A past-millennium maximum in postglacial activity from Volcán Chaitén, southern Chile

P.I. Moreno[1]*, B.V. Alloway[2], G. Villarosa[3], V. Outes[3], W.I. Henríquez[1], R. De Pol-Holz[4], and N.J.G. Pearce[5]

[1]Department of Ecological Sciences, Universidad de Chile, Santiago 7750000, Chile
[2]School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington 6140, New Zealand
[3]Instituto de Investigación en Biodiversidad y Medioambiente, CONICET–Universidad Nacional del Comahue, Bariloche 8300, Argentina
[4]Department of Oceanography, Universidad de Concepción, Concepción 4030000, Chile
[5]Department of Geography & Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, Wales, UK

ABSTRACT

Volcán Chaitén (southern Chile, ~43°S) initiated an historically unprecedented eruption in A.D. 2008, surprising the local inhabitants, Chilean and Argentine authorities, and the geologic community. Available data at the time indicated an absence of explosive eruptions from this rhyolitic volcano since a large-magnitude eruptive event dated at ca. 10,500 yr B.P. We present lake-sediment data from Lago Teo, a small closed-basin lake located in the immediate vicinity of both Chaitén township and the volcano, that spans the past ~10,000 yr and contains 26 pyroclastic fallout deposits. Glass-shard electron microprobe analyses revealed ten rhyolitic tephras indistinguishable in composition from the 2008 Volcán Chaitén eruption, and ten others potentially derived from the Michinmahuida volcanic complex. Among the rhyolites, we detected three closely spaced tephras deposited between ca. 9460 and 9680 yr B.P., followed by two thick tephras dated at ca. 7700 and ca. 5080 yr B.P. Three other closely spaced tephras occur between ca. 600 and 850 yr B.P., the most recent prehistoric event at ca. 420 yr B.P., and a 3-cm-thick tephra deposited during the 2008 event. We calculate a median recurrence of ~310 yr between eruptive events from all sources over the past ~10,000 yr, and ~200 yr between Volcán Chaitén events over the past millennium. Our results not only challenge the notion of an ~10,500-yr-long quiescence for Volcán Chaitén activity, but also suggest that the 2008 eruption was an overdue phenomenon in the context of its postglacial eruptive history, illustrating the advantage and absolute necessity of utilizing lake-sediment archives for developing continuous well-dated time series inventories of explosive volcanic events.

INTRODUCTION

A large rhyolitic eruption from Volcán Chaitén (southern Chile, 42°49′S, 72°38′W) began on 2 May 2008 (Lara, 2009), ending an ~10,500-yr-long interval of apparent quiescence since its sole explosive eruption documented at the time (Naranjo and Stern, 2004). Chilean authorities forced the evacuation of the Chilean towns of Chaitén and Futaleufú, located ~9 km downstream along the Río Chaitén valley and ~75 km southeast downwind from Volcán Chaitén (Fig. DR1 in the GSA Data Repository[1]), respectively, considering the proximity of the towns to, and imminent hazard posed by, this highly explosive volcano. Tephra distributed downwind from Volcán Chaitén also caused significant disruption to communities located eastward across the frontier in Argentina, adversely affecting all aspects of their economies. Initial assessment of volcanic hazards in the vicinity of Volcán Chaitén was based on eruptive records described from the soil-forming environment (Naranjo and Stern, 2004) where post-depositional weathering and biological mixing has effectively masked the accretion of fine and/or thin tephra to the ground surface. This situation in a temperate, humid, high-weathering environment creates a descriptive bias toward very large-magnitude and/or coarse-grained eruptive units that are prominently represented in the andic soil profile (Alloway et al., 1995), making thin and/or fine-grained tephra deposited within andic soil sequences unlikely to have been preserved and difficult to date. Such deposits are usually better preserved as discrete layers within fast- and constant sediment–accumulating systems such as lake sediments.

