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The magmatic evolution and the regional context of the 1835 AD Osorno volcano products (41°06´S, Southern Chile)

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ABSTRACT

Osorno volcano (41º06´S, 72º20´W) is a composite stratovolcano of the Central Southern Volcanic Zone of the Chilean Andes. It is the southernmost member of a NE-SW trending alignment of volcanic edifices including La Picada and Puntiagudo volcanoes and the Cordón Cenizos chain. According to contemporary descriptions recorded by Charles Darwin in 1835, two eruptive events occurred: the first during January-February, and the second during November-December 1835 and January 1836. The volcano erupted basaltic andesite lavas and tephra fall deposits (52.4 to 52.9 SiO_2 wt. %) which contain phenocrysts of olivine, plagioclase, clinopyroxene, and spinel. The compositions of these phenocryst phases, together with those of olivine-hosted melt inclusions, allowed us to constrain intensive parameters for the pre-eruptive magmas. These varied from 1060 to 1140 ºC, with an oxygen fugacity buffer of ~ΔQFM +1.1, dissolved water concentrations of up to 5.6 wt. % (average of ~4.2 wt. %) and maximum pressures equivalent to ~7 km depth. Textural relations, such as crystal accumulations and clots, zoning in crystals and other indications of disequilibrium, lead us to infer the involvement of a crystal mush, rich in individual crystals and clots of crystals, which underwent a degree of disaggregation and entrainment into the transiting magma prior to eruption. Comparison of trace element abundances, including rare earth elements, fluid-mobile elements, and relatively fluid-immobile elements, combined with $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotope ratios, allow us to consider variations in slab-derived fluid input and the minor role of crustal contamination on the Osorno eruptive products and those from neighbouring volcanic systems. Our results suggest both a greater contribution from slab-derived fluid and a higher degree of partial melting in the systems supplying

stratovolcanoes (Osorno, Calbuco, and La Picada) relative to those supplying small eruptive centres built over the major regional Liquiñe-Ofqui Fault Zone.

INTRODUCTION

In subduction zones, geochemical features of relatively evolved volcanic products across-arc may be preserved (Watt et al., 2013). This allows to contrast whole-rock chemical compositions of products from different volcanoes to understand mantle- and slab-related contributions. Specifically in Southern Andean volcanoes, several studies (e.g., Hickey-Vargas et al., 1989; 2002; López-Escobar et al., 1992; 1995a; Watt et al., 2013; Jacques et al., 2014; Morgado et al., 2015; Rawson et al., 2016; McGee et al., 2017) have reported chemical variations of erupted material over small spatial scales and have attributed crustal and subcrustal processes as causes for the observed variations in magma composition. However, studies combining major and trace elements, isotopic ratios, and mixing modellings of products from different volcanoes at the same latitude, are uncommon.

Besides whole-rock chemistry, recent articles (e.g., Ruth et al., 2018; Weller and Stern, 2018; Morgado et al., 2019a; Couperthwaite et al., 2020; Tassara et al., 2020) have also considered melt inclusion composition, mineral chemistry, and diffusion chronometry in volcanic rocks, which have placed observed chemical variabilities in a geological context, permitting events occurring during the magmatic evolution to be identified. Particularly, melt inclusion compositions, which have been used to constrain pressure of the magmatic storage and water dissolved in melt, could undergo significant reequilibration after recrystallisation in the rims and volatile loss, leading to misinterpretations of magmatic processes.

In Southern Chile, from 1575 to 1835, Osorno volcano had an eruptive frequency of one event per ~25 years, but its last eruption occurred in 1835 (Darwin, 1839a; Moraleda y Montero, 1888; Martin, 1901; O'Compley, 1936; Petit-Breuilh, 1999). Despite this relatively long quiescence, Osorno has shown an elevation of seismicity base level in recent years, interpreted as a sign of volcanic unrest (SERNAGEOMIN−OVDAS 2017a; 2018a, b, c; 2019; 2022). Here, we report our findings on the last eruption cycle (in 1835 AD) of Osorno volcano (Central Southern Volcanic Zone of the Southern Andes of Chile; Fig. 1); eruptions that lack detailed studies of the magmatic conditions that preceded volcanic activity. We describe crustal magmatic processes and assess the pre-eruptive physical magmatic conditions via mineral chemistry and coupling melt inclusion compositional profiles and diffusion chronometry. Finally, to place the Osorno volcano into a wider context with neighbouring volcanic activity, we compare and contrast the nature of the chemical enrichment/depletion of the erupted products across-arc from volcanoes at roughly the same latitude (41º06´S) from W to E, i.e., from Calbuco, Osorno, La Picada and La Viguería volcanoes. Comparison of volcanoes at the same latitude decreases the uncertainties related to the mantle source and minimises the potential effects of latitudinal variability in the supply of material associated with trench sediments (Watt et al., 2013) or other geodynamic anomalies (e.g., subduction of oceanic fracture zones; Sellés et al., 2004).

GEOLOGICAL SETTING

Southern Volcanic Zone

The Southern Volcanic Zone (SVZ; Fig. 1) of the Andes is a volcanic chain produced by the subduction of the oceanic Nazca plate below the South American continental plate (e.g., Jarrard 1986; Dewey and Lamb 1992; DeMets et al., 1994; Angermann et al., 1999). The SVZ comprises over 70 Pleistocene and Holocene stratovolcanoes and several large volcanic fields (Stern et al., 2007). The whole volcanic segment is ~1400 km long (33° to 46ºS) and is accompanied by the NS regional Liquiñe-Ofqui Fault Zone (LOFZ), which is an intra-arc fault that runs along-strike, just like the much of the arc volcanism between ~38º and ~46ºS (Cembrano and Lara, 2009; Sánchez et al., 2013; Pérez-Flores et al., 2016). The SVZ has been subdivided into four segments on the basis of tectonic setting, geochemical and petrologic considerations (Tormey et al., 1991; López-Escobar et al., 1995a; Stern, 2004; Stern et al., 2007). These subdivisions are shown in Fig. 1 and comprise the Northern (NSVZ, 33.3 to 34.4ºS), Transitional (TSVZ, 34.4 to 37ºS), Central (CSVZ, 37 to 42ºS), and Southern (SSVZ, 42 to 46ºS) zones.

The present study focuses on volcanic centres from the CSVZ, the most active region of the SVZ (and the whole Andes; Stern et al., 2007), in particular on Osorno volcano considering a geochemical comparison with products from other volcanoes at the latitude of ~41°S: La Picada, and Calbuco stratovolcanoes and La Viguería cone. Osorno volcano is the westernmost member of a NW alignment together with La Picada, Puntiagudo, and Cordón Cenizos (Moreno et al., 2010; Vander Auwera et al., 2019; Fig. 2). The nearby Calbuco volcano is not located directly upon any major regional structure (Sellés and Moreno, 2011). Conversely, La Viguería cone (41°22'S) belongs to Cayutué-La Viguería small eruptive centres built over the LOFZ master fault. According to the conceptual model of Cembrano and Lara (2009), NW alignments are related to tension cracks at depth, which may reach the surface and then provide pathways for magma ascent and, therefore, allow the building of either a stratovolcano or an elongated cluster of minor eruptive centres, depending on the balance between strain rate and magma input (cf. Takada, 1994). Magmas erupted at small eruptive centres can be shown to have ascended rapidly (e.g. Morgado et al., 2017), and with no pronounced interaction with the crust (e.g., McGee and Smith, 2016; Hickey-Vargas et al., 2016; Smith and Németh, 2017). This style of volcanism is usually related to extensional domains (e.g., Nakamura, 1977; Takada, 1994; Piochi et al., 2005).

Osorno volcano: general features

Osorno is an active stratovolcano of the Central Southern Volcanic Zone of the Chilean Andes. Its maximum height is 2661 meters above sea level (m.a.s.l.) and its base level is between 50 and 250 m.a.s.l. with an estimated volume of 130 to 160 km^3, covering an area of 250 km^2 (Moreno et al., 2010; Völker et al., 2011). It is located at 41º06'S, 72º20'W, and lies ~13 km west of the main trace of the LOFZ (Fig. 2). Osorno volcano is the southernmost member of an NE-SW alignment that includes La Picada volcano and the Puntiagudo–Cordón Cenizos volcanic chain (Fig. 2).

Osorno volcano has been active since the Middle Pleistocene (ca. 200 ka; Moreno et al., 2010). Its postglacial activity has been reported as summit crater eruptions, fissure-fed lava flows, parasitic cones and dacitic domes on the flanks (Moreno et al., 2010). The basement beneath Osorno volcano comprises Cretaceous granitoids (ca. 70 Ma; Moreno et al., 2010) and Miocene plutonic rocks from the Northern Patagonian Batholith (López-Escobar et al., 1992; Adriasola et al., 2006). Vander Auwera et al (2019) found Miocene-age (ca. 9.6 Ma) gabbroic xenolith blocks within the volcanic products of the adjacent La Picada volcano and Hickey-Vargas et al. (1995) described gabbroic and granulitic xenoliths recovered from volcanic material of the 1961 eruption of the neighbouring Calbuco volcano. All the xenoliths from previous studies have been interpreted as being derived from the local basement.

The products of Osorno volcano vary from basalts to dacites (~50-70% SiO_2; e.g., Tagiri et al., 1993; Moreno et al., 2010; Bechon et al., 2022) and have been classified into four units (1, 2, 3, and 4) depending on the age of the deposits. In the unit Osorno 4, several historical eruptions during the years 1575, 1640, 1644(?), 1719, 1737, 1765, 1778 to 1779, 1790, and 1834 to 1835 have been recognised and briefly described, whereas activity since 1834 has been confined to fumarolic episodes in 1852, 1882 to 1883, 1911 to 1915, 1963, 1969, 1985, and 1993 (Petit-Breuilh, 1999).

The 1835 AD Osorno eruption: History

Charles Darwin (1839b; 1840) described two eruption stages of Osorno volcano during 1835. Although he recognised release of "smoke" in November 1834 (Darwin, 1839a), the first stage of the 1835 Osorno eruption started on January 19th with moderate to vigorous strombolian activity (VEI 2; according to the Pyle (2000) catalogue; Lara et al., 2012). The volcano was still erupting in this manner on February 18th, two days before the large-magnitude earthquake (M_w 8.0-8.3; Watt et al., 2009) of Concepción, Southern Chile (Darwin, 1840). During the shock period, Darwin (1839b) described the emission of a dark blue "smoke" column from the summit, following the eruption cessation, ending the first period of eruption. Basaltic lavas are associated with this first period (Moreno et al., 2010), which were emitted from an array of eruptive fissures and small pyroclastic cones (see Fig. 3). According to Darwin (1840), the second stage of eruptive activity, which started on November 11th, resumed from the vents of the first stage (Lara et al., 2012). During December

5th, a fissure eruption occurred, associated with lava flows (Gillis, 1855) and lahars, which burnt trees (Petit-Breuilh, 1999). The volcano was still erupting on the January 20th 1836 (Gillis, 1855).

SAMPLING AND ANALYTICAL METHODS

Sample collection

We collected samples from three volcanic systems: Calbuco, Osorno, and La Viguería.

Calbuco volcano products.

Calbuco samples correspond to four lapilli-sized pyroclasts from fall deposits and five bombs from pyroclastic density current deposits from the 2015 eruption. The locations from which they were taken, detailed quantification of the main petrographic features, and whole-rock chemistry (major, minor, and trace elements) of Calbuco samples are available in Morgado et al. (2019a).

1835 AD Osorno volcano products.

The collected samples from the 1835 AD Osorno eruption correspond to ten from lava flows erupted from the main crater (reaching lengths from 10 to 14 km long) from five locations (Table 1) and lapilli fall deposits erupted from parasitic cones in one location (Fig. 3; Table 1). Examination and quantification of the main petrographic features (e.g. crystallinity, vesicularity, and modal percentages of phenocryst phases) from the collected samples was done by optical microscope and image processing of pseudo-coloured images via the freeware JmicroVision, respectively (Roduit, 2005).

La Viguería cone.

