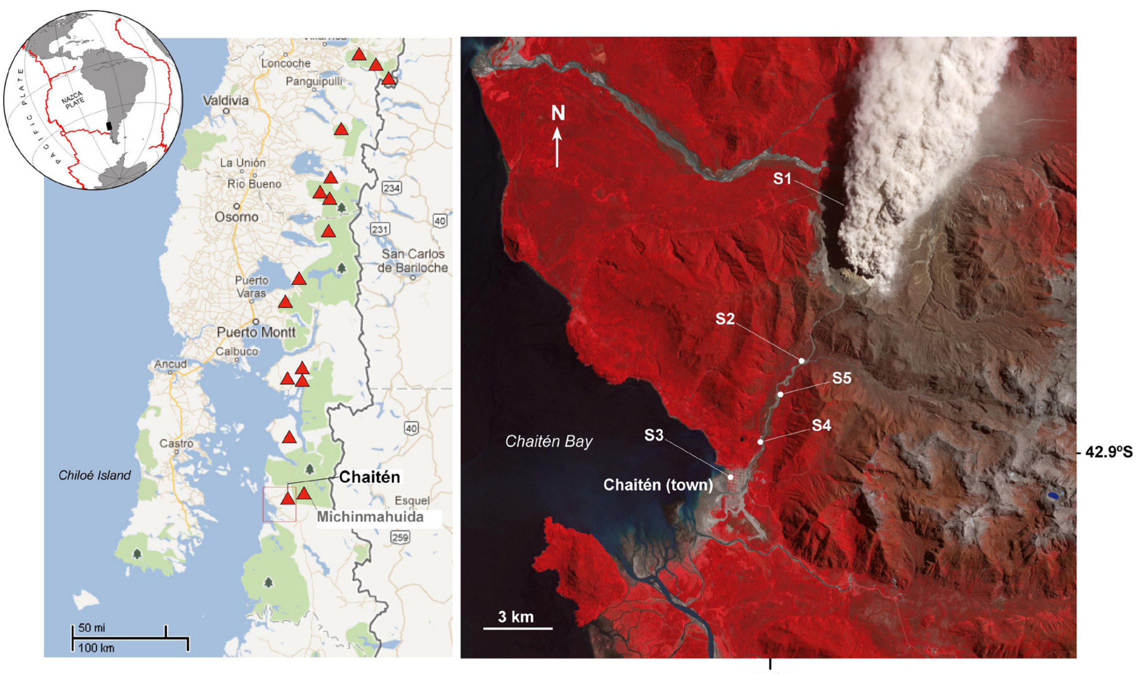

FIG. 1. Location map of Chaitén Volcano (left; red triangles for active volcanoes) and Chaitén town, now severely damaged by rapid channel aggradation. Radiocarbon sampling sites (right; see Table 1 for details) are shown on a Terra-ASTER image acquired on 19 January 2009 (courtesy of NASA/GSFC/MET/ERSDAC/JAROS and U.S./Japan ASTER Science Team).

TABLE 1. CHAITÉN ^{14}C AGES.

Site No.	Location	Lab No.	Sample No.	Method	^{13}C/^{12}C ratio	Radiocarbon age yBP (±1 σ)	Calibrated age (2σ) cal AD
S1	S42º49.294/W72º39.435'	WW8094	CH#7-1	AMS	-25.27	405±25	1453-1625
S2	S42º52.274'/W72º40.439'	WW8097	CH 100123-1	AMS	-26.54	375±30	1464-1632
S3	S42º55.259'/W72º42.445'	Beta 248142	LL260708-3A	Conventional	-25.7	320±40	1480-1795
S4	S42º54.204'/W72º41.663'	Beta 305811	110305-1.8	Conventional	-25.9	240±30	1639-1805
S1	S42º49.294/W72º39.435'	Beta 330347	CH#7-2	AMS	-24.1	240±30	1639-1805
S5	S42º53.170'/W72º41.112'	Beta 305812	110396-3.2	Conventional	-25.6	230±30	1642-1952
S3	S42º55.259'/W72º42.445'	Beta 248143	LL260708-3B	AMS	-31.5	210±40	1646-1953

Note: Pretreatment was acid/alkali/acid. WW8094 and WW8097 were performed at AMS Lab of the United States Geological Survey; the others at Beta Analytic Inc. Dates reported as radiocarbon years before present ('present' is 1950 by convention). Calibration was done with SHCal04 Southern hemisphere atmospheric curve (McCormac *et al*., 2004) using OxCal v4.1.7 (Bronk Ramsey, 2009).

a detailed survey of the geology, and only two main units were evident at the time of 2008 eruption: a pre-caldera volcanic pile and a post-caldera rhyolitic dome. The latter was considered older than 5.6 ka based on ages from archeological sites where grey obsidian artifacts, derived from the Chaitén dome, were found (Stern *et al*., 2002). The 3 km wide caldera would have been produced by an explosive event characterized by pumice fall and pyroclastic-surge deposits. Such deposits north of the volcano yielded radiocarbon ages of *ca*. 9.8-9.4 ka (Naranjo and Stern, 2004). A distant downwind Holocene rhyolitic pumice-fall deposit, dated *ca*. 4.2 ka, was assigned to the neighboring Michinmahuida Volcano (Naranjo and Stern, 2004) despite the fact that its geochemical signature resembled that of Chaitén. More recently, Watt *et al*. (2013, this volume) reinterpreted the stratigraphic record near the volcano and suggested that proximal pumice-fall deposits and a pair of younger pumice and ash horizons originated from Chaitén Volcano within the past 5 ky. Amigo *et al.* (2013, this volume) reached similar conclusions from studies of both proximal and distal outcrops (Fig. 2a). Thus, Chaitén Volcano has been much more active than previously thought, and consequently its threat score has been increased (Lara *et al.*, 2011).