The 2008 reactivation of Volcán Chaitén presents an unprecedented opportunity for the ongoing study of an explosive eruption of silicic composition (an uncommon type of volcanism in historic times) using a combination of modern monitoring systems (Castro and Dingwell, 2009; Lowenstern et al., 2012; Pina-Gauthier et al., 2013; Reich et al., 2009; Watt et al., 2009; Wicks et al., 2011) and mineral geochemistry for assessing the subsurface conditions and magmatic processes that can be attributed to the reactivation of apparently long-dormant rhyolitic volcanoes (Carn et al., 2009). The occurrence of multiple tephras within sediments of Lago Teo (42°54′8.13″S, 72°42′22.42″W, 45 m above sea level) affords an opportunity to firmly place the 2008 Volcán Chaitén eruption within the context of a near-complete inventory of intermittent events that have occurred at the same eruptive center over postglacial time.

THE LAGO TEO RECORD

We set out to study the timing, recurrence, and origin of postglacial explosive volcanism in northwestern Patagonia using lake sediment cores from Lago Teo (a small, closed-basin lake located between the Chaitén township and the volcano), the cover-bed stratigraphy from nearby sectors (Fig. DR1), and field and laboratory analyses on the tephra deposit derived from the Chaitén 2008 eruption. The sedimentary record from Lago Teo consists of 302 cm of organic lake mud with 26 discrete pyroclastic layers (Fig. 1; Table DR1 in the Data Repository), including tephra from the 2008 Volcán Chaitén eruption, that typically display concordant horizontal beds of well-sorted, coarse to fine ash with sharp upper and lower contacts in X-radiographs (Fig. DR2). Our chronology indicates continuous deposition in Lago Teo since 10,000 yr B.P. (Fig. DR3; Table DR2).

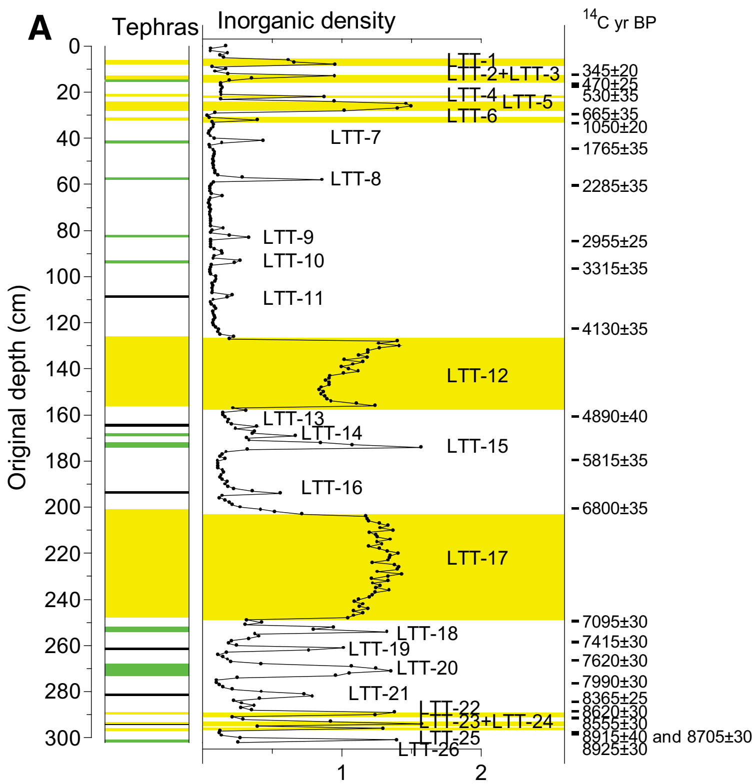
We sampled the most prominent tephras and, where possible, analyzed glass shards for major element compositions. Major oxide chemistry of glass shards reveals a wide range for SiO_2, between 54 and 78 wt%, and $K_2O + Na_2O$ of 3–9.7 wt% (Fig. 1; Table DR3). Samples cluster into three compositional groupings, ranging from rhyolite (LTT-1, LTT-2, LTT-4, LTT-5, LTT-6, LTT-12, LTT-17, LTT-22, LTT-23, LTT-25; group 1), to trachyte to dacite (LTT-8, LTT-18, LTT-20; group 2), to basalt to basaltic andesite (LTT-3, LTT-7, LTT-9, LTT-10, LTT-14, LTT-15, LTT-26; group 3) fields (Fig. 1) (LTT, Lago Teo tephra). Tephra beds can be distinguished on the basis of glass major element oxides such as FeO_t versus CaO and K_2O (wt%) (Fig. 2). The clustering corresponds with compositional groupings identified in Figure 1, suggesting that the tephras recorded in Lago Teo could represent the products of three compositionally discrete sources.