The collected samples from La Viguería cone correspond to one from a lava flow (~1.2 km length) and one from fall deposits (locations in Table 1). We performed the quantification of the main petrographic features using the same methods described for Osorno samples.

Whole-rock major elements

Whole-rock major elements compositions of lapilli deposits of one location (Os-164), three lava samples from three locations from the 1835 AD Osorno eruption (Os-144, Os-147, and Os-154), and two samples (one lava and one bomb) from La Viguería monogenetic cone (Fig. 2) were determined on fused glass discs by XRF (major elements) at ACME labs (now Bureau Veritas Minerals, Canada) using OREAS-184 and SY-4 standards for all the major elements except for FeO, for which CCU-1D, and OREAS-700 standards were used for FeO. Accuracy for major elements in all standards is better than 3% (relative) except for TiO_2 in SY-4 which is 4.5% (relative) and P_2O_5 in OREAS-184 and SY-4, which were 14% and 17% (relative), respectively. The detection limits are reported in Table 2.

Whole-rock trace element abundances

The major and trace element chemistry of the 1835 Osorno volcano products and La Viguería cone was obtained from bulk-rock powders. All trace element measurements were performed on an ICP-MS Agilent 7500a at The Open University (Milton Keynes, UK). 0.1 g of finely powdered sample was weighed out and 1 mL of Romil UpA HNO_3 and 4 mL of Romil UpA HF were added. The samples were heated in sealed Teflon vials to 130 ºC and agitated in an ultrasonic bath for 20 minutes every 12 hours until they had completely dissolved. The samples were then dried down to incipient dryness and the resulting gel brought up in 2 mL of Romil UpA HNO_3 and agitated in an ultrasonic bath for 20 minutes then returned to the hot plate overnight. After drying down for a second time the samples were redissolved in concentrated UpA Romil HCl and returned to the hot plate overnight, before drying down a third time. The residue was converted to a nitrate matrix using 1 mL of concentrated UpA HNO_3, dried down and re-dissolved in 100 mL of 2 % UpA HNO_3 to give a final solution with a thousandfold dilution, ready for mass spectrometry.

All element concentrations were corrected for blank effects (which resulted in corrections of less than 1 % for all elements) and subsequently corrected offline for instrumental drift. Where more than one analysis of a sample was undertaken during the same run the mean value was taken prior to offline corrections were performed. Detection limits were estimated to be five times the blank concentration for each element analysed and all data points with concentrations lower than the detection limits were discarded. The precision was better than 8% (relative, 2σ) and accuracy in the trace elements of standards JB-2 (n = 5), BHVO-2 (n = 2) and AGV-1 (n = 2) is better than 10% (relative) except in Ni (21% relative, in AGV-1) and Pb (13% relative, in BHVO-2). The uncertainties (2σ) of measurements are reported in Table 2.

Strontium and neodymium isotope measurements

Strontium and neodymium isotopes were measured in volcanic products from Osorno volcano, La Viguería cone (see section 4.1), and six samples from 5 locations on the nearby Calbuco stratovolcano (Cal-149Ta, Cal-157, Cal-158, Cal-159, Cal-160; Morgado et al., 2019a). All $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ analyses in this study were conducted on a Thermo Scientific Triton Thermal Ionization Mass Spectrometer (TIMS) fitted with 10^{11} Ohm amplifiers at the University of Leeds. Analyses were performed on ca. 100 mg of bulk rock powders digested using a combination of Romil-UpA HF, HNO_3 and HCl, using the same method as described for the trace element determinations. Once in solution, samples were centrifuged prior to loading onto Eichrom Sr Spec^{TM} columns with a bed volume of approximately 100 µL. The REE fraction was collected before elution of the Sr fractions into different vials. Prior to loading onto W filaments with a $TaCl_5$ activator, the Sr fraction was passed through the Sr spec column a second time and dried with two drops of dilute $HClO_4$ to remove any organic contaminants derived from the resin. The REE fraction was passed first through a TRU Spec^{TM} column (ca. 100 µL bed volume) and finally a LN Spec^{TM} column (bed volume ca. 2 mL) before loading onto Re filaments. The USGS reference material BHVO-2 was processed alongside the samples (Table 3), together with two total procedural blanks spiked with highly enriched ^{84}Sr, and ^{150}Nd solutions. Mean total procedural blanks for Sr and Nd were 326 pg and 153 pg, respectively. Accuracy of the radiogenic isotope analyses was assessed by analysing standard solutions of known composition alongside the unknowns – NBS987 for Sr, La Jolla for Nd, and the reference material BHVO-2 for Sr and Nd, which yielded ^{87}Sr/^{86}Sr = 0.710241 ± 0.000006 for NBS987, ^{143}Nd/^{144}Nd = 0.511842 ± 0.000002 for La Jolla, ^{87}Sr/^{86}Sr = 0.703461 ± 0.000007 and ^{143}Nd/^{144}Nd = 0.512977 ± 0.000004 for BHVO-2, in agreement with published results (e.g., GeoReM and GEOROC databases; Weis et al., 2005).

A static multicollection routine with standard cup configurations was used for all of the isotopic analyses. All measured ^{87}Sr/^{86}Sr ratios were corrected for mass bias relative to ^{88}Sr/^{86}Sr of 8.375209, using an exponential law. Data acquisition comprised the integration of two hundred 8 second measurements of masses 84, 85, 86, 87 and 88 for Sr isotope analyses. Mass 85 was measured to correct for any Rb interference on mass 87 assuming a natural ^{87}Rb/^{85}Rb of 0.386. For Nd isotope measurements, masses 143, 144, 146, 147, 148 and 150 were acquired in the same way as Sr isotopes. Mass 147 was measured to correct for Sm interferences on mass 144, 148 and 150. Natural ^{144}Sm/^{147}Sm, ^{144}Sm/^{148}Sm, and ^{144}Sm/^{150}Sm of 0.2048, 0.7498 and 0.4923, respectively were assumed for this correction.

Mineral chemistry

The phenocryst and microlite phases were identified using Scanning Electron Microscopy (FEI Quanta 650) at Leeds Electron Microscopy and Spectroscopy Centre at the University of Leeds (LEMAS, Leeds, UK). The compositions of olivine, pyroxene, plagioclase, spinel, ilmenite, titanomagnetite, and glass were measured using an electron probe microanalyser (JEOL JXA8230) at LEMAS (Leeds, UK). Details of the analytical conditions of electron microprobe measurements are available in Table 4. For ilmenite, pyroxene, and spinel the values of Fe^{3+} were obtained following the formulations of Droop (1987) and for titanomagnetites, using the formulations of Stormer (1983).

Crystallographic orientation

Crystallographic orientations of olivine crystals were determined using electron back-scatter diffraction in olivine crystals (EBSD; Prior et al. 1999) on a FEI Quanta 650 FEGSEM equipped with a Nordlys EBSD camera at the School of Earth and Environment, University of Leeds (Leeds, UK).

RESULTS

Petrography

Osorno 1835 AD products

The lava flow samples have a vesicularity of 4 to 17 vol. % and the lapilli samples have a higher vesicularity of 31 to 61 vol. % (Table 5). The main phenocryst phases are plagioclase, olivine, and clinopyroxene, as described for other Osorno materials in previous studies (Tagiri et al., 1993; Bechon et al., 2022). The nature of the groundmass depends on the sample; those collected from lava flows (Table 5) possess a glass-free microcrystalline groundmass, and those corresponding to lapilli samples contain microlites and interstitial glass. The microlite phases comprise plagioclase, olivine, clinopyroxene and titanomagnetite. We also recognised several volcanic cognate xenoliths (up to ~1 cm long) in the lapilli deposits at location Os-164 (Fig. 3). Their mineralogy comprises plagioclase, orthopyroxene, olivine, ilmenite, and titanomagnetite as phenocrysts, with plagioclase, clinopyroxene and titanomagnetite as microlites (details in Supplementary Data 1) in a glass-free groundmass.

La Viguería cone

The lava flow sample has a vesicularity of ~12 vol. % and the lapilli sample has a higher vesicularity of ~43 vol. % (Table 5). The main phenocryst phases are olivine and clinopyroxene and the microlite phases identified using Scanning Electron Microscopy comprise plagioclase, olivine, and clinopyroxene (Table 5).

Mineral chemistry and textural features of Osorno 1835 products

The main features of the mineral phases from the samples of the 1835 AD Osorno eruption are available in the Table 6.

Plagioclase.

Plagioclase crystals are found as isolated crystals, as inclusions in olivine and clinopyroxene, and as crystal clots, together with olivine and clinopyroxene. They are characterized by compositional zoning that can be categorized into three distinct zones: Zone 1 corresponds to cores of phenocrysts with composition of An_{80-89}. Zone 2 corresponds to plagioclase surrounding Zone 1 or core composition where Zone 1 is absent, with compositions of An_{70-79}. Zone 3 (An_{60-66}) corresponds to plagioclase rims, mainly observed in plagioclase phenocrysts from lava samples (Fig. 4). Plagioclase exhibit a composition equivalent to Zone 3 of plagioclase phenocrysts and display no zoning patterns. Plagioclase microlites have compositions of An_{52-59}.

Several plagioclase phenocrysts exhibit resorption textures in Zone 1 and Zone 2. Additionally, the composition observed in plagioclase phenocryst rims and that filling the spaces created because of resorption are the same and correspond to Zone 3 (Fig. 4).

Olivine

Olivine phenocrysts are present as both isolated crystals (e.g., Figure 5) and clots of crystals (together with plagioclase, and clinopyroxene). There are two groups of olivine phenocrysts regarding core compositions: Group 1 corresponds to crystals in the compositional range of Fo_{76-79}. Group 2 are crystals in the compositional range of $Fo_{69–73}$. All the olivine phenocrysts have normal zoning consisting of thin rims (< 15 μm) of composition Fo_{67-75}. EBSD maps (cf. Prior et al., 1999) show no measurable deformation in olivine phenocrysts (Fig. 6). Olivine microphenocrysts exhibit the same compositions as Group 1 and Group 2 of olivine phenocrysts (including ~3 μm thick rims with normal zonation). Olivine microlites have a composition of $Fo_{52–60}$.

Pyroxene

Clinopyroxene phenocrysts occur as isolated crystals, inclusions in olivine, and as members of crystal clots. The clinopyroxene compositional range corresponds to augite: $En_{43-52}Wo_{33-44}Fs_{8-16}$. The pyroxenes coupled with olivine grains from Group 1 in crystal clots have a composition in the range of $En_{48-49}Wo_{40-42}Fs_{8-9}$ and those coupled with olivine grains from Group 2 have a composition in the range of $En_{43-52}Wo_{33-44}Fs_{11-16}$.

Spinel

Spinel crystals are found as octahedral crystals typically preserved as inclusions in olivine phenocrysts and rarely (< 5% of the Cr-spinel crystals) as isolated crystals. The Mg# and Cr# (Cr#= molar Cr/(Fe^{3+}+Al+Cr)) values yield ranges from 0.28 to 0.44 and from 0.27 to 0.36, respectively. Spinel as inclusions in olivine phenocrysts from Group 1 have a Mg# ranging from 0.36 to 0.44 and Cr# from 0.32 to 0.36, whereas those preserved as inclusions in olivine phenocrysts from Group 2 have a Mg# from 0.28 to 0.29 and Cr# from 0.27 to 0.28. Measured SiO_2 concentrations were low (< 0.2 wt. %) suggesting that analyses were not affected by significant secondary fluorescence (Coogan et al., 2014) and that all the measured spinel contents are reliable.

Glass

Glass occurs in the groundmass, interstitial between crystal clots, and as melt inclusions in olivine and plagioclase phenocrysts (Fig. 4; 5). Olivine-hosted melt inclusions are generally spherical with radii from 15 to 150 μm, whereas plagioclase-hosted melt inclusions have elliptical outlines with long-axis lengths from 40 to 160 μm and short-axis widths from 20 to 50 μm. Different compositional groups are recognised in glasses; glass from groundmass, which has SiO_2 contents of 53.9 to 57.1 wt. %, versus interstitial glass between crystals from clots and olivine-hosted melt inclusions, which both exhibit SiO_2 contents of 51.9 to 54.7 wt. % (see Table 7, details in Supplementary Data 2).