3. The 2008-2009 eruption and clues to the .historical record

The May 2008-2009 eruptive events of Chaitén Volcano have been ranked as a VEI 4-5 eruption (Lara, 2009; Carn *et al*., 2009; Watt *et al*., 2009; Alfano *et al*., 2011). The explosive stage started at 08:00 UTC (04:00 local time) on 2 May and occurred over about a week. An effusive stage began about 12 May. Several explosions, the largest of which occurred on 6 May, produced subplinian columns and erupted *ca*. 1 km^3 of bulk rhyolitic tephra (76% SiO_2; Reich *et al*., 2009; Castro and Dingwell, 2009; Watt *et al*., 2009; Alfano *et al*., 2011), similar to the known composition of the pre-2008 dome complex (López-Escobar *et al*., 1993). Minor column-collapse and explosively generated pyroclastic density currents were restricted to the proximal area within the caldera and to both the northern and eastern flanks of the volcano (Major *et al*., 2013, this volume). As a consequence, thick tephra fall blanketed the proximal area, with thicknesses exceeding 1 m in the headwaters of the Chaitén River (Alfano *et al*., 2011; Pierson *et al*., 2013). On 11 May modest rainfall triggered rapid sedimentation by a prolonged and complex lahar-flood, which filled the lower Chaitén River channel and caused overbank flooding and subsequent avulsion of Chaitén River through the town of Chaitén (Pierson *et al*., 2013).

A remarkable consequence of the rapid channel aggradation and consequent avulsion was the formation of large gullies through the town, exposing the pre-settlement stratigraphy (Fig. 3). Pumice-rich alluvial strata crop out only half a meter below the first evidence of settlement, identified by the so-called 'envaralado', which is the log cover that people used for stabilizing the marshland before construction. Thus,

FIG. 2. Photographs of the 17th century deposits. **a.** Ash fall deposit (marked with a white arrow), more than 10 cm thick, located 25 km downwind from Chaitén Volcano. Typically, its base is composed of yellowish coarse ash while the center and the top of the deposit is mostly white fine ash. The ash is buried by a weak fine-grained soil forming the present surface; **b.** Photograph of an outcrop on the outer slope of the north rim of Chaitén caldera (site S1, Fig.1). The deposit above the white line was emplaced in 2008 by a pyroclastic density current (PDC). An older charcoal-bearing PDC deposit lies immediately below the 2008 PDC. The shovel handle is about 50 cm long; **c.** Tree stump in growth position (above and to left of person, marked with a white arrow) that was rooted in a paleosol formed on a bouldery paleoterrace in the Chaitén River valley, about 5 km downstream of the Chaitén caldera (site S2, Fig.1). This tree was likely killed by rapid burial in volcaniclastic alluvial sediment (visible in vertical bank behind stump) that had been mobilized during the penultimate major eruptive episode of Chaitén Volcano. This indistinctly stratified, horizontally bedded, moderately sorted, coarse volcanic sand with pumice-rich lenses and layers is the type of sediment typically deposited in shallow rivers carrying very high sediment loads. Similar beds were deposited in May 2008 by a sediment-laden water flood in the river during the 2008 eruption of Chaitén.

at shallow depth below the surface, the geological record provides evidence of previously unrecognized volcanic events.

4. Geologic evidence of an historical eruption

4.1. Tephra deposit southeast of Chaitén caldera

A white, rhyolite tephra-fall deposit has been recognized atop an early Holocene pyroclastic sequence between 15 and 30 km southeast of Chaitén Volcano (Fig. 2a). The tephra is a coarse to fine ash layer with an irregular thickness of 5 to 15 cm; it has not been observed in distal areas (>50km). It directly overlies a dacite pumice lapilli fall deposit derived from Michinmahuida Volcano and dated at 390±40 ^{14}C yBP (Amigo *et al*., 2013, this volume). The white ash-fall deposit is the most recent tephra identified in this area, and as discussed in a later section, both its composition and distribution point to Chaitén Volcano as its source. On the basis of thickness measurements in the field, this deposit is considered to have originated from an eruption similar in magnitude to the explosive phase of the 2008 eruption.