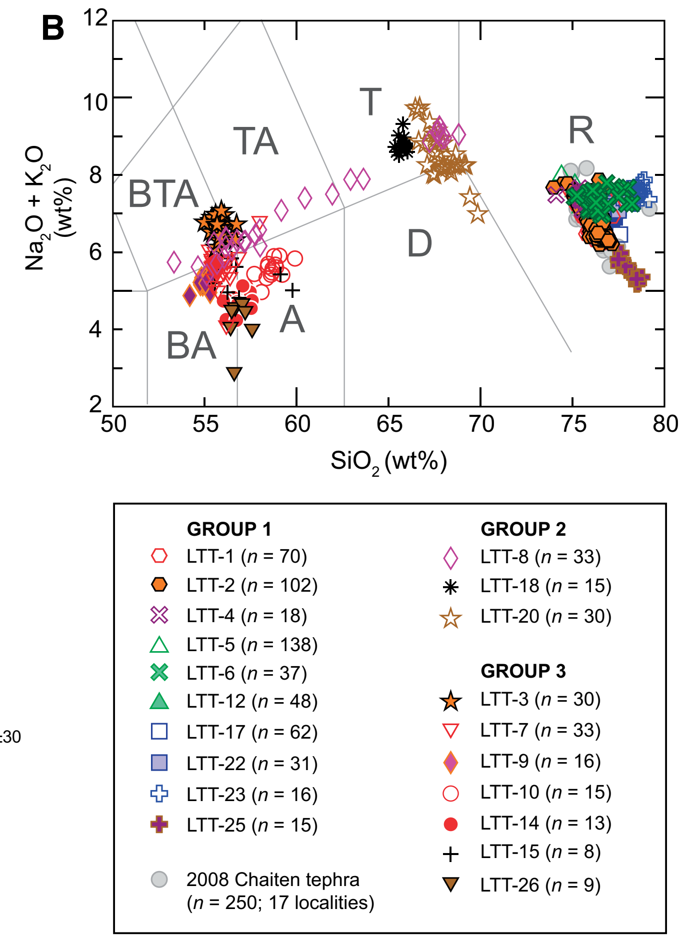
We observed a tight clustering of rhyolitic tephras from Lago Teo around values characteristic of the 2008 Chaitén eruption (LTT-1 and surface samples) on the basis of major element glass chemistry (group 1; Fig. DR4; Table DR3). Most of these tephras occupy closely spaced

*E-mail: pimoreno@uchile.cl

[1]GSA Data Repository item 2015031, site setting, methods, figures, and tables, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, January 2015; v. 43; no. 1; p. 47–50; Data Repository item 2015031 | doi:10.1130/G36248.1 | Published online 21 November 2014