Major and trace element geochemistry

The collected 1835 Osorno eruption samples are comparatively uniform with respect to their major element concentrations. All are of basaltic andesite composition (52.4 to 52.9 SiO_2 wt. %; Fig. 7) with high Al_2O_3 contents (19.6 to 20.7 wt. %), MgO contents from 4.09 to 4.55 wt. %, Mg# (Mg#= molar $Mg/(Mg+Fe^{2+})$) between 0.56 and 0.59, K_2O from 0.49 to 0.51 wt. % and CaO contents from 10.2 to 10.9 wt. %. The 1835 Osorno products plot in the tholeiitic trend (Fig. 8; Calbuco products in the tholeiitic trend and La Viguería products plot in the calc-alkaline trend). Comparison with other nearby volcanic products erupted during the Holocene can be seen in Fig. 7. Trace element concentrations are also similar between samples, with invariant multi-element diagram and Rare Earth Element (REE) patterns and a narrow range of La_N/Yb_N (2.1 to 2.2; Fig. 9, where the subscript N refers to values normalised to Primitive Mantle concentrations; Sun and McDonough, 1989). The 1835 Osorno products show similar values and REE patterns to volcanic materials from the nearby Calbuco and La Picada volcanoes, and the La Viguería cone (Fig. 9). In addition, the incompatible trace element diagram of the 1835 Osorno products shows similar trends in all samples with positive Pb and Sr anomalies and negative Nb, P, and Ti anomalies, typical of magmas from arc settings (Sun and McDonough, 1989; Fig. 9). The trends are consistent with those reported by Bechon et al. (2022).

Sr-Nd isotopic compositions

Osorno (samples Os-144a, Os-147a, Os-154a, and Os-164a; see locations in Fig. 3) and Calbuco (samples Cal-149Ta, Cal-149Tb, Cal-157a, Cal-158a, Cal-159a, and Cal-160; see location in Morgado et al., 2019a) volcanic products each show a narrow range of $^{87}Sr/^{86}Sr$ values (0.704309 to 0.704333, Osorno; 0.704384 to 0.704438, Calbuco), which though very close, do not overlap (Fig. 10). $^{143}Nd/^{144}Nd$ in Osorno and Calbuco volcanic products show ranges of 0.512741 to 0.512784 (Osorno) and 0.512680 to 0.512835 (Calbuco). Two samples from La Viguería (LV-152a and LV-153a), a volcanic cone overlying the LOFZ, exhibit lower $^{87}Sr/^{86}Sr$ (0.703705 to 0.703753), but $^{143}Nd/^{144}Nd$ (0.512763 to 0.512829) in the range of those obtained in Osorno and Calbuco volcanic samples (Fig. 10). Non-volcanic crustal rocks of the region are potential contaminants of Osorno and Calbuco products (granulites, gabbros, and granitoids, Hickey-Vargas et al., 1995; Aragón et al., 2011) and most of their isotopic values differ from the ranges of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ of Osorno and Calbuco products (see Table 3).

DISCUSSION

Calculated groundmass composition

Oxygen fugacity modelling was performed using the compositions of both glass inclusions in olivine phenocrysts (Group 1 and Group 2) and the calculated anhydrous matrix composition (Os-144* composition, calculated from the composition of the sample Os-144, representing the more evolved residual melt, present immediately before eruption; see Table 8). Being low in the sequence, the sample Os-144 has experienced limited interaction with the atmosphere and most likely preserves a record of the oxygen fugacity most similar to pre-eruptive conditions (Mollo et al., 2013). In addition, this sample has a representative whole-rock chemistry, typical mineral assemblages and displays textural features observed in all the volcanic products analysed (see Tables 2 and 5), making Os-144 a representative effusive product of the 1835 AD eruption. The fall deposits corresponding to the second eruptive phase (Os-164) are excluded from this type of modelling because they are more prone to rapid oxidation during the eruption than those from lava flows (Mollo et al., 2013). We determined the groundmass composition (glass and microlites) by considering Os-144 (fresh and with no evident signs of oxidation) as representative of the mean whole-rock composition (Table 2). To obtain groundmass composition, we subtracted the composition of representative phenocryst mineral phases, considering mass balance and modal abundances (Table 5). From now on that composition is named as Os-144* (Table 8, details of calculation are available in Supplementary Data 2). The calculated composition of Os-144* is similar to those reported for several aphyric products of Osorno volcano from Unit 3 reported by Tagiri et al. (1993) and Group 2 of measured glasses measured as part of this study.

Thermodynamic equilibrium

Chemical equilibrium between olivine and clinopyroxene was tested using equations from Grove et al. (1997). According to these equations, we calculated a hypothetical melt composition in equilbrium with each measured crystal composition. We did this by checking their partition coefficient K_D^{Fe-Mg}, where $K_D^{Fe-Mg} = \left[X_{Fe}^{Mineral\ phase} \times X_{Mg}^{Melt}\right] / \left[X_{Mg}^{Mineral\ phase} \times X_{Fe}^{Melt}\right]$ (Roeder and Emslie, 1970). If the phases are in equilibrium with the same melt, then we considered the whole system, consisting of those solid phases to be in equilibrium too (details in Supplementary Data 3).

Olivine-melt equilibrium and diffusive reequilibrium

The equilibrium conditions between melt inclusions and the olivine host (Fig. 11) are tested using the Toplis (2005) equation for K_D^{Fe-Mg}, considering Fe^{2+} and Fe^{3+} values in melt following the methods of Maurel and Maurel (1982). This equilibrium filter is used prior to the application of other methods that will be used to estimate intensive parameters. Most of the olivine compositions (n=6) from Group 1 (Fo_{76-79}) and the two olivine crystals from Group 2 ($Fo_{69–73}$) are in equilibrium with the hosted melt inclusions (Fig. 11). We only consider glassy melt inclusions in olivine to ensure their compositions lie on the liquid line of descent (Kent, 2008). Although inclusions with visible daughter and/or co-trapped minerals exist, they are discarded from our attempt to obtain representative host melt contents (Sinton et al., 1993; Danyushevsky et al., 2002a; Kent, 2008). We also discarded melt inclusions linked to the exterior of the host mineral. The host mineral (in this case, olivine) crystallises in melt inclusions at the boundary between the melt inclusion and the host mineral, which has a lower nucleation energy than homogeneous nucleation (cf. Roedder, 1979). According to Kent (2008), this growth on the inclusion wall may be apparent in compositional profiles and also BSE images. This growth causes fractionation of the melt within the inclusion, which can subsequently be modified by diffusion during magma residence at high temperatures (Danyushevksy et al., 2000; 2002a). Larger melt inclusion diameters are associated with longer re-equilibration timescales (Danyushevsky et al. 2000; 2002b). To study pre-eruptive conditions via melt inclusions, we examine the core compositions of the largest melt inclusions (diameter > 50 μm), which we interpret would represent pre-eruptive composition before re-equilibration (cf. Danyushevsky et al., 2002b). The only evidence of post-entrapment crystallisation is a thin rim (< 1 μm) of olivine growth.

Compositional traverses were measured in olivine-hosted melt inclusions and show MgO variations because the growth of the olivine thin rims were balanced by MgO consumption from the melt inclusion. We can be confident that the compositional profiles of olivine-hosted melt inclusions represent diffusion and are not affected by convolution effects because the host olivine phenocrysts have higher MgO contents than the melt inclusions. Hence, they can be used to calculate timescales of re-equilibration. If secondary fluorescence is affecting the measurements, then the compositional profiles within melt inclusions would show an apparent increase in MgO content towards the rims. In contrast, we recognise a decrease in MgO content (Fig. 12). In small melt inclusions (diameter < 50 µm) the compositional profiles do not show the MgO content depletion towards the rim that we observed in > 50 µm diameter melt inclusions. Compositional changes in melt inclusions from core to rim may record the evolution of the melt close to the melt/mineral interface, influenced partially by a high growth rate (Watson and Müller, 2009) and short timescales, hindering compositional re-equilibrium. The calculated timescales of re-equilibration of six compositional traverses for an unrealistically low temperature of 850 ºC are only a few minutes (Fig. 12; Table 9) and for more credible magmatic temperature of 1060 ºC, are few seconds (Table 9). As such, the compositions of the rims of olivine-hosted melt inclusions were modified only during syn-eruptive process and the plateaus of uniform melt inclusion composition represent pre-eruptive composition. Then the core compositions of olivine-hosted melt inclusions would not be significantly affected by the olivine growth in the olivine-melt interface. According to the experiments of Newcombe et al. (2014), concentration profiles could affect the centres of large melt inclusions in up to 100 minutes.

Using finite element methods, we modelled the variation of Mg concentration (C_{MgO}, in wt. %) resulting from Mg diffusion in the olivine-hosted melt inclusions, of the radial component of the time-dependent diffusion equation in spherical polar coordinates (Crank, 1975), following the equation 1:

$$\left(\frac{\partial C_{MgO}}{\partial t}\right) = D_{MgO}\left(\frac{\partial^2 C_{MgO}}{\partial r^2} + \frac{2}{r}\cdot\frac{\partial C_{MgO}}{\partial r}\right) \qquad equation\ 1$$

where r is radius (in m), D_{MgO} is diffusivity (in m^2/s), and t is time (in s). We calculated the diffusivity of MgO in melt inclusions (D_{MgO}) following the equation of Chen and Zhang (2008):

$$\ln(D_{MgO}) = -7.895 - \frac{26\,257}{T} \qquad equation\ 2$$

where T is in K. The modelled timescales, obtained for different input temperatures, are available in Table 9. Details of all olivine-hosted melt inclusions can be found in Supplementary Data 2 and example videos of modelled diffusion of MgO within melt inclusions (and the corresponding MATLAB® codes) of the previously mentioned Osorno samples are available in Supplementary Data 4. The uncertainties related to the Chen and Zhang (2008) equation and glass chemistry measurement do not change significantly the calculations performed. Therefore, the compositions of the core melt inclusions fit for calculations of intensive variables.

Physical intensive variables

The propagations of uncertainties for the calculation of all the intensive conditions (temperature, pressure, oxygen fugacity, and dissolved magmatic water content) were carried out assuming a Gaussian distribution of uncertainties and considering both internal uncertainties (associated with the experimental method) and external uncertainties (associated with precision and accuracy of electron microprobe analyses) uncertainties. A summary of the intensive variables is in Table 10.

Olivine-augite thermometry

We used the olivine-augite Fe-Mg exchange geothermometer of Loucks (1996) in the cores of olivine-augite equilibrated pairs, which yielded temperatures from 1100 to 1140 ºC (± 15 ºC), with an average of 1114 ºC (σ = 16 ºC) for olivine-augite pairs involving Group 1 olivine grains (Fo_{76-79}) and similar temperatures from 1091 to 1166 ºC (± 15 ºC), with an average of 1125 ºC (σ = 24 ºC) for olivine-augite pairs involving Group 2 olivine grains (Fo_{69-73}). We determined the thermodynamic equilibrium state between olivine and augite (n=30) via the Loucks (1996) parametrisation (see section Supplementary Data 3 for details).

Ca-in-olivine thermometry

We used the Ca-in-olivine thermometer of Shejwalkar and Coogan (2013) in olivine cores (Fo_{70-76}), which yielded temperatures from 1094 to 1097 ºC (± 22 ºC), with an average of 1096 ºC (σ = 2 ºC) for Group 1 olivine phenocrysts (Fo_{76-79}) and temperatures from 1049 to 1173 ºC (± 22 ºC), with an average of 1129 ºC (σ = 40 ºC) for Group 2 olivine phenocrysts (Fo_{69-73}). We assume contemporary growth in clots of olivine together with clinopyroxene and plagioclase based on their textural relations.

