Quaternary Science Reviews 200 (2018) 141–159

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

A widespread compositionally bimodal tephra sourced from Volcán Melimoyu (44°S, Northern Patagonian Andes): Insights into magmatic reservoir processes and opportunities for regional correlation

C.A. Geoffroy [a, b], B.V. Alloway [c, d, *], À. Amigo [b, e], M.A. Parada [a, b], F. Gutierrez [f], A. Castruccio [a, b], N.J.G. Pearce [g], E. Morgado [b, h], P.I. Moreno [i]

[a] Departmento de Geología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile
[b] Centro de Excelencia en Geotermia de Los Andes (CEGA), Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile
[c] School of Environment, The University of Auckland, Private Bag, 92019, Auckland, New Zealand
[d] Centre for Archaeological Science (CAS), School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW, 2522, Australia
[e] Servicio Nacional de Geología y Minería (SERNAGEOMIN), Red Nacional de Vigilancia Volcánica, Temuco, Chile
[f] Geoexpeditions, Las Barrancas 25, Pirque, Santiago, 9480000, Chile
[g] Department of Geography & Earth Sciences, Aberystwyth University, Wales, UK
[h] Institute of Geophysics and Tectonics, School of Earth and Environment, University of Leeds, UK
[i] Instituto de Ecología y Biodiversidad, Departamento de Ciencias Ecológicas, Universidad de Chile, Santiago, Chile

A R T I C L E I N F O

Article history:
Received 8 July 2018
Received in revised form
24 September 2018
Accepted 25 September 2018

Keywords:
Volcán Melimoyu
Andean southern volcanic zone
Northern Patagonia
Bimodal tephra
Magma bodies
Zonation
Magma mingling
Eruption triggering

A B S T R A C T

We describe the stratigraphy, age, constituent geochemistry and phenocryst thermobarometry of a closely spaced Holocene tephra couplet from Volcán Melimoyu (VMm), located in the Northern Patagonian Andes. The lower tephra unit (La Junta Tephra, Mm-1) is distinctly banded comprising a dominant lower layer of rhyodacitic (~70% SiO_2) pumiceous ash and lapilli (Mm-1p) that abruptly transitions to a subordinate upper scoriaceous layer (Mm-1s) of basaltic andesite composition (~53% SiO_2). This bimodality within Mm-1 contrasts significantly with the closely overlying Santa Ana Tephra (Mm-2) that has a homogeneous trachyte-dacite (~63% SiO_2) composition and is intermediate between the two magmatic end members of Mm-1. We propose a genetic affiliation between Mm-1 and Mm-2, and that the latter event likely represents a hybridised-remnant of those discrete magmas involved in the earlier Mm-1 eruption. To test this hypothesis we applied whole rock elemental mixing and fractional crystallisation model to reproduce the composition and crystallinity of Mm-2. Results indicate that Mm-2 can be reproduced by mixing ~70% Mm-1p with ~30% Mm-1s, with subsequent ~13% fractional crystallisation of plagioclase, and minor amphibole, orthopyroxene, magnetite and biotite.

Equilibrium P-T conditions calculated from Mm-1p phenocrysts point towards magma residency at moderately shallow depths (200–290 MPa, ~7–10-km depth, 850–1000 °C), whereas Mm-1s phenocrysts indicate higher overall P-T conditions (240–480 MPa, ~8.5–17-km depth, 1080–1150 °C). P-T conditions determined for Mm-2 (~290 MPa, ~10-km depth, 930–1000 °C) are similar to those of Mm-1p. There is no physical and/or geochemical evidence of mafic magma involvement in the Mm-2 eruption.

Similar compositionally bimodal tephra are known from other Northern Patagonian Andean centres (i.e. Playas Blanca-Negra Tephra, Antillanca; Lepue Tephra, Michimahuida; Ho and H3 eruptions of Hudson) suggests that the intrusion of mafic magma into more silicic magma bodies is a common occurrence throughout this Andean sector. These widely dispersed, compositionally bimodal tephra not only provide key insights into pre-eruptive magmatic conditions and triggering processes, but can also be readily identified geochemically, and thereby be more fully utilised within future hazard- and paleoenvironmental-related studies.