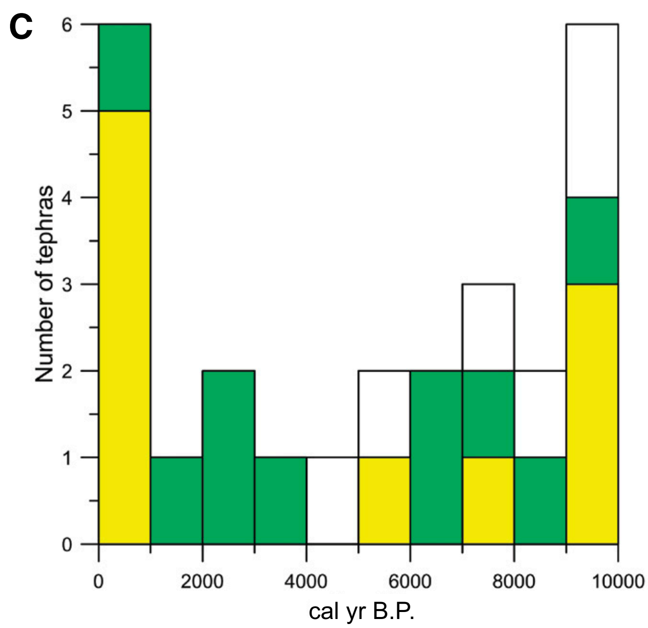


Figure 1. A: Simplified stratigraphic column and inorganic density data derived from loss-on-ignition analysis of Lago Teo (southern Chile) core. Lago Teo tephra (LTT) numbers represent tephra identification codes (see Table DR1 [see footnote 1]); numbers along right side indicate uncalibrated radiocarbon dates and their corresponding 1σ errors (Table DR1). Horizontal yellow rectangles indicate rhyolitic tephras derived from Volcán Chaitén identified in this study. B: Total alkali–silica (TAS) diagram (wt% SiO_2 versus wt% $Na_2O + K_2O$) showing all Lago Teo tephra analyzed. Analyses from A.D. 2008 Volcán Chaitén eruption are included for comparison (Alloway and Villarosa, this study). Compositional fields from Le Maitre (1984): A—andesite; BA—basaltic andesite; BTA—basaltic trachyandesite; D—dacite; T—trachyte; TA—trachyandesite; R—rhyolite. C: Histogram showing number of tephras per non-overlapping 1000-yr-long time windows in Lago Teo record. Yellow rectangles represent number of rhyolitic tephras; green rectangles represent occurrence of tephras of putative Michinmahuida volcanic complex origin (group 3, ~53%–60% SiO_2); black rectangles represent all other tephras (group 2, intermediate compositions). We incorporated the 2008 Volcán Chaitén eruption in the 0–1000 yr B.P. interval.

but discretely clustered populations indicating that they represent genetically related but separate eruptive products, ruling out the possibility of repeated reworking up the sediment core. With an age of ca. 9680 yr B.P. (Table DR1), LTT-25 closely corresponds in age and geochemistry with the ca. 10,500 yr B.P. Cha1 tephra described by Naranjo and Stern (2004), more recently mapped and redated at 9750 yr B.P. (Watt et al., 2011). The high, constant sedimentation rates within Lago Teo, reduced weathering, and biological mixing suggest that the event named Cha1 recognized northward from Volcán Chaitén and on the steep-sided surfaces bounding the Andean range front (i.e., Watt et al., 2011) may be a composite of three closely spaced eruptions as recorded in the Lago Teo interval 9460–9680 yr B.P. (LTT-22, LTT-23, LTT-25). In addition, this composite tephra layer at many localities is either visibly overthickened or stratigraphically dispersed by a combination of post-depositional downslope remobilization and biological mixing. These scenarios, based on a sparse and directional array of thickness data, potentially render modeled eruptive volumes and calculated volcanic explosivity index essentially meaningless.

The Cha1 tephra was considered to represent the last explosive eruption from Volcán Chaitén prior to the 2008 eruption (Naranjo and Stern, 2004; Watt et al., 2011). Clearly the data presented in our study suggest otherwise with the occurrence of additional eruptions (Table DR1), two of which deposited the thickest rhyolitic tephras in the Lago Teo record (LTT-12 and LTT-17) and four additional during the past millennium (LTT-2, LTT-4, LTT-5, LTT-6) (Fig. 1; Table DR1). More recent studies in