Olivine-spinel thermometry

We used the olivine-spinel thermometer of Coogan et al. (2014) for spinel inclusions in olivine phenocryst cores (see Wan et al., 2008), which yielded temperatures from 1051 to 1070 ºC (± 42 ºC) with an average of 1061 ºC (σ = 6 ºC) for Group 1 olivine phenocrysts ($Fo_{76\text{-}79}$). We also obtained temperatures from 1104 to 1122 ºC (± 42 ºC) with an average of 1113 ºC (σ = 13 ºC) for Group 2 olivine phenocrysts ($Fo_{69\text{-}73}$).

Olivine-spinel oxybarometry

We used the olivine-spinel oxybarometer of Ballhaus et al. (1991) in spinels inclusions in olivine phenocryst cores, which yielded an oxygen fugacity buffer of ΔQFM + 2.3 (± 0.7) for Group 1 olivine phenocrysts ($Fo_{76\text{-}79}$) and ΔQFM + 2.7 (± 0.7) for Group 2 olivine phenocrysts ($Fo_{69\text{-}73}$). We calculated the values of oxygen fugacity buffer considering the temperatures obtained using the olivine-spinel thermometry (see Olivine-spinel thermometry section) and a constant pressure of 2 kbar (results do not show significant variations with pressure). The total uncertainty considers uncertainties of pressure, temperature, EPMA measurements, and inherent errors of the method.

Spinel-melt oxybarometry in melt inclusions

For these calculations, we considered the same pairs of spinel inclusions and olivine phenocrysts that we used for the determination of equilibrium olivine-spinel (following the procedure of Kamenetsky et al. (2001). The equilibrium test of olivine-spinel pairs shows a positive correlation of Mg# of spinel inclusions and the hosting forsterite olivine phenocryst (details in Supplementary Data 3). Melt inclusion-olivine host equilibrium is determined as explained in the Thermodynamic Equilibrium section. When the olivine host phenocryst is in equilibrium with both the hosted melt inclusion and the hosted spinel inclusion, we use the Maurel and Maurel (1982) method to determine the Fe^{2+}/Fe^{3+} ratio of olivine-hosted melt inclusions considering the Fe^{2+}/Fe^{3+} of the olivine-hosted spinel composition (see Mineral Chemistry section), which we assume equilibrated by transitivity. Finally, we applied the Borisov et al. (2018) equation to calculate oxygen fugacity values recorded in olivine-hosted melt inclusions:

$$log\left(\frac{FeO_{1.5}}{FeO}\right) = k \cdot log(f_{O_2}) + \frac{h}{T} + c + \sum d_i \cdot X_i + d_{SiAl} \cdot X_{SiO_2} \cdot X_{Al_2O_3} + d_{SiMg} \cdot X_{SiO_2} \cdot X_{MgO} \qquad equation\ 3$$

where T is temperature (in K), X_i is the anhydrous mole fraction of melt components, and c, h, k, d_i, and d_{Xi} are regression coefficients (constant values as supplied in Supplementary Data 5).

The calculations yield an oxygen fugacity buffer range of ΔQFM +1.1 (± 0.5) for Group 1 olivine phenocrysts and ΔQFM +1.4 (± 1) for Group 2 olivine phenocrysts. We performed these calculations considering a temperature of 1060 ºC and 1113 ºC, respectively (± 42 ºC; see Olivine-spinel thermometry). The uncertainty of temperature depends on the uncertainty of both the Fe^{2+}/Fe^{3+} ratio in olivine-hosted spinel inclusions and the method of Borisov et al. (2018; Equation 3). These oxygen fugacity values are also consistent with those yielded by the method of Jayasuriya et al. (2004): ΔQFM + 0.7 (± 0.3) and ΔQFM + 1.4 (± 0.3) for Group 1 and Group 2 of olivine phenocrysts, respectively.

Water dissolved in melt inclusions

We calculated the water dissolved in magma in the olivine-hosted melt inclusions (representing an early stage of magmatic evolution) using the Ca-in-olivine hygrometer of Gavrilenko et al. (2016). The calculations yielded water contents from 3.4 to 4.8 wt. % (±

0.8 wt. %), with an average of 4.3 wt. % (σ = 0.5 wt. %) for Group 1 olivine phenocrysts and from 3.4 to 5 wt. % (± 0.8 wt. %) H_2O, with an average of 4.2 wt. % (σ = 1.1 wt. %) for Group 2 olivine phenocrysts. We applied the Gavrilenko et al. (2016) method only in those cases when the melt inclusions are in equilibrium with the host olivine phenocryst (see Fig. 12). These results are consistent with those obtained using the Kelley and Cottrell (2009) method for our olivine-hosted melt inclusions to determine water solubility in primitive melts. Although Ca is sensitive to changes in olivine growth (e.g., Simkin and Smith, 1970; Shejwalkar and Coogan, 2013), this effect is negligible for the studied olivine-melt inclusion system because the timescales in which post-entrapment crystallisation could affect the Ca in olivine composition would be relatively long, in contrast with the very short timescales calculated for post-entrapment crystallisation in our samples. In consequence, the Ca in olivine is not significantly affected by dissolution, reprecipitation and other processes. Our calculated ranges of water dissolved in magmas are consistent with other values measured for olivine-hosted melt inclusions from Llaima Volcano, in the SVZ (up to 4.4 wt.%; Bouvet de Maisonneuve et al., 2012; Ruth et al., 2016). Also, our calculated ranges and averages of water dissolved in magmas are consistent with those measured and reported for olivine-hosted melt inclusions from other arc geological settings, such as Marianas (e.g., Shaw et al., 2008; Kelley et al., 2010; Brounce et al., 2014), Central America (e.g., Roggensack et al., 1997; Sadofsky et al., 2008; Portnyagin et al., 2014), and Kamchatka (e.g., Auer et al., 2009; Tobelko et al., 2019).

We also used the Putirka (2005; 2008) and Zhang et al. (2007) equations to determine H_2O wt. % dissolved in melts and pressure iteratively, considering the plagioclase phenocrysts composition (An_{75}, Zone 2) and the corresponding plagioclase-hosted melt inclusion compositions. The calculations yielded water dissolved concentration between 2.1 and 4.2 wt. % and pressures up to 2.6 kbar (details in Supplementary Data 6). Those values are consistent with our other water dissolved calculations. In addition, the “accurate volatiles by difference” method of Hughes et al. (2019) yielded water dissolved contents from 0 to 3 wt. % in olivine-hosted melt inclusions. Due to the slow diffusivity of Ca in olivine (Coogan et al., 2005) compared to the high diffusivity of volatiles in melts (e.g., Zhang and Ni, 2010; Zhang et al., 2010; Zhang and Gan, 2022), we infer that the method of Gavrilenko et al. (2016) would yield water content representing an initial stage after melt inclusion entrapment. Although CaO is very sensitive to olivine growth rate, the relatively constant core CaO concentration in olivine phenocrysts suggest they did not change significantly in time. In contrast, the procedure of Hughes et al. (2019) would likely give dissolved water content in melts after diffusive hydrogen (and other volatiles) loss, which occurs rapidly in response to changes in intensive conditions (e.g., Hauri, 2002; Chen et al., 2011; 2013; Gaetani et al., 2012).

Fe-Ti oxides thermometry and oxybarometry in xenoliths

We used the Ghiorso and Evans (2008) thermometer and oxybarometer in ilmenite-titanomagnetite grain pairs from the volcanic xenoliths within the 1835 AD Osorno volcano products. The cores yielded temperatures from 751 to 841 °C (± 15 °C), with an average of 782 °C ($\sigma = 33$ °C) and oxygen fugacity buffer from ΔQFM-0.1 to ΔQFM+0.7 (± 0.1), with an average of ΔQFM+0.2 ($\sigma = 0.3$). The rims yielded higher temperatures from 751 to 983 °C (± 15 °C), with an average of 843 °C ($\sigma = 90$ °C), and an oxygen fugacity buffer ranging from ΔQFM-0.4 to ΔQFM+1.5 (± 0.1), with an average of ΔQFM+0.4 ($\sigma = 0.8$).

Thermodynamic modelling

We performed thermodynamic modelling using the freeware Petrolog3 (Danyushevsky and Plechov, 2011) to obtain physical magmatic intensive conditions of two melt compositions: olivine-hosted melt inclusions (both representing an early stage of magmatic evolution) in Group 1 olivine phenocrysts (Fo_{76-79}) and Group 2 olivine phenocrysts (Fo_{69-73}). Via Petrolog3, we determined the equilibrium between melt inclusions and their host olivine phenocrysts by crystallisation modelling (for details see Supplementary Data 7). We modelled the equilibrium at different oxygen fugacity buffer (from ΔQFM+0.4 to ΔQFM+2.4) and pressure conditions for water-saturated systems. Our objective was to construct a model that was consistent with the calculated water content dissolved in the melt inclusions. Melt inclusions hosted by Group 1 olivine phenocrysts (Fo_{76-79}) reached equilibrium with up to 1 wt. % crystallisation (see Supplementary Data 7) at pressures of up to 2.5 kbar (equivalent to 7 km depth). Melt inclusions hosted by Group 2 olivine phenocrysts (Fo_{69-73}) reached equilibrium with up to 4 wt. % crystallisation (see Supplementary Data 7) at the same pressure conditions as inclusions hosted in Group 1 olivine phenocrysts (up to 2.5 kbar). Consequently, the melt inclusions were close to equilibrium with the host mineral. These results confirm the validity of the chemical filter to determine the melt-olivine equilibrium and suggest that the early stage of magmatic evolution occurred in the upper crust, at depths up to 7 km depth (i.e., at pressures up to 2.5 kbar). These pressure conditions yielded by thermodynamic modelling are consistent with those calculated, considering measured dissolved water concentrations, in olivine-hosted melt inclusions from arc volcanic products (e.g., Shaw et al., 2008; Auer et al., 2009; Werner et al., 2020; Rasmussen et al.,

2022) and those yielded by thermodynamic modelling for Osorno products (Rhyolite-MELTS; Bechon et al., 2022).

A shallow reservoir beneath Osorno volcano

We calculated the pre-eruptive temperature using several complementary methods. Calculations via Fe-Mg exchange geothermometer (Loucks, 1996) yielded temperatures of 1114 ºC and 1125 ºC (± 15 ºC) for olivine phenocrysts of composition in the range of Group 1 (Fo_{76-79}) and Group 2 (Fo_{69-73}), respectively. Ca-in-olivine thermometry (Shejwalkar and Coogan, 2013) yielded slightly different temperatures of 1096 and 1129 (± 22 ºC) for Group 1 and Group 2 olivine phenocrysts, respectively. Olivine-spinel thermometry (Coogan et al., 2014) yielded lower temperatures of 1061 ºC and 1113 ºC (± 42 ºC) for Group 1 (Fo_{76-79}) and Group 2 (Fo_{69-73}) olivine phenocrysts, respectively. Experiments by Müller et al. (2013) suggest diffusion in clinopyroxene is limited. This suggests that olivine-augite thermometer records temperatures that would be representative of the first stage of early magmatic evolution for systems with up to 2 wt. % of water dissolved in melt (Loucks, 1996), which is not the case for Osorno volcanic products. However, experiments performed in andesitic and basaltic rocks from Santorini volcano (Andújar et al. 2015; 2016) yielded pressure (2-4 kbar), temperature (1000-1040 °C) and dissolved water content in the melt (3-5 wt.%), which are consistent with those we obtained from samples of the 1835 AD Osorno eruption.

According to Coogan et al. (2014), it seems likely that most of the Al in olivine phenocrysts is due to reaction with the spinel Al component, and therefore olivine-spinel thermometry would preserve a lower temperature more representative of the coexistence of olivine and spinel rather than a liquidus temperature.

The oxygen fugacity of the early stage of evolution of the magmatic systems is represented by the compositions of olivine-hosted melt inclusions. The melt inclusion oxybarometry yielded an oxygen fugacity buffer from ΔQFM+1.1 to ΔQFM+1.4, suggesting that the oxygen fugacity buffer remained relatively constant during the crystallisation of the olivine phenocrysts from Group 1 and Group 2 of 1835 AD Osorno samples. The absence of orthopyroxene in our samples and the calibration for spinel-bearing mantelic rocks of the Ballhaus et al. (1991) olivine-orthopyroxene-spinel oxybarometer lead us to favour the oxygen fugacity buffer values yielded by other methods.