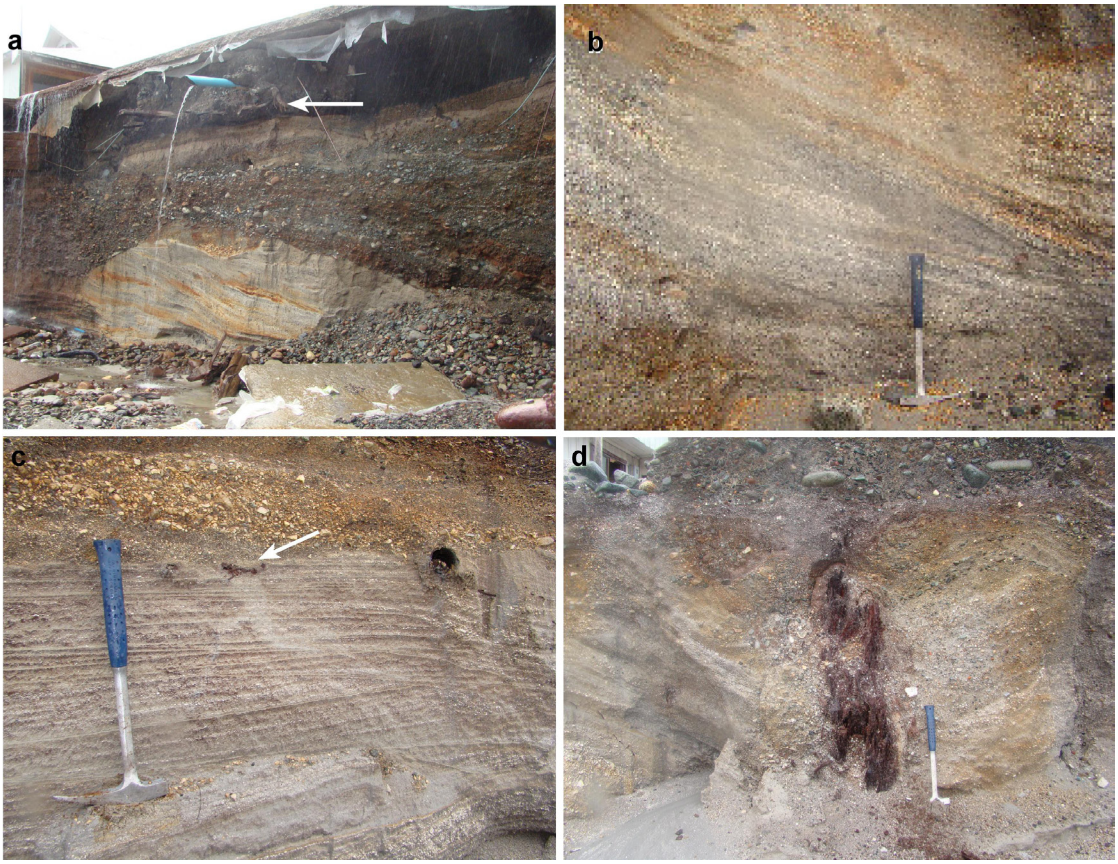

FIG. 3. Photographs of alluvial deposits beneath Chaitén town; **a.** Steeply dipping assemblage of pumice layers and fine ash from site S3 (see Fig. 1 for location details). White arrow shows the wood level that marks the onset of settlement in the Chaitén area at the beginning of the 20th century; **b.** Detail of (a) where centimeter-thick layers show asymptotic lamination towards the base; **c.** Fine laminated pumice-rich layers from site 2 that contain a dated wood sample; **d.** Section with a tree in growth position encased by eruption-related flood sediment.

4.2. Pyroclastic deposits at the caldera rim

Rills on the northern rim of the Chaitén caldera expose an orange-brown pyroclastic density current (PDC) deposit that, aside from color, strongly resembles the 2008 PDC deposit that overlies it (Major *et al*., 2013, this volume) (Fig. 2b). The orange-brown deposit is more than one meter thick and is composed of ash, lapilli, and blocks as much as 20 cm in diameter. The clasts are composed dominantly of pumice and subordinately of obsidian and other rhyolitic lithics. Abundant centimeter-to-decimeter diameter carbonized tree limbs are embedded in the deposit and are oriented roughly down-slope. No evidence of a distal facies has been found yet.

4.3. Volcaniclastic deposits in the Chaitén River valley

Evidence of pre-2008 eruption-related sedimentation is found along the middle to lower reaches of the Chaitén River valley. There, latest pre-2008 deposits were observed and sampled in freshly exposed faces of alluvial valley-fill terraces and along the walls of gullies newly eroded through Chaitén town. Exposures along the valley and in town also show substantial deposition of volcaniclastic sediment related to the recent 2008 eruptive activity at Chaitén Volcano.