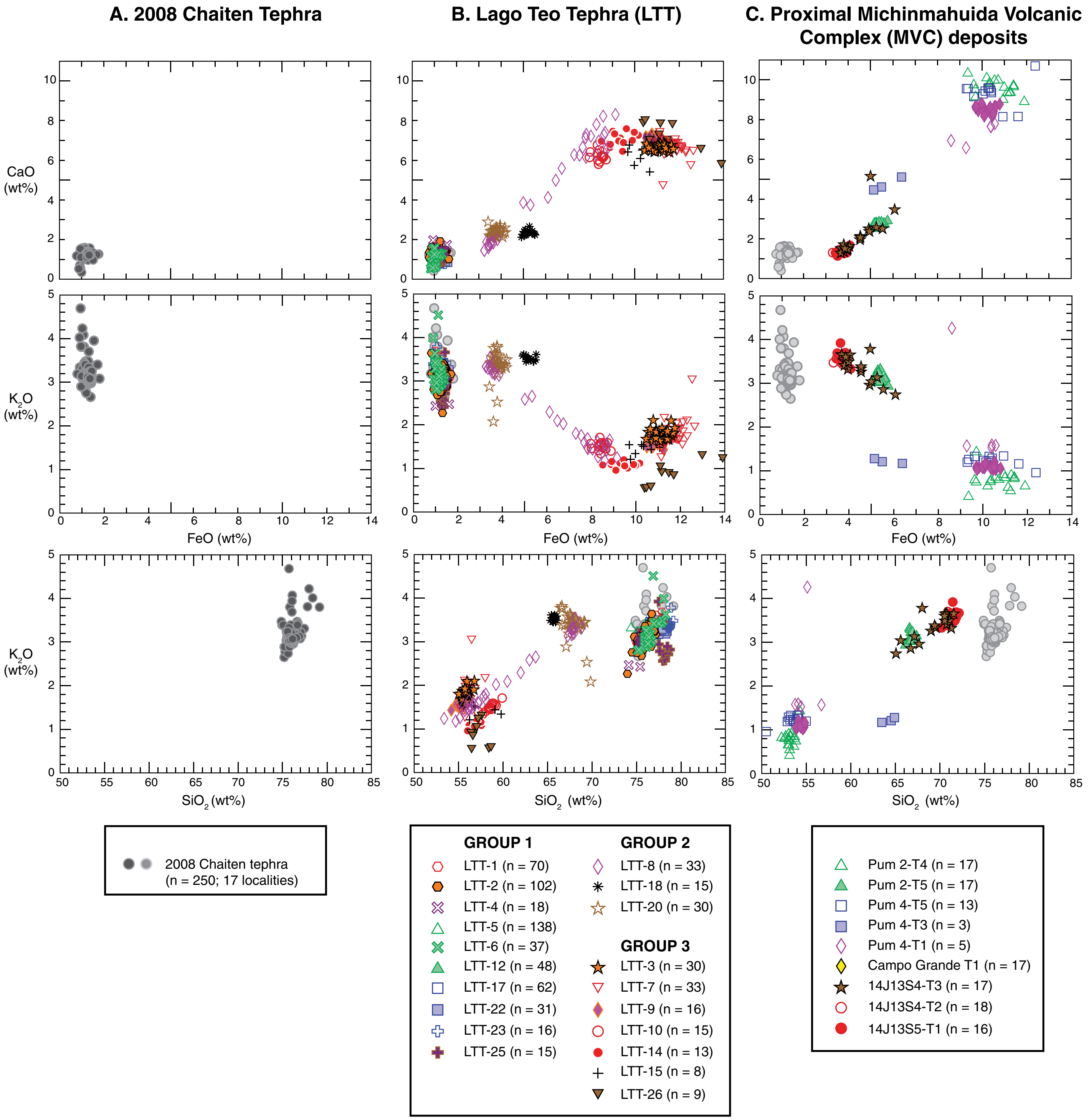


Figure 2. CaO and K_2O versus FeO_t, and K_2O versus SiO_2 (wt%) for glass shards from tephra layers preserved in Lago Teo (southern Chile) sediment core. Lago Teo tephra (LTT) are divided into three broad compositional groupings based on glass shard major element geochemistry. In order to identify potential eruptive sources, these groupings are compared with glass shard analyses from the A.D. 2008 Volcán Chaitén eruption (Alloway and Villarosa, this study), as well as equivalent-aged proximal Michinmahuida volcanic complex–sourced tephra preserved in the adjacent andic soil-forming environment (see Fig. DR1 [see footnote 1]).

road and river outcrops along the western side of the Andes, including in the vicinity of Volcán Chaitén (Amigo et al., 2013; Lara et al., 2013; Watt et al., 2013), reported five rhyolitic tephras, including two preliminarily dated at <8200 yr B.P. and ca. 5000 yr B.P., two undated tephras <4000 yr B.P., and the most recent during the 17th century. Tentatively, these findings could correspond with some of the rhyolites identified in our study.