In the cognate xenoliths, the core of the Fe-Ti oxide grains yielded a temperature range of 751 to 841 °C and oxygen fugacity conditions up to ΔQFM+1.5, which correspond to subsolidus conditions, according to Rhyolite-MELTS modelling (Ghiorso and Sack, 1995; Gualda et al., 2012). This suggests that Fe-Ti oxide crystals recorded a compositional equilibrium after a quenching event, which does not represent pre-eruptive magmatic conditions. This re-equilibrium at low temperature occurs because elements in Fe-Ti oxide grains show much higher interdiffusivity than in silicate phases (Aragon et al. 1984; Aggarwal and Dieckmann 2002a, b). Among the six measured traverses in ilmenite-titanomagnetite pairs, we recognised a heating event in only three ilmenite-titanomagnetite pairs (details in Supplementary Data 8). This heating recorded in the grain boundaries suggests the xenoliths were incorporated during the magma ascent or shortly before it. We could not determine the timescales from heating to eruption with a spacing of ~2 µm between single measurements by EPMA.

Petrolog3 modelling of olivine-hosted melt inclusion compositions suggests that the early stage of magmatic evolution occurred in the upper crust, which is consistent with the shallow magmatic reservoir beneath Osorno volcano inferred by Díaz et al. (2020) at 4-8 km depth and 2 km to the E of the summit of Osorno volcano. This is also corroborated by SERNAGEOMIN–OVDAS (2017b; 2018a, b; 2019), who reported recent volcano-tectonic seismic activity, in which the associated sources correspond to 2.6–3.9 km depth. In conclusion, all approaches that estimate magmatic pressure conditions suggest the existence of a magmatic reservoir in the upper crust, which seems to be a common feature in the plumbing systems of the SVZ of the Chilean Andes (e.g., Calbuco volcano, Nikkhoo et al., 2016; Delgado et al., 2017; Morgado et al., 2019a; Arzilli et al., 2019; Llaima volcano, Bouvet de Maisonneuve et al., 2012; Villarrica volcano, Lohmar et al., 2012, Morgado et al., 2015; Quetrupillán, Brahm et al., 2018). Moreover, Díaz et al. (2020) also reported (based on magnetotellurics) the presence of a deep (7-18 km depth) magmatic reservoir in the Osorno volcano system.

Several prior studies have suggested that relatively reducing magmatic conditions produce tholeiitic magmas, whereas oxidizing magmatic conditions produce calc-alkaline magmas (e.g., Druitt et al., 1999; Andújar et al., 2015; 2016). However, Tatsumi et al. (2008) reported that calc-alkaline and tholeiitic magmas could coexist in temporal and spatial proximity and inferred the existence of both types of basaltic magmas beneath Zoa volcano (Japan). Moreover, Elburg (2010) show that oxybarometers can yield lower oxygen fugacity conditions for calc-alkaline compared to tholeiitic magmas, suggesting fO_2 is not the only variable controlling the differentiation trend. Tholeiitic trends in volcanic products are usually associated with relatively lower concentrations of water dissolved in melts (< 4 wt. %) than calc-alkaline, which would play a role in the tholeiitic trend (e.g., Zimmer et al., 2010; Parman et al., 2011; Hamada et al., 2014). However, recent experiments (Firth et al.,

2019) have shown that other reasons also could be invoked to explain both calc-alkaline and tholeiitic trends in volcanic products: contrasting conditions for magmatic fractionation or differences in the parental magma. We suggest the tholeiitic trend recognised in whole-rock and melt inclusion compositions (considering an enrichment of total Fe from melt inclusions to groundmass composition) from the 1835 AD Osorno eruption could initially evolve in the lower crust, in a deep reservoir beneath Osorno volcano (7-15 km depth; Díaz et al., 2021), generating a tholeiitic trend (as in Santorini volcanic products; Andújar et al., 2016). This magma did not subsequently deviate from the tholeiitic trend during subsequent evolution in the shallow magmatic reservoir (Bechon et al., 2022) because the composition of the melt is not controlled solely by fO_2, but also by dissolved water content, fractionation, and mixing (Elburg, 2010).

Volatile exsolution between early and late evolution stages

We determined the water dissolved in magmas considering olivine-hosted melt inclusions composition representing an early stage of magmatic evolution, which yielded values of up to 5.6 wt. % (following the method of Kelley and Cottrell, 2009) and ~4.2 wt. % average (following the method of Gavrilenko et al., 2016). Other methods to determine water dissolved concentration are related to higher uncertainties: the iterative use of Putirka (2005; 2008) and Zhang et al. (2007) equations (which yielded concentrations between 2.1 and 4.2 wt. %) and the Hughes et al. (2019) method (up to 3 wt. % concentration), suggest volatile exsolution after the early stage of magmatic evolution before the 1835 AD Osorno eruption. This likely volatile exsolution process could be associated with an accumulation of gas phases in the magma reservoir before the eruption (presumably at the top of the system), the release of which may have been described by Darwin (1839a) as the “smoke” emitted around two months before the onset of the 1835 AD eruption of Osorno.

Crystal-mush within the magma reservoir and crystallisation events

The existence of a crystal mush in the magmatic reservoir can be inferred using several lines of evidence: (i) glomerocrysts, (ii) interstitial glass between grains of crystal clots with different composition from the outer glass (Fig. 6, Table 7), (iii) disequilibrium textures (zoning and resorption) in isolated crystals as well as crystals from clots, and (iv) high degrees of crystallinity (25 to 45 vol. %, Table 5). Based on textural features and the narrow temperature crystallisation range (considering overlapping uncertainties), we infer that the magma was multiply-saturated with the minerals observed throughout the crystallisation sequence. However, the zoning patterns preserved in plagioclase phenocrysts suggest a complex crystallisation history for that phase. The resorption observed in several plagioclase phenocrysts, affecting plagioclase Zones 1 and 2, suggests the occurrence of plagioclase destabilisation after initial crystallisation events. We interpret this destabilisation as relating to processes that caused mush disaggregation. Several authors have given different interpretations of resorption and sieve textures – typical features of disequilibrium between plagioclase and melt – such as fluid-absent rapid decompression (Nelson and Montana, 1992; Annen et al., 2006) or magma mixing (thermal and compositional mixing) usually related to heating (Johannes et al., 1994; Ginibre and Wörner, 2007; Pietranik et al., 2006; Lohmar et al., 2012). Additionally, the existence of patchy zoning with the same composition as plagioclase phenocryst rims and microphenocrysts, equivalent to Zone 3 composition, is consistent with a late pre-eruptive crystallisation episode, after mush disaggregation (Fig. 13). Tagiri et al. (1993) inferred that the porphyritic products from Osorno volcano, similar to the volcanic products studied in this work, resulted from the addition of calcic plagioclase to the aphyric products. The most reasonable explanation for this is melting of ~ 20 wt. % of XAn_{70-80}, similar to Zone 2 plagioclase compositions. Compositions of aphyric materials (Tagiri et al., 1993) are similar to Os-144* (groundmass composition), suggesting that aphyric products from Units 1 and 3 from Osorno volcano also could be explained as interstitial melt extracted from a crystal-mush magma reservoir.

Group 1 and Group 2 olivine phenocrysts exhibit fairly constant (unzoned) compositions with only syn-eruptive zoning patterns in the crystal rims. This absence of pre-eruptive zoning patterns suggests that there were either at least two crystal mushes or a zoned crystal mush, where Group 1 and Group 2 olivine phenocrysts grew independently. For this, we conclude that there could not have been any protracted interaction between Groups 1 and 2 olivine phenocrysts with a common melt. Moreover, the difference in compositions of pyroxene coupled with Group 1 and those coupled with Group 2 in crystal clots, also suggests the olivine phenocrysts Groups 1 and 2 grew independently of each other. Recent studies (e.g., Bergantz et al., 2015; 2017; Schleicher et al., 2016; Morgado et al., 2019b) have shown that crystal mushes within a magma reservoir interact with a magma intrusion in a “mixing bowl”, above the location of the intrusion itself. This “mixing bowl” corresponds to the lower parts of the crystal mush where thermo-mechanical effects are at a maximum, whereas those places located relatively far from it could form and maintain the distinct identities of the unzoned Group 1 and Group 2 olivine crystals observed in this study of a magma reservoir beneath Osorno volcano (e.g., Morgado et al., 2019b; Cheng et al., 2020). Although we favour the "zoned crystal mush" alternative, Díaz et al. (2020) inferred at least two magma reservoirs below Osorno volcano; one at upper crustal depths (between 4 and 8 km depth) and a second at lower in the crust (between 7 and 15 km). The existence of those reservoirs could explain two crystal mushes that evolved separately and interacted just before the eruption, rather than one single “zoned crystal mush”. The Cr-Al-Fe^{3+} composition of spinel inclusion in olivine phenocryst follow the oxidation trend in cumulus: increasing Fe^{3+} at constant Cr composition (e.g., Simakin et al., 2021; details in Supplementary Data 3). The composition of those spinels would suggest that the interstitial melt is reduced during olivine oxidation (e.g., Knafelc et al., 2019; Simakin et al., 2021). Moreover, embayments in some olivine phenocrysts suggest a disequilibrium event (presumably a heating event), which could be related to crystal mush disaggregation with interstitial melt close to water saturation (Alidibirov and Dingwell, 1996) prior the 1835 AD Osorno eruption, but it did not generate zoning patterns at the upper levels of the zoned crystal mush. The very thin rims of olivine phenocrysts would represent a syn-eruptive quenching overgrowth (e.g., Pankhurst et al., 2018; Couperthwaite et al., 2020).

Regional geochemical heterogeneity: Osorno in context

In volcanic rocks of relatively primitive composition, whole-rock chemistry can give insights into other pre-eruptive processes, such as mantle source and crustal contamination, which complement the information yielded by mineral chemistry and allow comparison with different nearby volcanic systems. The composition of the 1835 AD Osorno products shows similar major element chemistry and trace-element patterns to those reported by Tagiri et al. (1993), Moreno et al. (2010), and Bechon et al. (2022) for Units 4 from the Osorno volcano (Figure 14). Therefore, we consider the volcanic products of the 1835 AD Osorno eruption as representatives of Holocene Osorno volcanic products in general.

Volcanic products from Calbuco, Osorno, and La Picada – a stratovolcano on the same NE-SW lineament as Osorno – possess higher whole-rock fluid-mobile to fluid-immobile trace elemental ratios (e.g., Ba/La vs Rb/Nd, Fig. 14) than La Viguería, a nearby small eruptive centre built over the main trace of the LOFZ. We propose that the higher fluid-mobile to fluid-immobile element ratios can be linked with a higher slab-derived fluid component in the mantle source beneath Calbuco, Osorno and La Picada than La Viguería. Moreover, Calbuco, Osorno, and La Picada volcanic products also have lower La/Yb ratios than La Viguería volcanic material, with the lower La/Yb ratios being associated with either a higher degree of partial melting (Fig. 14c), or melting of a previously melt-depleted source. Although La Viguería samples are the most primitive of the studied region (lowest SiO_2 wt. % and highest Mg#, and MgO wt. %; see Fig. 8 and Fig. 14), they also contain the highest K_2O concentrations. Higher K_2O concentrations and a decrease in H_2O content in the volcanic products from La Viguería could be derived from slab sediment melting, resulting from a temperature increase of the slab surface (Hermann and Spandler, 2008). Temperature increases at higher slab depth (Molnar and England, 1995) yielding water-poor sub-arc mantle melts, lower H_2O supply to the mantle wedge and, in consequence, lower degrees of partial melting recorded in volcanic products eastward from the Peru–Chile trench. This is consistent with the conclusions of McGee et al. (2017) and Hickey-Vargas et al. (1989) for the volcanic material from Caburgua-Huelemolle small eruptive centres, located eastward from the nearby Villarrica volcano (39.3ºS, Southern Andes), which is, like La Viguería, built over the main trace of the LOFZ. Watt et al. (2013) also came to similar conclusions in their study of the nearby Apagado and Hornopirén volcanoes at the latitude of 42ºS.