1. Introduction

Compositional zoning of magmas has been noted at many

* Corresponding author. School of Environment, The University of Auckland, Private Bag, 92019, Auckland, New Zealand.
E-mail address: brent.alloway@gmail.com (B.V. Alloway).

https://doi.org/10.1016/j.quascirev.2018.09.034
0277-3791/

volcanic centres typically within arc settings worldwide. Initially, the origin of this zoning was controversial (Eichelberger et al., 2000, 2001; de Silva, 2001) with chemical heterogeneities within discrete eruptive events attributed to either: a) zoned reservoirs formed *by in-situ* fractional crystallisation of mafic magma (Smith, 1979; Wolff et al., 1990; Firth et al., 2016) or; b) by the intrusion of mafic magma into a more silicic magma body (*i.e.* Bacon and Druitt, 1988; Kent et al., 2010; Hernando et al., 2016; Singer et al., 2016) and/or inter-connected magma bodies. However, nowadays with the availability and breadth of precise microanalytical (grain-discrete) tools that can be used to characterise magmatic constituents, determining those factors directly influencing the type and tempo of compositional zoning is becoming more common-place. Many centres within the Southern Volcanic Zone (SVZ) of the Andes typically range from mafic cinder cones to volumetrically larger stratovolcanoes with basaltic through to rhyodacitic compositions with potential for sub-kilometer to kilometer-scale lateral partitioning of sub-volcanic magmatic bodies and conduits (*see* Shane et al., 2017). Compositional zoning is well documented within eruptive products from Quizapu (Hildreth and Drake, 1992; Ruprecht et al., 2012) and Hudson Volcanoes (Kratzmann et al., 2009; Weller et al., 2014). Mafic recharge-induced reheating of silicic magma and subsequent magma viscosity reduction leading to enhanced degassing has been implicated to trigger large eruptive events at these centres.

In this study, we analyse two closely spaced tephra layers from Volcán Melimoyu (VMm), a large stratovolcano located in a remote area of southern Chile, that exhibit contrasting characteristics. We first refine the tephrostratigraphic work of Naranjo and Stern (2004) and produce a series of detailed stratigraphic columns showing the correlation of Mm-1 and Mm-2 (equivalent to MEL1 and MEL2, respectively) from key descriptive sections located at medial distances from VMm. Previous volume estimates are re-evaluated. We then conduct geochemistry and thermobarometry of glass and mineral constituents from this tephra couplet to ascertain the temperature and depth of sub-volcanic magma (bodies) beneath VMm, explore possible causative factors involved in their triggering as well as evaluate temporal magmatic relationships between these two closely spaced eruptions. Our ultimate objectives are to better understand magmatic processes in this remote sector of Northern Patagonia, as well as characterise the resultant eruptive products so that they can be effectively utilised as regional chronostratigraphic markers.

1.1. Geological setting

Volcán Melimoyu (44°05′ S, 72°53′W; 2408 m above sea level) is a little studied composite stratovolcano located in a remote area of southern Chile (Stern, 2004; Stern et al., 2007) and within the southern segment of the Southern Volcanic Zone (SVZ) of the Andes (see Fig. 1). VMm is a larger-than-average edifice compared to other SVZ centres (~142 km^3; Völker et al., 2011) constructed of basalt, andesite and dacite lava flows (López-Escobar et al., 1993). The volcanic massif is broadly elongated ~10 km in an E-W direction with a ~1 km diameter summit crater and is permanently ice-covered. The areas surrounding VMm are sparsely populated, with La Junta (~1200 residents) located along the Carretera Austral (Ruta 7) being the largest settlement situated in the area, ~39 km to the northeast and downwind of the volcano.