The modern Chaitén River valley terraces are stratigraphically complex, having several different generations of valley-fill deposits stacked on top of, and inset against, buried paleoterraces that originally had surfaces at different elevations. In many places, the 2008-2009 deposits form the uppermost layer on the modern terraces. On a low paleoterrace surface slightly more than a kilometer upstream of town, pre-2008 volcaniclastic deposits (beneath the modern forest soil) overlie a well-developed paleosol formed on still older volcaniclastic sediment. This paleosol hosted a mature forest that was buried and killed by the aggrading river bed during a major episode of pre-2008 eruptive activity. The deposits of this younger pre-2008 sequence are composed of a fine-grained, hyperconcentrated-flow lahar deposit at the base of the sequence (70 cm thick), overlain (without evidence of a time break) by about 2 m of horizontally bedded, pumice-rich sand and gravel having the sedimentologic characteristics of highly sediment-laden water-flood deposits. On higher paleoterrace surfaces farther upstream, the hyperconcentrated-flow lahar deposit is absent, and only horizontally bedded, volcaniclastic, muddy flood deposits 2-5 m thick encase the trunks of trees buried by channel aggradation (Fig. 2c). These post-eruptive fluvial deposits were probably emplaced within one or a few years of eruptive activity, based on observations of aggradation following eruptions elsewhere (Newhall and Punongbayan, 1996; Major *et al*., 2000; Hayes *et al*., 2002; Pierson *et al*., 2011). At all visited locations, the modern soil developed on the pre-2008 deposits is immature (O and weak A horizons±incipient B_{ox} horizon).

The depositional sequence immediately beneath Chaitén town (at least 2 m thick) is also composed of eruption-related volcaniclastic sediment (Fig.3). It consists of a basal, fine-grained, pumice-rich lahar (hyperconcentrated flow or dilute debris flow) deposit overlain by several meters of horizontally bedded, pumice-rich fluvial sand alternating with pumice-gravel lenses and beds (Fig. 3a-c). In places, these beds are capped by massive pumice-rich fluvial gravel, which largely fills channels cut into the aggradational fill. These deposits appear to have formed a prograding alluvial fan (providing relatively flat, stable terrain for construction of the town), which likely graded seaward into a delta in Chaitén Bay. Foreset beds are found along a coastal exposure. At one location a tree was buried and probably killed by the deposits (Fig. 3d). These pre-2008 deposits are remarkably similar to the overlying 2008-2009 deposits, suggesting that the older deposits were produced by processes similar to those that emplaced the modern deposits: at least one rainfall-generated hyperconcentrated flow (lahar), combined with one or more sediment-laden floods (Pierson *et al*., 2013). The abundance of pumice in the pre-2008 Chaitén valley and town deposits, similar to that in the 2008-2009 flood-related deposits in the Chaitén River, and a lack of evidence for a correlative pumiceous PDC deposit on the valley floor suggest that sediments must have been eroded from tephra deposited in the Chaitén River watershed from an eruption of Chaitén Volcano.

4.4. Radiometric dating of pre-2008 deposits

Five radiocarbon ages were obtained from pre-2008 alluvial deposits in the Chaitén River valley (Table 1), and the dates fall into two groups. The older two dates overlap: **1.** A date of 320±40 ^{14}C yBP, from outer wood extracted from the most external rings (bark absent; only a partially abraded surface exposed) of a tree in growth position beneath Chaitén town (Table 1; site 3 in Fig. 1). The tree was killed when it was engulfed by aggrading sediment. **2.** A date of 375±30 ^{14}C yBP from a root of a tree stump in growth position that was engulfed and killed in 3.1 m of horizontally bedded pumice-rich sand and gravel in the middle Chaitén River valley (Table 1; site 2). The three younger radiocarbon ages also overlap: **1.** A date of 210±40 14C yBP obtained on detrital wood from a branch fragment contained within the horizontally bedded deposits engulfing the first tree stump noted above (Table 1; site 3); **2.** A date of 240±30 ^{14}C yBP from the outer rings of a detrital log buried in a pumice-rich, fine-grained lahar deposit located in the lower Chaitén River valley (site 4); and **3.** A date of 230±30 ^{14}C yBP obtained from the outer rings (immediately beneath bark) of a tree stump in growth position that was buried by 4.6 m of horizontally bedded, pumice-rich, gravelly fluvial sand in the middle Chaitén River valley (site 5).

In addition, two radiocarbon ages were obtained for the PDC deposit at the caldera rim (Table 1; site 1). The outermost 5-10 rings from two well-preserved carbonized limbs yielded radiocarbon ages of 405±25 ^{14}C yBP and 240±30 ^{14}C yBP (Table 1, site 1). The older date is similar to those in the older group of dates from alluvial deposits, while the younger date falls into the younger group.

Recent studies have shown that sedimentation responses in rivers during and following eruptions can be rapid, similar to the sedimentation response to the 2008 Chaitén eruption (Newhall and Punongbayan, 1996; Hayes *et al*., 2002; Pierson *et al*., 2011;

Pierson *et al*., 2013). If sediment remobilization and downstream transport was similarly rapid during the major penultimate eruption of Chaitén Volcano, ages of the pyroclastic deposits and the downstream valley-fill deposits should be similar.

On the other hand, there is some implicit uncertainty in the radiometric dating of organic material embedded in the volcaniclastic deposits. For example, if collected wood fragments came from the inner parts of tree roots or trunks, some offset in ages would be expected. In addition, natural variations in atmospheric ^{14}C production can lead to complications in calibrating standard radiocarbon ages, resulting in multiple intercepts on the calibration curves for a single radiocarbon date (Taylor, 2001). Such is the case for the Chaitén radiocarbon dates under consideration, and this significantly increases the calendar age range for a specified analytical error. Thus, even though the conventional radiocarbon dates for the two groups of dates in Table 1 appear significantly different, there is overlap in the calendar age ranges. The 2σ intervals of both groups yield an overall range of AD 1516-1658 if they are merged, but their most probable ranges overlap between AD 1625 and 1658 (Fig. 4), which is in good agreement with the age of the PDC deposit at the caldera rim and the historical accounts that we describe below.