A comparison of the REE systematics of the volcanic products from Calbuco, Osorno, La Picada, and La Viguería (Fig. 9) suggests all these volcanic systems have a similar mantle source. La Viguería cone samples (particularly the sample LV-152) show high Ni, Cr, and low Rb values (Fig. 8 and 14), also suggesting their products are the most primitive of the region.

Sources of volcanic products composition at latitude ~41º06`S

^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd isotope ratios can be used to identify the possible involvement of subduction-related fluids and crustal contamination in the generation of the volcanic products from Osorno, Calbuco, and La Viguería (we do not possess isotopic data from the other nearby volcanic centres). We used the compositions of several representative end-member rocks, whose chemistry could influence the Calbuco and Osorno whole-rock chemistry, should the original magma interact with them in any significant way. The mantle source for magmas supplying these volcanoes lies close to a mixing line in ^{87}Sr/^{86}Sr vs. ^{143}Nd/^{144}Nd space between a representative depleted MORB mantle (DMM; Workman and Hart, 2005) and a representative enriched mantle end member EM-I (enriched mantle, Zindler and Hart, 1986; Garapić et al., 2015; Fig. 15). The most primitive samples from La Viguería plot on this mixing line, whereas those from Osorno and Calbuco have, by comparison, elevated ^{87}Sr/^{86}Sr for a given ^{143}Nd/^{144}Nd (Fig. 15). This primitive composition of La Viguería volcanic products could be related to the LOFZ, which would facilitate a more rapid magmatic ascent, minimising the interaction with the crust (e.g., López-Escobar et al., 1995a; Cembrano and Lara, 2009; Segovia et al., 2021). Figure 15 also shows a mixing line between altered oceanic crust (AOC; Jacques et al., 2014, via Arc Basalt Simulator; Kimura et al., 2009) and CSVZ trench sediments (Kilian and Behrmann, 2003); both are likely potential contaminants during the production of magma in this region. Possible sources of crustal contamination are also shown on Figure 15 (details on Table 3). These include lower crustal granulites, gabbros (Hickey-Vargas et al., 1995), and upper crustal granodiorites (Aragón et al., 2011), all of which have been identified in the basement of this region.

In terms of potential fluid inputs, Calbuco, Osorno, and La Viguería volcanic products have lower $^{87}Sr/^{86}Sr$ than AOC and sediments. Also, in terms of $^{143}Nd/^{144}Nd$, the studied samples of volcanic products plot in between AOC (higher ratio) and sediments (lower ratio). Using a simple mixing model (Fig. 15; details in Supplementary Data 9), the composition of a fluid that is likely to have influenced the composition of the magmas investigated in this study likely consists of contributions from both AOC and trench sediments. Using the composition of La Viguería volcanic products as the end-member best representing the mantle source, in order to reach the composition of Calbuco and Osorno volcanic products, the contributions of the fluid component should have sediment:AOC ratios ranging from 0.15 to 9 (details of calculations are available as Supplementary Data 9). These significant variations probably occur because the sediments from the trench of CSVZ (Kilian and Behrmann, 2003) can be extremely heterogeneous in terms of its $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ signature (Kilian and Behrmann, 2003; Fig. 15). Although it is reasonable to consider some contributions from sediments in the slab-derived fluid, calculations of the fractions are unlikely to be conclusive. The deviation of the Calbuco and Osorno products from the simple mixing line between the representatives DMM and EM1 values likely reflects the influence of these slab-derived fluids. This model does not consider mantle heterogeneity (as suggested for the CSVZ, at ~39º30'S latitude by McGee et al., 2017), primarily because the similarities in the non fluid mobile elements systematics of these three volcanoes preclude significant heterogeneity in the mantle source. Chemical variations of slab-derived fluid input have also been suggested for the CSVZ, at ~39º30'S latitude by Hickey-Vargas et al., 1989), but are not accounted for in this first-order model. While chemical heterogeneity has been suggested, we are unable to determine the effect, if any, that different elemental concentrations would likely have on the final isotopic composition of the slab fluids, so we are reluctant to speculate and complicate our model unnecessarily.

In terms of assimilation, the presence of both granulite and gabbro xenoliths (Hickey-Vargas et al., 1995) in the volcanic products of the 1961 eruption of Calbuco and the presence of the North-Patagonian batholith in the region (Adriasola et al., 2006; Aragón et al., 2011), infer the possibility of interaction between those crustal rocks and the ascending magma. Following the mixing lines described above for fluid input, we modelled granodiorite, granulite, and gabbro assimilation to assess the $^{143}Nd/^{144}Nd$ variations observed in the Calbuco and Osorno products (details in Supplementary Data 9). In order to shift the Osorno volcanic products from the mixing line between DMM and EM1, the assimilation of 40% of granulite would be necessary to reproduce the $^{143}Nd/^{144}Nd$ range observed, but this value is unrealistic (Taylor Jr., 1980; DePaolo, 1981). In constrast, less than 10 % assimilation of gabbro and granodiorite is required to reproduce the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ranges observed. For Calbuco samples, granulite, gabbro, and granodiorite mixing models cannot reproduce the $^{143}Nd/^{144}Nd$ range observed and they are not considered as significant contaminants.

These models suggest the most important factors controlling the Sr-Nd isotopic ratios of the studied volcanic products (at ~41ºS) are the nature of the mantle source and fluid input from the subduction zone rather than crustal assimilation. This is consistent with the conclusions of Jacques et al. (2014), who investigated the compositions of volcanic products from the whole CSVZ. Similarly, the $^{87}Sr/^{86}Sr$ of the volcanic material interpreted as xenoliths in 1835 Osorno volcanic products from the volcanic vent would not modify considerably the $^{87}Sr/^{86}Sr$ ratios because the volcanic units 1, 3 and 4 of Osorno (unit 2 data are not reported) exhibit similar values to those we present in this study (Tagiri et al., 1993; Fig. 10).

CONCLUSIONS

The last eruption of Osorno volcano occurred in 1835-1836 in two eruptive stages, with similar erupted products of basaltic andesite lavas and fall deposits, with plagioclase, olivine, and clinopyroxene as phenocrysts and spinels as inclusions in olivine phenocrysts. We used the composition of mineral phases, together with olivine-hosted melt inclusions to infer the following pre-eruptive features for the Osorno 1835 AD eruption (representative of the Osorno Unit 4):

- There is at least one upper-crustal magma reservoir beneath Osorno volcano at depths up to ~7 km (equivalent to 2.6 kbar, based on thermodynamic modelling and the use of the plagioclase-melt hygrometer-barometer equations iteratively), consistent with geophysical constraints. Calculated pre-eruptive magma temperatures derived from olivine-hosted spinel inclusions range from 1060 ºC to 1113 ºC with oxygen fugacity buffer of ~ΔQFM +1.1. Dissolved water concentrations in the olivine-hosted melt inclusions are estimated to have been up to 5.6 wt. %, with an average of ~4.2 wt. %.
- Disequilibrium textures in combination with evidence of local crystal accumulations make it likely that there was interaction of the erupted magmas with a pre-existing crystal mush. in erupted products (Fig. 16). This material underwent disaggregation due to either increased temperatures or volatile concentrations (Fig.16).

- Major and trace element concentrations in volcanic products from the latitude of Osorno volcano (41º06’S) indicate a higher fluid contribution to their mantle sources combined with higher degrees of source melting beneath the composite volcanoes (Calbuco, Osorno, and La Picada) than for the smaller calc-alkaline eruptive centres (represented by La Viguería cone), which are built over the LOFZ at the same latitude, but several km eastward of the main volcanic arc.
- Mixing models suggest that the most dominant factors controlling the composition of volcanic products at 41º06’S latitude are mantle source (depleted peridotite) and slab-derived fluid (with its sediment contribution). The contribution of crustal assimilates (represented by granites and gabbros) are restricted to < 10 wt.%. Our results have implications for the prediction of eruption characteristics in future eruptions of Osorno and neighbouring volcanoes.
- The approach we employ here, using olivine-hosted melt inclusions composition coupled to diffusion chronometry is adequate to study pre-eruptive and could be used for future studies, together with whole-rock chemistry and geophysical techniques to assess magmatic and volcanic systems holistically.

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Supplementary Data

Supplementary Data are available at Journal of Petrology online.

REFERENCES

Adriasola, A.C., Thomson, S.N., Brix, M.R., Hervé, F. & Stöckhert, B. (2006). Postmagmatic cooling and late Cenozoic denudation of the North Patagonian Batholith in the Los Lagos region of Chile, 41− 42 15′ S. International Journal of Earth Sciences 95(3), 504-528.

Aggarwal, S., & Dieckmann, R. (2002a). Point defects and cation tracer diffusion in $(Ti_xFe_{1-x})_{3-\delta}O_4$ 1. Non-stoichiometry and point defects. Physics and Chemistry of Minerals, 29(10), 695-706.

Aggarwal, S., & Dieckmann, R. (2002b). Point defects and cation tracer diffusion in $(Ti_xFe_{1-x})_{3-\delta}O_4$. II. Cation tracer diffusion. Physics and Chemistry of Minerals, 29(10), 707-718.

Alidibirov, M., & Dingwell, D. B. (1996). Magma fragmentation by rapid decompression. Nature, 380(6570), 146-148.

Andújar, J., Scaillet, B., Pichavant, M., & Druitt, T. H. (2015). Differentiation conditions of a basaltic magma from Santorini, and its bearing on the production of andesite in arc settings. Journal of Petrology, 56(4), 765-794.

Andújar, J., Scaillet, B., Pichavant, M., & Druitt, T. H. (2016). Generation conditions of dacite and rhyodacite via the crystallization of an andesitic magma. Implications for the plumbing system at Santorini (Greece) and the origin of tholeiitic or calc-alkaline differentiation trends in arc magmas. Journal of Petrology, 57(10), 1887-1920.

Angermann, D., Klotz, J. & Reigber, C. (1999). Space-geodetic estimation of the Nazca-South America Euler vector. Earth and Planetary Science Letters, 171(3), 329-334.

Annen, C., Blundy, J.D. & Sparks, R.S.J. (2006). The genesis of intermediate and silicic magmas in deep crustal hot zones. Journal of Petrology 47(3), 505-539.

Aragón, E., Castro, A., Díaz-Alvarado, J. & Liu, D-Y. (2011). The North Patagonian batholith at Paso Puyehue (Argentina-Chile). SHRIMP ages and compositional features. Journal of South American Earth Sciences 32, 547-554.

Aragon, R., McCallister, R. H., & Harrison, H. R. (1984). Cation diffusion in titanomagnetites. Contributions to Mineralogy and Petrology, 85(2), 174-185.

Arzilli, F., Morgavi, D., Petrelli., M, Polacci., M, Burton, M., Di Genova, D., Spina, L., La Spina, G., Hartley, M.E., Romero, J.E. & Fellowes, J. (2019). The unexpected explosive sub-Plinian eruption of Calbuco volcano (22–23 April 2015; southern Chile): Triggering mechanism implications. Journal of Volcanology and Geothermal Research 378, 35-50.

Auer, S., Bindeman, I., Wallace, P., Ponomareva, V., & Portnyagin, M. (2009). The origin of hydrous, high-δ18O voluminous volcanism: diverse oxygen isotope values and high magmatic water contents within the volcanic record of Klyuchevskoy volcano, Kamchatka, Russia. Contributions to Mineralogy and Petrology, 157(2), 209-230.

Ballhaus, C., Berry, R. F., & Green, D. H. (1991). High pressure experimental calibration of the olivine-orthopyroxene-spinel oxygen geobarometer: implications for the oxidation state of the upper mantle. Contributions to Mineralogy and Petrology, 107(1), 27-40.

Bechon, T., Billon, M., Namur, O., Bolle, O., Fugmann, P., Foucart, H., Devidal, J-L., Delmelle, N., & Vander Auwera, J. (2022). Petrology of the magmatic system beneath Osorno volcano (Central Southern Volcanic Zone, Chile). Lithos, 426, 106777.