Most volcanoes within this segment of the SVZ (with the exception of Vn Hudson) are typically located along, or west of, a major structural feature known as the Liquiñe-Ofqui Fault Zone (LOFZ). This zone is marked by a set of north-northeast-trending lineaments, faults and ductile shear zones that parallels the magmatic arc from near the Nazca-South America-Antarctica triple junction and extends northwards for ~1000 km (Cembrano et al., 2000). Numerous monogenetic mafic cinder cones are similarly roughly aligned along the LOFZ trend indicating a clear structural influence upon the spatial distribution of emergent volcanism with different sources within this region (Gutierrez et al., 2005).

1.2. Evidence of explosive activity centred at Volcán Melimoyu

While there have been no historical accounts of activity, two prominent and closely spaced pumiceous lapilli layers (MEL1 (lower) and MEL2 (upper)) were identified in the pioneering cover-bed reconnaissance work of Naranjo and Stern (2004) close to present-day ground surface in road sections eastwards of VMm. A series of stratigraphic columns and provisional isopachs were constructed for this closely spaced tephra ‘couplet’ with non-Dense-Rock Equivalent (non-DRE) volumes determined. Radiocarbon ages of ~2.8 and 1.7 ^{14}C ka BP were similarly determined for MEL1 (T-04F and T07, charcoal) and MEL2 (T-04B, bulk ‘organic soil’), respectively (Naranjo and Stern, 2004; see Table 1).

The occurrence of Melimoyu-sourced tephra has also been noted within soil-dominated cover-bed and lake sequences within the Río Cisnes valley (44°20′-44°50′S, ~120 km SE from the volcano) (Stern et al., 2015; Weller et al., 2017). For example, Stern et al. (2015) analysed 18 tephra layers within lake cores and glacial-lacustrine sediment outcrops. Based on their petrography and chemistry, six of those layers were ascribed a Melimoyu-source, with two layers in two separate cores correlated with MEL2 (Naranjo and Stern, 2004). Older tephra of presumed Melimoyu-source were identified at 4.6–4.8, 8.3 and 19.7 cal. ka BP (see also tephra layers E, M and O of Weller et al., 2017) but no subaerial exposures of these same tephra have so far been recognised. Further north towards Vanguardia (*this study*, see Fig. 2) and to the south toward Coyhaique, no Melimoyu-sourced tephra have so far been recognised (Weller et al., 2015, 2017).

In this study, informal tephra designations (Mm-1 (lower) and Mm-2 (upper)) are equivalent to MEL1 and MEL2, respectively, as previously assigned by Naranjo and Stern (2004). However, our intention is to formalise Mm-1 and Mm-2 in accordance with the International Stratigraphic Guide (e.g. Murphy and Salvador, 1999) and ascribe new geographical place-names and reference sections (see Supplementary Information 1.0). Consequently, Mm-1 and Mm-2 are renamed La Junta and Santa Ana Tephra, respectively. The rationale for this formalisation is outlined in Alloway et al. (2017b) and intended to remove numeric labelling of eruptive units and/or any inference to eruptive source.

2. Results

2.1. Stratigraphy and age

Two transects (N–S and W-E) are presented to show spatial variability of Mm-1 and Mm-2, as well as the presence of tephra inter-beds originating from other eruptive centres (i.e. Vga-tephra from the Vanguardia Cone Complex (VCC)) (Figs. 2 and 3; Table 1). At all described sections, the lower tephra (Mm-1) is distinctly banded comprising a dominant lower layer of white pumiceous ash and lapilli (Mm-1p) that abruptly transitions to a subordinate upper dark-grey scoriaceous layer (Mm-1s). This banding significantly contrasts with the closely overlying Mm-2 comprised entirely of shower-bedded white pumiceous ash and lapilli. Radiocarbon ages determined from charcoal material immediately underlying Mm-1 and Mm-2 (this study; see Table 1) are indistinguishable from those originally determined for MEL1 and MEL2, and confirm a late Holocene age with eruptions separated by ~1100 years. One aspect of the cover-bed stratigraphy that