5. Historical reports of Chaitén's eruptive activity

Because of the remoteness of Chaitén Bay, the area around Chaitén Volcano was uninhabited until the first half of the 20th century. The first inhabitants reached the bay in 1921; by 1933 there were just 3 houses. Chaitén village had about 4,600 inhabitants by 2008. The prolific record of historical eruptions in southern Chile, in particular from Villarrica and Llaima Volcanoes (*e.g*., Petit-Breuilh, 2004), is due to the presence of Jesuit priests and foreign explorers and begins in the 16th century. But the record is sparse south of Reloncaví fjord (about 41ºS), and Petit-Breuilh (2004) compiled only uncertain reports of volcanic activity for Chaitén and Michinmahuida Volcanoes. In fact, Chaitén Volcano was designated as possibly active in 1742, 1766, 1834-35, and 1870. Interestingly, Michinmahuida Volcano is also cited as potentially active in 1656, 1742, 1800, 1833 and 1834-35. However, from an historical perspective, most of these reports are questionable and should be considered with care.

A few maps or nautical charts produced during the 16th and 17th centuries provide a remarkable source of geographical information about the inland territory at this latitude. In particular, the Dutch expedition of Hendrik Brouwer in 1643 produced the first detailed maps of the Chiloé region (Vázquez de Acuña, 1992). After this first cartographic effort, the Spanish kingdom ordered a new reconnaissance of the Chilean coast and several maps were produced. In 1669, a map of the archipelago (Fig. 5) showed for the first time in the Chaitén Bay area a single erupting volcano depicted as a cone with red flames on top (Guarda and Moreno, 2008). Although the 1669 map is anonymous and differs from the famous map frequently attributted to Alonso de Ovalle, a Jesuit priest on Chiloé Island at that time, and was probably drawn earlier by Lázaro de las Casas, a former resident of the Chiloé mission and an experienced explorer (Moreno, 2007). Cartographic typology of the 1669 map is more typical of the first half of the 17th century and hence probably dates to *ca*. 1644, when Jesuit priests started the cartographic reconnaissance (Moreno, 2007). Interestingly, none the maps and charts drawn after 1670 include any representation of erupting volcanoes. The question of whether the erupting volcanoes are real observations or just artistic imagery can be addressed considering that these charts had a practical purpose and great value, because no other geographical reference was available at this time. As an illustration of the significance of these maps in the 17th century, a copy of the 1669 nautical chart was captured in 1671 by the well-known buccaneer Sir Henry Morgan during his assault on Panama (*e.g*., Black, 1989). Thus, on the basis of the 17th century nautical chart, there was probably an eruption shortly after 1644. This eruption might have lasted for several years (at least as a degassing process) but must have ended no later than 1670. From the nautical charts it is hard to determine whether this eruption was at Chaitén or Michinmahuida Volcanoes (Fig. 5), although the proximity of the shoreline to the erupting volcano suggests it might be Chaitén.

6. Source analysis: confirming the origin of ash fallout and alluvial beds

Because the watershed of the Chaitén River can catch volcanic sediment erupted from Chaitén and Michinmahuida (and even Huequi) Volcanoes, the