Bergantz, G. W., Schleicher, J. M., & Burgisser, A. (2015). Open-system dynamics and mixing in magma mushes. Nature Geoscience, 8(10), 793-796.

Bergantz, G. W., Schleicher, J. M., & Burgisser, A. (2017). On the kinematics and dynamics of crystal- rich systems. Journal of Geophysical Research: Solid Earth, 122(8), 6131-6159.

Borisov, A., Behrens, H., & Holtz, F. (2018). Ferric/ferrous ratio in silicate melts: a new model for 1 atm data with special emphasis on the effects of melt composition. Contributions to Mineralogy and Petrology, 173(12), 1-15.

Bouvet de Maisonneuve, C., Dungan, M.A., Bachmann, O. & Burgisser, A. (2012). Insights into shallow magma storage and crystallization at Volcán Llaima (Andean Southern Volcanic Zone, Chile). Journal of Volcanology and Geothermal Research 211, 76-91.

Brahm, R., Parada, M.Á., Morgado, E., Contreras, C. & McGee, L.E. (2018) Origin of Holocene trachyte lavas of the Quetrupillán Volcanic Complex, Chile (39º30'S): Examples of residual melts in a rejuvenated crystalline mush reservoir. Journal of Volcanology and Geothermal Research 357, 163-176.

Brounce, M. N., Kelley, K. A., & Cottrell, E. (2014). Variations in $Fe^{3+}/\sum Fe$ of Mariana Arc basalts and mantle wedge fO_2. Journal of Petrology, 55(12), 2513-2536.

Castruccio, A., Clavero, J., Segura, A., Samaniego, P., Roche, O., Le Pennec, J. L., & Droguett, B. (2016). Eruptive parameters and dynamics of the April 2015 sub-Plinian eruptions of Calbuco volcano (southern Chile). Bulletin of Volcanology, 78(9), 1-19.

Cembrano, J., Hervé, F. & Lavenu, A. (1996). The Liquiñe Ofqui fault zone: a long-lived intra-arc fault system in southern Chile. Tectonophysics 259(1-3), 55-66.

Cembrano, J. & Lara, L. (2009). The link between volcanism and tectonics in the southern volcanic zone of the Chilean Andes: A review. Tectonophysics 471, 96-113.

Chen, Y., & Zhang, Y. (2008). Olivine dissolution in basaltic melt. Geochimica et Cosmochimica Acta, 72(19), 4756-4777.

Chen, Y., Provost, A., Schiano, P., & Cluzel, N. (2011). The rate of water loss from olivine-hosted melt inclusions. Contributions to Mineralogy and Petrology, 162(3), 625-636.

Chen, Y., Provost, A., Schiano, P., & Cluzel, N. (2013). Magma ascent rate and initial water concentration inferred from diffusive water loss from olivine-hosted melt inclusions. Contributions to Mineralogy and Petrology, 165(3), 525-541.

Cheng, L., Costa, F., & Bergantz, G. (2020). Linking fluid dynamics and olivine crystal scale zoning during simulated magma intrusion. Contributions to Mineralogy and Petrology, 175, 1-14.

Coogan, L. A., Hain, A., Stahl, S., & Chakraborty, S. (2005). Experimental determination of the diffusion coefficient for calcium in olivine between 900 C and 1500 C. Geochimica et Cosmochimica Acta, 69(14), 3683-3694.

Coogan, L. A., Saunders, A. D., & Wilson, R. N. (2014). Aluminum-in-olivine thermometry of primitive basalts: Evidence of an anomalously hot mantle source for large igneous provinces. Chemical Geology, 368, 1-10.

Couperthwaite, F. K., Thordarson, T., Morgan, D. J., Harvey, J., & Wilson, M. (2020). Diffusion timescales of magmatic processes in the Moinui lava eruption at Mauna Loa, Hawaii, as inferred from bimodal olivine populations. Journal of Petrology, 61(7), egaa058.

Crank, J. (1975). The mathematics of diffusion. Oxford University Press.

Danyushevsky, L. V., Della-Pasqua, F. N., & Sokolov, S. (2000). Re-equilibration of melt inclusions trapped by magnesian olivine phenocrysts from subduction-related magmas: petrological implications. Contributions to Mineralogy and Petrology, 138(1), 68-83.

Danyushevsky, L. V., McNeill, A. W., & Sobolev, A. V. (2002a). Experimental and petrological studies of melt inclusions in phenocrysts from mantle-derived magmas: an overview of techniques, advantages and complications. Chemical Geology, 183(1-4), 5-24.

Danyushevsky, L. V., & Plechov, P. (2011). Petrolog3: Integrated software for modeling crystallization processes. Geochemistry, Geophysics, Geosystems, 12(7).

Danyushevsky, L. V., Sokolov, S., & Falloon, T. J. (2002b). Melt inclusions in olivine phenocrysts: using diffusive re-equilibration to determine the cooling history of a crystal, with implications for the origin of olivine-phyric volcanic rocks. Journal of Petrology, 43(9), 1651-1671.

Darwin, C.R. (1839a). Narrative of the surveying voyages of His Majesty's Ships Adventure and Beagle between the years 1826 and 1836, describing their examination of the southern shores of South America, and the Beagle's circumnavigation of the globe. Journal and remarks. London: Henry Colburn.

Darwin, C.R. (1839b). Journal of Researches into the Geology and Natural History of the various countries visited by H.H.S. Beagle. London: Henry Colburn.

Darwin, C.R. (1840). On the connexion of certain volcanic phenomena in South America; and on the formation of mountain chains and volcanos, as the effect of the same powers by which continents are elevated. Transactions of the Geological Society of London 5(3), 601-631.

Delgado, F., Pritchard, M.E., Ebmeier, S., González, P. & Lara, L. (2017). Recent unrest (2002-2015) imaged by space geodesy at the highest risk Chilean volcanoes: Villarrica, Llaima, and Calbuco (Southern Andes). Journal of Volcanology and Geothermal Research 344, 270-288.

DeMets, C., Gordon, R. G., Argus, D. F., & Stein, S. (1994). Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophysical Research Letters, 21(20), 2191-2194.

DePaolo, D.J. (1981). Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. Earth and Planetary Science Letters, 53(2), 189-202.

Dewey, J. F., & Lamb, S. H. (1992). Active tectonics of the Andes. Tectonophysics, 205(1-3), 79-95.

Díaz, D., Zuñiga, F., & Castruccio A. (2020). The interaction between active crustal faults and volcanism: A case study of the Liquiñe-Ofqui Fault Zone and Osorno volcano, Southern

Andes, using magnetotellurics. Journal of Volcanology and Geothermal Research, 393, 106806.

Droop, G.T.R. (1987). A general equation for estimating Fe^{3+} concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. Mineralogical Magazine 51(361), 431-435.

Druitt, T. H., Edwards, L., Mellors, R. M., Pyle, D. M., Sparks, R. S. J., Lanphere, M., Davies, M. & Barreirio, B. (1999). Santorini volcano. Geological Society Memoir, 19.

Elburg, M. A. (2010). Sources and processes in arc magmatism: The crucial role of water (An inaugural lecture to the Society). Geologica Belgica.

Firth, C., Adam, J., Turner, S., Rushmer, T., Brens, R., Green, T. H., Erdmann, S., & O'Neill, H. (2019). Experimental constraints on the differentiation of low-alkali magmas beneath the Tonga arc: Implications for the origin of arc tholeiites. Lithos, 344, 440-451.

Gaetani, G. A., O'Leary, J. A., Shimizu, N., Bucholz, C. E., & Newville, M. (2012). Rapid reequilibration of H_2O and oxygen fugacity in olivine-hosted melt inclusions. Geology, 40(10), 915-918.

Garapić, G., Jackson, M.G., Hauri, E.H., Hart, S.R., Farley, K.A., Blusztajn, J.S. & Woodhead, J.D. (2015). A radiogenic isotopic (He-Sr-Nd-Pb-Os) study of lavas from the Pitcairn hotspot: Implications for the origin of EM-1 (enriched mantle 1). Lithos 228, 1-11.

Gavrilenko, M., Herzberg, C., Vidito, C., Carr, M. J., Tenner, T., & Ozerov, A. (2016). A calcium-in-olivine geohygrometer and its application to subduction zone magmatism. Journal of Petrology, 57(9), 1811-1832.

Ghiorso, M. S., & Evans, B. W. (2008). Thermodynamics of rhombohedral oxide solid solutions and a revision of the Fe-Ti two-oxide geothermometer and oxygen-barometer. American Journal of Science, 308(9), 957-1039.

Ghiorso, M.S. & Sack, R.O. (1995). Chemical mass transfer in magmatic processes IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures. Contributions to Mineralogy and Petrology 119(2-3), 197-212.

Gillis, J.M. (1855). The US Naval Astronomical Expedition to the Southern Hemisphere during the Years 1849-'50-'51-'52: Chile: its geography, climate, earthquakes, government, social condition, mineral and agricultural resources, commerce 79. Nicholson.

Ginibre, C. & Wörner, G. (2007). Variable parent magmas and recharge regimes of the Parinacota magma system (N. Chile) revealed by Fe, Mg and Sr zoning in plagioclase. Lithos 98(1-4), 118-140.

Grove, T.L., Donnelly-Nolan, J.M. & Housh, T. (1997). Magmatic processes that generated the rhyolite of Glass Mountain, Medicine Lake volcano, N. California. Contributions to Mineralogy and Petrology 127(3), 205-223.

Gualda, G. A., Ghiorso, M. S., Lemons, R. V., & Carley, T. L. (2012). Rhyolite-MELTS: a modified calibration of MELTS optimized for silica-rich, fluid-bearing magmatic systems. Journal of Petrology, 53(5), 875-890.

Hamada, M., Okayama, Y., Kaneko, T., Yasuda, A., & Fujii, T. (2014). Polybaric crystallization differentiation of H_2O-saturated island arc low-K tholeiite magmas: a case study of the Izu-Oshima volcano in the Izu arc. Earth, Planets and Space, 66(1), 1-10.

Hauri, E. (2002). SIMS analysis of volatiles in silicate glasses, 2: isotopes and abundances in Hawaiian melt inclusions. Chemical Geology, 183(1-4), 115-141.

Hickey-Vargas, R., Abdollahi, M.J., Parada, M.Á., López-Escobar, L. & Frey, F.A. (1995) Crustal xenoliths from Calbuco Volcano, Andean Southern Volcanic Zone: implications for crustal composition and magma-crust interaction. Contributions to Mineralogy and Petrology 119(4), 331–344.

Hickey-Vargas, R., Holbik, S., Tormey, D., Frey, F.A. & Moreno-Roa, H. (2016). Basaltic rocks from the Andean Southern Volcanic Zone: Insights from the comparison of along-strike and small-scale geochemical variations and their sources. Lithos 258, 115-132.

Hickey-Vargas, R., Moreno-Roa, H., López-Escobar, L. & Frey, F.A. (1989). Geochemical variations in Andean basaltic and silicic lavas from the Villarrica-Lanin volcanic chain (39.5 S): an evaluation of source heterogeneity, fractional crystallization and crustal assimilation. Contributions to Mineralogy and Petrology 103(3), 361-386.

Hickey-Vargas, R., Sun, M., López-Escobar, L., Moreno-Roa, H., Reagan, M.K., Morris, J.D. & Ryan, J.G. (2002). Multiple subduction components in the mantle wedge: evidence from eruptive centers in the Central Southern volcanic zone, Chile. Geology 30(3), 199-202.

Hughes, E. C., Buse, B., Kearns, S. L., Blundy, J. D., Kilgour, G., & Mader, H. M. (2019). Low analytical totals in EPMA of hydrous silicate glass due to sub-surface charging: Obtaining accurate volatiles by difference. Chemical Geology, 505, 48-56.

Jacques, G., Hoernle, K., Gill, J., Wehrmann, H., Bindeman, I. & Lara, L.E. (2014). Geochemical variations in the Central Southern Volcanic Zone, Chile (38–43 S): the role of fluids in generating arc magmas. Chemical Geology 371, 27-45.