Specific eruptive source locations for multiple Lago Teo tephras of trachyte-dacite (group 2) to basaltic andesite (group 3) composition are mostly unknown. However, based on major element compositional similarities of group 2 and group 3 tephras with prominent coarse-grained tephra analyzed from sections located directly adjacent to Volcán Michinmahuida and its satellite eruptive centers (here termed the Michinmahuida volcanic complex) (Fig. 2; Fig. DR5), it appears that most are locally sourced from the compositionally diverse Michinmahuida volcanic complex and, furthermore, that the overall eruptive frequency of the Michinmahuida volcanic complex is broadly similar to that of Volcán Chaitén.

DISCUSSION AND CONCLUSIONS

The detailed record from Lago Teo allows assessment of the time evolution of explosive volcanic events in the Chaitén sector of northwestern Patagonia. We constructed a histogram with the number of pyroclastic layers in Lago Teo per thousand-year bin, using the median probability age for each Lago Teo tephra (Fig. 1). This plot reveals a background of 1–2 pyroclastic events per thousand years, upon which we detect millennial-scale increases driven by rhyolitic explosive events from Volcán Chaitén, with prominent maxima between 9000 and 10,000 yr B.P. and during the past millennium (including LTT-1). The thick Volcán Chaitén tephras at ca. 5080 and ca. 7700 yr B.P. also increased the frequency of pyroclastic events, but only marginally. We calculate median time steps of 310 yr between pyroclastic layers from all sources over the past ~10,000 yr, and 200 yr between Volcán Chaitén events over the past millennium, considering the correct calendar age for LTT-1 in both cases. Based on these calculations and the ~480 yr elapsed since LTT-2, we conclude that the timing of the 2008 Chaitén eruption falls within the expected pacing of pyroclastic events from all sources over the past 10,000 yr, and was an overdue phenomenon considering the tempo of Volcán Chaitén eruptions recorded in Lago Teo over the past millennium irrespective of their size. The frequency of eruptive activity at Volcán Chaitén is likely to extend back prior to ca. 10,000 yr B.P., but this record is regionally masked by the effects of widespread glacial erosion and associated landscape instability that has mostly removed this record from the western flank of the Patagonian Andes.

Our results from Lago Teo show a more dynamic explosive volcanic history than previously acknowledged in the Chaitén sector of northwestern Patagonia, featuring a significantly more-frequent eruptive record of Volcán Chaitén that includes ten discrete events over the past ~10,000 yr. The past millennium in particular has witnessed the highest activity of Volcán Chaitén, a factor that remained undetected by previous studies in the region. Thus, the notion of an ~10,500- or ~9780-yr-long quiescence for Volcán Chaitén activity (Naranjo and Stern, 2004; Watt et al., 2011) is not supported by our lake-sediment archive and the recent findings from soil-forming environments mentioned above. The results presented in this paper underscore the advantage, and absolute necessity, of utilizing lake-sediment archives for developing continuous well-dated time series inventories of explosive volcanic events, and reconciling these archives against equivalent-aged records preserved within the andic soil-forming environment. Only then can volcanic hazards be critically evaluated and the risk posed to the communities, infrastructure, and economy from a particular eruptive center be accurately assessed. Our results will need to be carefully considered by both the Chilean authorities and the local community as they continue with restoration and rebuilding in the aftermath of the 2008 eruption.

ACKNOWLEDGMENTS

This study was funded by Iniciativa Científica Milenio grants P02-51 and NC120066, Fondecyt 1110612, a Victoria University of Wellington Science Faculty Research Grant, PIP CONICET 2011 0311, and Aberystwyth University Research Fund. We thank R.A. Flores, M.R. Kaplan, C.M. Moy, I .Vilanova, and R. Villa for field assistance; T. Guilderson and C.M. Moy collaborated in the initial radiocarbon chronology of this study.

REFERENCES CITED

Alloway, B.V., Neall, V.E., and Vucetich, C.G., 1995, Late Quaternary tephrostratigraphy of northeast and central Taranaki: Journal of the Royal Society of New Zealand, v. 25, p. 385–458, doi:10.1080/03014223.1995.9517496.