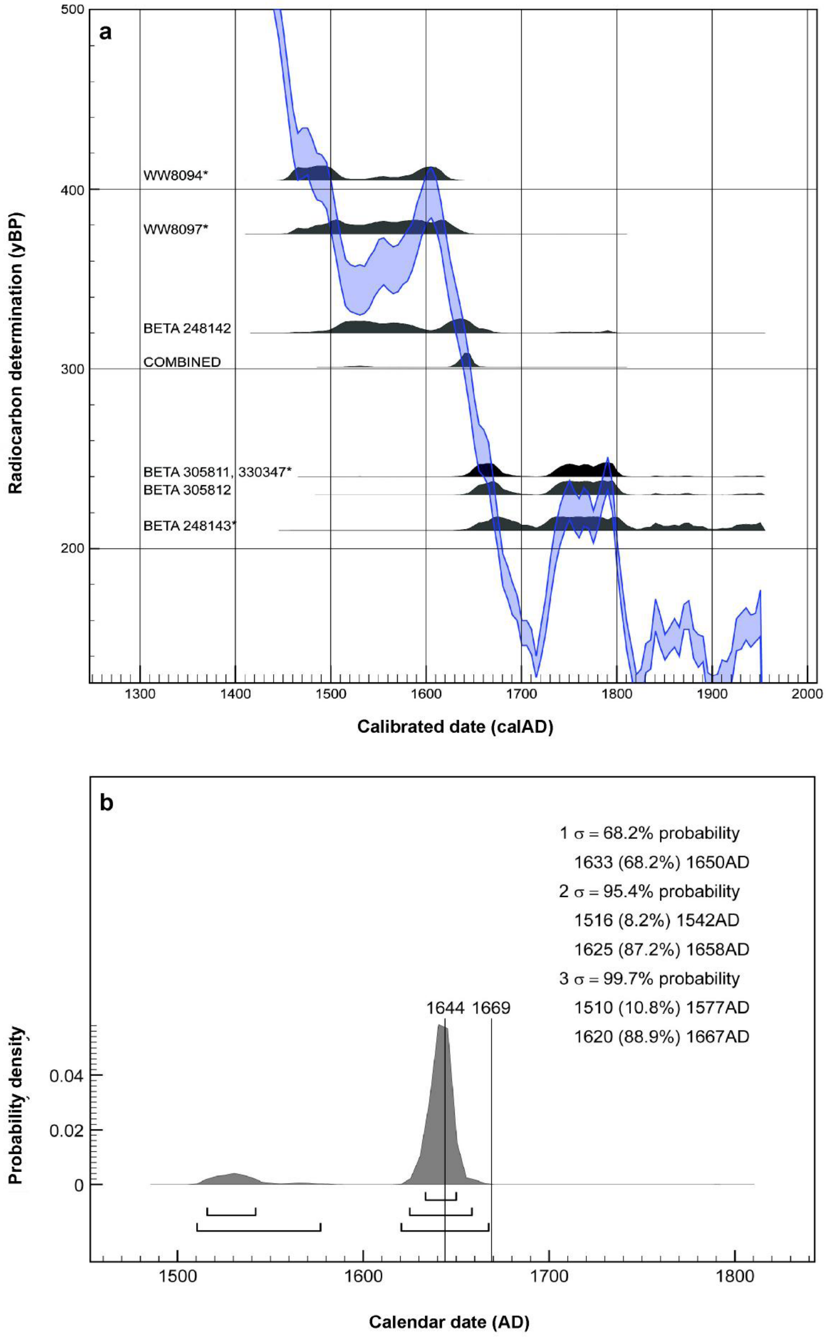

FIG. 4. **a.** Plot showing probability density functions for calibrations of the seven individual radiocarbon samples given in Table 1 and for the combination of the seven individual functions. Data analysis performed with OxCal v.4.1.7 (Bronk Ramsey, 2009) with SHCal04 Southern hemisphere atmospheric curve (McCormac *et al.,* 2004). Analysis resolution is 5 years. Asterisks indicate AMS dates; **b.** Plot of the combined probability density function, calculated by multiplying the seven individual probability density functions together. Horizontal brackets show age ranges for (top to bottom) 1, 2, and 3σ confidence intervals. Vertical line marks AD 1644, the year that cartographic reconnaissance was started by the Jesuits mission in Chiloé. In AD 1669 a map of the archipelago first depicted an erupting volcano in the Chaitén Bay area, although it was probably produced earlier. The fact that the lower limit of the map-derived date range (1644-1669) falls within the high-probability part of the probability density function increases the likelihood that Chaitén did indeed erupt shortly after 1644.

FIG 5. Nautical chart dated *ca*. AD 1669 (first copy probably dated shortly after AD 1644; see text for details) by an anonymous author (Guarda and Moreno, 2008) with mention of volcanic activity in the Chaitén area. This is the only representation of an active volcano during the 17th century; later versions (*e.g.*, AD 1657 chart by Sanson d'Abbeville) do not contain such a representation. Although geographical references are often imprecise, the active volcano is clearly across from Chiloé Island. Because Chaitén is a small flat-topped volcano, eruptive activity in the region would probably be attributed to Michinmahuida Volcano, which is bigger and visible from the Chiloé Island and fjords. No clear explanation for the 'tilted' volcano in lower right of chart.

source of pyroclastic components contained in the alluvial deposits must be carefully analyzed. According to Naranjo and Stern (2004), and more recently to Watt *et al*. (2009) and Amigo *et al.* (2013, this volume), the eruptive products from these volcanoes display geochemical signatures that allow unambiguous discrimination of their sources. For instance, both pumice and obsidian fragments from the pre-2008 deposits studied here are indistinguishable (major and trace elements, within analytical error) from the 2008 eruptive products of Chaitén Volcano (Fig. 6). In addition, they differ from the main trends of Michinmahuida eruptive products. Bulk ash from the white pre-2008 tephra-fall deposit identified downwind of Chaitén also has a composition similar to the products of the 2008 eruption of Chaitén (Fig. 6).

7. Discussion

New radiocarbon dates and historical reports of possible eruptions in the vicinity of Chaitén Bay point to a previously unrecognized eruption of Chaitén Volcano in the 17th century (probably starting shortly after AD 1644). Taken together with evidence provided by Watt *et al*. (2013, thisvolume) and Amigo *et al*. (2013, this volume), Chaitén Volcano seems to be more frequently active than previously thought. Two primary products of this pre-2008 event are an ash-fall deposit identified southeast (downwind) of Chaitén and a PDC deposit identified on the outer slope of the north caldera rim. A 17th century age for these primary deposits is consistent with radiocarbon dates from pumice-

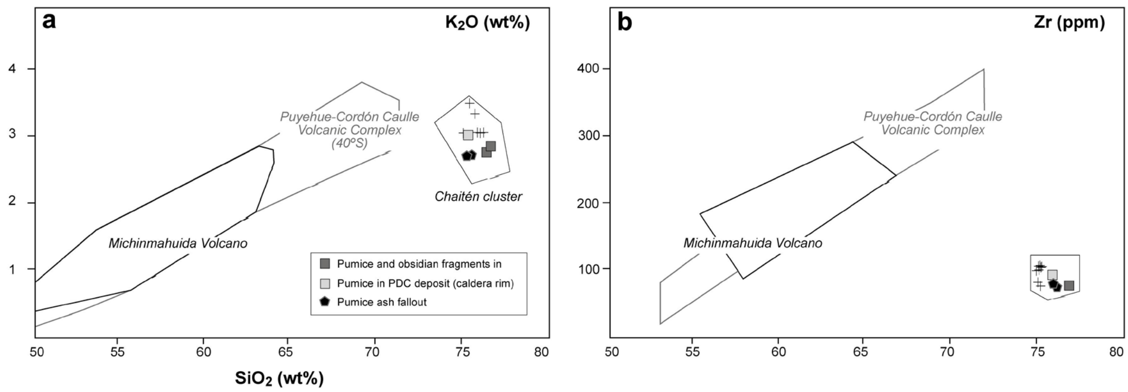

FIG. 6. Select geochemical data used to discriminate among possible sources of historical eruptions; **a.** Silica-K_2O diagram shows a tight cluster of products from Chaitén Volcano. In contrast, Michinmahuida Volcano exhibits a linear trend with higher K_2O at a given silica content; **b.** Zr contents for Chaitén deposits clearly depart from the Michinmahuida trend. Fields are from published data from several sources: López *et al*. (1993), Stern *et al*. (2002), Naranjo and Stern (2004), Lara *et al*. (2006b), Singer *et al*. (2008), Horwell *et al*. (2008)[1], and Watt *et al*. (2009). Data for 2008 eruption (black crosses) is mostly from Watt *et al*. (2009), Watt *et al*. (2013, this volume), Amigo *et al*. (2013, this volume), and Pallister *et al*. (2013, this volume).

rich alluvial deposits downstream of the volcano in the Chaitén River valley. Those alluvial deposits have a composition similar to the primary deposits. But the question might be asked if these alluvial deposits are related to a 17th century eruption. After all, the watershed is steep and densely forested, and large amounts of detrital wood and sediment can be produced by watersheds disturbed by other processes, such as fire or extreme storms (*e.g*., Iroume *et al*., 2012). However, two factors suggest disturbance by volcanic eruption: **1.** the rapid burial of forest trees on river terraces by the alluvial sediment, which at one site encased a ~30-40-cm-diameter tree trunk in growth position from the base to the top of the deposit (*i.e*., full burial of the tree before it could rot and break off or fall over); and **2.** The high pumice content of the alluvial sediments comprising the aggradational valley fill. Rapid burial of the Chaitén River channel by a pumic-rich lahar-flood occurred during the 2008 eruption of Chaitén Volcano. Forest burial occurred within days of the explosive phase of the eruption, and tephra flushed from the upper watershed composed virtually all of the sediment forming the deposits (Pierson *et al*., 2013).

An apparent discrepancy among the radiocarbon dates (Table 1) can be interpreted in two ways: **1.** Despite the wide range in the ages, all the sampled deposits were emplaced as a consequence of a single eruptive episode; or **2.** The wide age range and two apparent age groups reflect two separate eruptive periods. The fact that the two carbonized limbs from a single deposit at site 1 yielded dates that fall in both age groups strongly supports the first alternative. These two limbs were unequivocally incorporated into the crater-rim PDC deposit and carbonized at the same time. If two limb samples incorporated in a deposit in a single moment in time fall into both age groups, we have no reason to conclude that the two age groups reflect separate eruptive periods.

There are several possible explanations for the wide range in radiocarbon dates. One source of age scatter occurs from sampling wood that died before it was incorporated into a volcanic deposit. A substantial fraction of the wood in a forest is dead, and the dead wood is just as likely as living wood to be incorporated into a PDC, lahar, or alluvial deposit. Even if a tree died at the time of a volcanic event, samples may be from interior wood instead of outer rings. Another source of scatter occurs from variation in the radiocarbon calibration curve. A kink in the calibration curve owing to variations in radiocarbon production produces a 3-fold ambiguity. The seven dates in this study involve two kinks

[1] Horwell, C.; Michnowicz, S.; Le Blond, J. 2008. Report on the mineralogical and geochemical characterisation of Chaitén ash for the assessment of respiratory health hazard (Unpublished), University of Durham-IVHHN-Natural Environmental Research Council: 36 p.

in the calibration curve (Fig. 4a). Therefore, the calibrated calendar dates computed from the standard radiocarbon ages for all of the samples fall within a wide age range. Using the wide 2σ calendar age ranges, there is a slight overlap (the period between AD 1625 and 1658), and this range is consistent with historical accounts.

A possible vent area for the 17th century eruption is still obscure. Photographs taken before the 2008 eruption show some patches on the older dome without vegetation, which could be related to a recent volcanic disturbance. A plausible candidate could be the crater-like feature that was visible in the apical section of the older dome close to a vegetation-free area (Fig. 7). Whether this eruption consisted of only an explosive phase is a matter of debate and requires further research.