Amigo, A., Lara, L.E., and Smith, V.C., 2013, Holocene record of large explosive eruptions from Chaitén and Michinmahuida Volcanoes, Chile: Andean Geology, v. 40, p. 227–248, doi:10.5027/andgeoV40n2-a03.

Carn, S.A., Pallister, J.S., Lara, L., Ewert, J.W., Watt, S., Prata, A.J., Thomas, R.J., and Villarosa, G., 2009, The unexpected awakening of Chaitén Volcano, Chile: Eos, (Transactions, American Geophysical Union), v. 90, p. 205–206, doi:10.1029/2009EO240001.

Castro, J.M., and Dingwell, D.B., 2009, Rapid ascent of rhyolitic magma at Chaitén volcano, Chile: Nature, v. 461, p. 780–783, doi:10.1038/nature08458.

Lara, L.E., 2009, The 2008 eruption of the Chaitén Volcano, Chile: A preliminary report: Andean Geology, v. 36, p. 125–129.

Lara, L.E., Moreno, R., Amigo, A., Hoblitt, R.P., and Pierson, T.C., 2013, Late Holocene history of Chaitén Volcano: New evidence for a 17th century eruption: Andean Geology, v. 40, p. 249–261, doi:10.5027/andgeoV40n2-a04.

Le Maitre, R., 1984, A proposal by the IUGS Subcommission on the Systematics of Igneous Rocks for a chemical classification of volcanic rocks based on the total alkali silica (TAS) diagram: Australian Journal of Earth Sciences, v. 31, p. 243–255, doi:10.1080/08120098408729295.

Lowenstern, J.B., Bleick, H., Vazquez, J.A., Castro, J.M., and Larson, P.B., 2012, Degassing of Cl, F, Li, and Be during extrusion and crystallization of the rhyolite dome at Volcán Chaitén, Chile during 2008 and 2009: Bulletin of Volcanology, v. 74, p. 2303–2319, doi:10.1007/s00445-012-0663-4.

Naranjo, J.A., and Stern, C.R., 2004, Holocene tephrochronology of the southernmost part (42°30′–45°S) of the Andean Southern Volcanic Zone: Revista Geológica de Chile, v. 31, p. 225–240.

Pina-Gauthier, M., Lara, L.E., Bataille, K., Tassara, A., and Baez, J.C., 2013, Co-eruptive deformation and dome growth during the 2008–2009 Chaitén eruption, Southern Andes: Andean Geology, v. 40, p. 310–323.

Reich, M., Zuniga, A., Amigo, A., Vargas, G., Morata, D., Palacios, C., Parada, M.A., and Garreaud, R.D., 2009, Formation of cristobalite nanofibers during explosive volcanic eruptions: Geology, v. 37, p. 435–438, doi:10.1130/G25457A.1.

Watt, S.F.L., Pyle, D.M., Mather, T.A., Martin, R.S., and Matthews, N.E., 2009, Fallout and distribution of volcanic ash over Argentina following the May 2008 explosive eruption of Chaitén, Chile: Journal of Geophysical Research, v. 114, B04207, doi:10.1029/2008JB006219.

Watt, S.F.L., Pyle, D.M., Naranjo, J.A., Rosqvist, G., Mella, M., Mather, T.A., and Moreno, H., 2011, Holocene tephrochronology of the Hualaihue region (Andean southern volcanic zone, ~42°S), southern Chile: Quaternary International, v. 246, p. 324–343, doi:10.1016/j.quaint.2011.05.029.

Watt, S.F.L., Pyle, D.M., and Mather, T.A., 2013, Evidence of mid- to late-Holocene explosive rhyolitic eruptions from Chaitén Volcano, Chile: Andean Geology, v. 40, p. 216–226, doi:10.5027/andgeoV40n2-a02.

Wicks, C., de la Llera, J.C., Lara, L.E., and Lowenstern, J., 2011, The role of dyking and fault control in the rapid onset of eruption at Chaitén volcano, Chile: Nature, v. 478, p. 374, doi:10.1038/nature10541.

Manuscript received 6 September 2014
Revised manuscript received 21 October 2014
Manuscript accepted 28 October 2014

Printed in USA