8. Conclusions

Terraces in the Chaitén River valley and gullies through Chaitén town eroded in 2008 have exposed deposits that we have dated and interpreted as the products of heavily sediment-laden water floods and a lahar associated with a major eruption of Chaitén Volcano in the 17th century. These flows deposited an alluvial fan composed mostly of remobilized ash interbedded with lenses of pumice and obsidian gravel. Sedimentological features of the pre-2008 valley-fill and fan deposits are remarkably similar to those of the aggradational assemblage formed during the 2008 eruption. The chemical compositions of the pumice and obsidian in the pre-2008 deposits strongly suggest that Chaitén Volcano was the source. Seven calibrated radiocarbon dates suggest that an

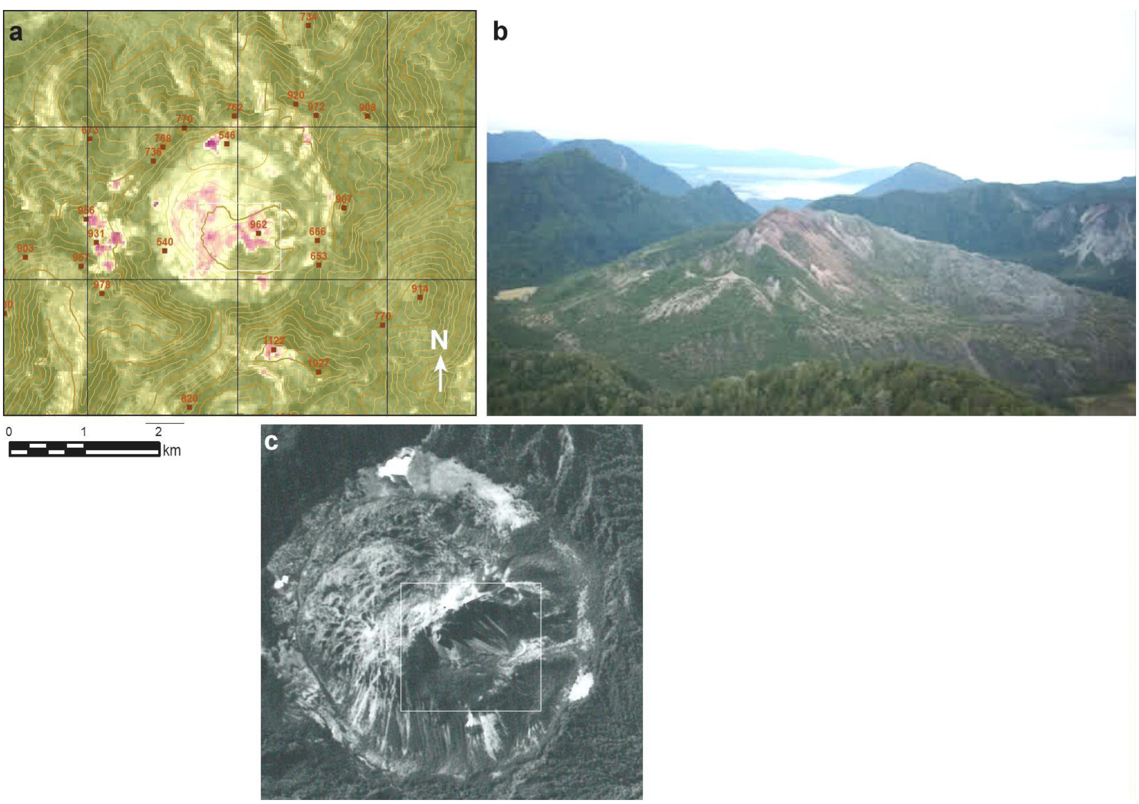

FIG. 7. Pre-2008 images of Chaitén Volcano; **a.** Landsat TM (LE72320902007359EDC00) image emphasizes the absence of vegetation on the upper part of the Holocene lava dome (NDVI index on image acquired on 2007/12/25; pink to yellow for areas without significant vegetation; red dots with numbers for spot elevations); **b.** Photograph of the Holocene dome also showing the absence of vegetation in some areas (courtesy of E. Manríquez). Note that terrain close to 1000 m a.s.l. is covered by thick forest, which is normal at this latitude; **c.** Enlargement of an aerial photograph (GEOTEC, 1:70,000 scale acquired on 1998) showing a crater-like feature (white box) that could be the source area for the historical 17th century eruption (see text for details).

eruption occurred between AD 1625 and 1658. This interval also brackets the most probable date of a nautical chart on which an erupting volcano was depicted near the shoreline of Chaitén Bay. Because no other volcanoes are depicted with active vents, and because subsequent maps lack depiction of erupting volcanoes, a 17th century eruption seems to have been observed by early explorers. Taken together, these findings suggest that Chaitén Volcano has been more frequently active than previously thought and therefore deserves a high priority for volcano monitoring. Chaitén town, situated 10 km south of the volcano at the mouth of the Chaitén River, is in a high hazard zone and any resettlement of the town should be carefully planned.

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