Jarrard, R. D. (1986). Relations among subduction parameters. Reviews of Geophysics, 24(2), 217-284.

Jayasuriya, K. D., O'Neill, H. S. C., Berry, A. J., & Campbell, S. J. (2004). A Mossbauer study of the oxidation state of Fe in silicate melts. American Mineralogist, 89(11-12), 1597-1609.

Johannes, W., Koepke, J. & Behrens, H. (1994). Partial melting reactions of plagioclases and plagioclase-bearing systems. In Feldspars and their Reactions (pp. 161-194). Springer, Dordrecht.

Kamenetsky, V.S., Crawford, A.J. & Meffre, S. (2001). Factors controlling chemistry of magmatic spinel: an empirical study of associated olivine, Cr-spinel and melt inclusions from primitive rocks. Journal of Petrology 42(4), 655-671.

Kelley, K.A. & Cottrell, E. (2009). Water and the oxidation state of subduction zone magmas. Science 325(5940), 605-607.

Kelley, K. A., Plank, T., Newman, S., Stolper, E. M., Grove, T. L., Parman, S., & Hauri, E. H. (2010). Mantle melting as a function of water content beneath the Mariana Arc. Journal of Petrology, 51(8), 1711-1738.

Kent, A.J. (2008). Melt inclusions in basaltic and related volcanic rocks. Reviews in Mineralogy and Geochemistry 69(1), 273-331.

Kilian, R. & Behrmann, J.H. (2003). Geochemical constraints on the sources of Southern Chile Trench sediments and their recycling in arc magmas of the Southern Andes. Journal of the Geological Society 160(1), 57-70.

Kimura, J. I., Hacker, B. R., van Keken, P. E., Kawabata, H., Yoshida, T., & Stern, R. J. (2009). Arc Basalt Simulator version 2, a simulation for slab dehydration and fluid- fluxed mantle melting for arc basalts: Modeling scheme and application. Geochemistry, Geophysics, Geosystems, 10(9).

Knafelc, J., Filiberto, J., Ferré, E. C., Conder, J. A., Costello, L., Crandall, J. R., Dyar, M. D., Friedman, S. A., Hummer, D. R., & Schwenzer, S. P. (2019). The effect of oxidation on the mineralogy and magnetic properties of olivine. American Mineralogist, 104(5), 694-702.

Lara, L.E., Orozco, G. & Piña-Gauthier, M. (2012). The 1835 AD fissure eruption at Osorno volcano, Southern Andes: Tectonic control by the intraarc stress field instead of remote megathrust-related dynamic strain. Tectonophysics 530, 102-110.

Le Bas, M.L., Maitre, R.L., Streckeisen, A., Zanettin, B. & IUGS Subcommission on the Systematics of Igneous Rocks (1986). A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27(3), 745-750.

Lohmar, S., Parada, M., Gutiérrez, F., Robin, C. & Gerbe, M.C. (2012). Mineralogical and numerical approaches to establish the pre-eruptive conditions of the mafic Lican Ignimbrite, Villarrica Volcano (Chilean Southern Andes). Journal of Volcanology and Geothermal Research 235, 55-69.

López-Escobar, L., Cembrano, J. & Moreno, H. (1995a). Geochemistry and tectonics of the Chilean Southern Andes basaltic Quaternary volcanism (37-46 S). Andean Geology 22(2), 219-234.

López-Escobar, L., Parada, M.Á., Hickey-Vargas, R., Frey, F.A., Kempton, P.D. & Moreno, H. (1995b). Calbuco Volcano and minor eruptive centers distributed along the Liquiñe-Ofqui Fault Zone, Chile (41–42 S): contrasting origin of andesitic and basaltic magma in the Southern Volcanic Zone of the Andes. Contributions to Mineralogy and Petrology 119(4), 345-361.

López-Escobar, L., Parada, M.Á., Moreno, H., Frey, F.A. & Hickey-Vargas, R. (1992). A contribution to the petrogenesis of Osorno and Calbuco volcanoes, Southern Andes (41º00' – 41º30'S): comparative study. Revista Geológica de Chile 19 (2), 211-226.

Loucks, R.R. (1996). A precise olivine-augite Mg-Fe-exchange geothermometer. Contributions to Mineralogy and Petrology 125(2-3), 140-150.

Martin, C. (1901). Los volcanes activos de Chile. Revista Chilena de Historia Natural. Imprenta Gillet. Valparaíso. Año V, 242-250.

Maurel, C. & Maurel, P. (1982). Etude expérimentale de l'equilibre Fe^{2+}-Fe^{3+} dans les spinelles chromifères et les liquides silicatés basiques coexistants a 1 atm. Comptes Rendus de l'Académie des Sciences 285, 209-215.

McGee, L.E., Brahm, R., Rowe, M.C., Handley, H.K., Morgado, E., Lara, L.E., Turner, M.B., Vinet, N., Parada, M.Á. & Valdivia, P. (2017). A geochemical approach to distinguishing competing tectono-magmatic processes preserved in small eruptive centres. Contributions to Mineralogy and Petrology 172(6), 44.

McGee, L.E. & Smith, I.E. (2016). Interpreting chemical compositions of small scale basaltic systems: a review. Journal of Volcanology and Geothermal Research 325, 45-60.

Mollo, S., Scarlato, P., Lanzafame, G. & Ferlito, C. (2013). Deciphering lava flow post-eruption differentiation processes by means of geochemical and isotopic variations: A case study from Mt. Etna volcano. Lithos 162, 115-127.

Moraleda y Montero, J. (1888). Exploraciones geográficas e Hidrográficas, 1789-1793. Introducción de Diego Barros Arana. Imprenta Nacional, 533.

Moreno, H., Lara, L. & Orozco, G. (2010). Geología del volcán Osorno. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geológica Básica, No. 126, Mapa escala 1:50000.

Morgado, E., Parada, M.Á., Contreras, C., Castruccio, A., Gutiérrez, F. & McGee, L.E. (2015). Contrasting records from mantle to surface of Holocene lavas of two nearby arc volcanic complexes: Caburgua-Huelemolle Small Eruptive Centers and Villarrica Volcano, Southern Chile. Journal of Volcanology and Geothermal Research 306, 1-16.

Morgado, E., Parada, M.Á., Morgan, D.J., Gutiérrez, F., Castruccio, A. & Contreras, C. (2017). Transient shallow reservoirs beneath small eruptive centres: Constraints from Mg-Fe interdiffusion in olivine. Journal of Volcanology and Geothermal Research 347, 327-336.

Morgado, E., Morgan, D.J., Castruccio, A., Ebmeier, S.K., Parada, M.Á., Brahm, R., Harvey, J., Gutiérrez, F. & Walshaw, R. (2019b). Old magma and a new, intrusive trigger: using diffusion chronometry to understand the rapid-onset Calbuco eruption, April 2015 (Southern Chile): Contributions to Mineralogy and Petrology 174(61).

Morgado, E., Morgan D.J., Harvey, J., Parada, M.Á., Castruccio, A., Brahm, R., Gutiérrez, F., Georgiev, B. & Hammond, S.J. (2019a). Localised heating and intensive magmatic conditions prior the 22-23 April 2015 Calbuco volcano eruption (Southern Chile). Bulletin of Volcanology 81(4).

Müller, T., Dohmen, R., Becker, H. W., Ter Heege, J. H., & Chakraborty, S. (2013). Fe–Mg interdiffusion rates in clinopyroxene: experimental data and implications for Fe–Mg exchange geothermometers. Contributions to Mineralogy and Petrology, 166(6), 1563-1576.

Munizaga, F., Hervé, F., Drake, R., Pankhurst, R.J., Brook, M. & Snelling, N. (1988). Geochronology of the Lake Region of south-central Chile (39–42 S): Preliminary results. Journal of South American Earth Sciences 1(3), 309-316.

Nakamura, K. (1977). Volcanoes as possible indicators of tectonic stress orientation—principle and proposal. Journal of Volcanology and Geothermal Research 2(1), 1-16.

Namur, O., Montalbano, S., Bolle, O., & Vander Auwera, J. (2020). Petrology of the April 2015 eruption of Calbuco volcano, southern Chile. Journal of Petrology, 61(8), egaa084.

Nelson, S.T. & Montana, A. (1992). Sieve-textured plagioclase in volcanic rocks produced by rapid decompression. American Mineralogist 77(11-12), 1242-1249.

Newcombe, M. E., Fabbrizio, A., Zhang, Y., Ma, C., Le Voyer, M., Guan, Y., Eiler, J. M., Saal, A. E. & Stolper, E. M. (2014). Chemical zonation in olivine-hosted melt inclusions. Contributions to Mineralogy and Petrology, 168(1), 1030.

Nikkhoo, M., Walter, T.R., Lundgren, P.R. & Prats-Iraola, P. (2016). Compound dislocation models (CDMs) for volcano deformation analyses. Geophysical Journal International 208, 877-894.

Pankhurst, M. J., Morgan, D. J., Thordarson, T., & Loughlin, S. C. (2018). Magmatic crystal records in time, space, and process, causatively linked with volcanic unrest. Earth and Planetary Science Letters, 493, 231-241.

Parman, S. W., Grove, T. L., Kelley, K. A., & Plank, T. (2011). Along-arc variations in the pre-eruptive H_2O contents of Mariana arc magmas inferred from fractionation paths. Journal of Petrology, 52(2), 257-278.

Pérez-Flores, P., Cembrano, J., Sánchez-Alfaro, P., Veloso, E., Arancibia, G., & Roquer, T. (2016). Tectonics, magmatism and paleo-fluid distribution in a strike-slip setting: Insights from the northern termination of the Liquiñe–Ofqui fault System, Chile. Tectonophysics, 680, 192-210.

Petit-Breuilh, M.E. (1999). Cronología eruptiva histórica de los volcanes Osorno y Calbuco, Andes del Sur (41º-41º30´S). Servicio Nacional de Geología y Minería (SERNAGEOMIN), Chile. Boletín (n.53): 46 p.

Pietranik, A., Koepke, J. & Puziewicz, J. (2006). Crystallization and resorption in plutonic plagioclase: implications on the evolution of granodiorite magma (Gęsiniec granodiorite, Strzelin Crystalline Massif, SW Poland). Lithos 86(3-4), 260-280.

Piochi, M., Bruno, P.P., & De Astis, G. (2005). Relative roles of rifting tectonics and magma ascent processes: Inferences from geophysical, structural, volcanological, and geochemical data for the Neapolitan volcanic region (southern Italy). Geochemistry Geophysics Geosystems 6(7).

Portnyagin, M. V., Hoernle, K., & Mironov, N. L. (2014). Contrasting compositional trends of rocks and olivine-hosted melt inclusions from Cerro Negro volcano (Central America):

implications for decompression-driven fractionation of hydrous magmas. International Journal of Earth Sciences, 103(7), 1963-1982.

Prior, D.J., Boyle, A.P., Brenker, F., Cheadle, M.C., Day, A., López, G., Peruzzo, L., Potts, G.J., Reddy, S., Spiess, R., Timms, N.E., Trimby P., Wheeler, J. & Zetterström, L. (1999). The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. American Mineralogist 84(11-12), 1741-1759.

Putirka, K. D. (2005). Igneous thermometers and barometers based on plagioclase + liquid equilibria: Tests of some existing models and new calibrations. American Mineralogist, 90(2-3), 336-346.

Putirka, K. D. (2008). Thermometers and barometers for volcanic systems. Reviews in mineralogy and geochemistry, 69(1), 61-120.

Pyle, D.M. (2000). Sizes of volcanic eruptions. In: Encyclopedia of Volcanoes. Sigurdsson, H., Houghton, B., McNutt, S.R., Rymer, H., Stix, J. Academic Press, San Diego.

Rasmussen, D. J., Plank, T. A., Roman, D. C., & Zimmer, M. M. (2022). Magmatic water content controls the pre-eruptive depth of arc magmas. Science, 375(6585), 1169-1172.

Rawson, H., Pyle, D. M., Mather, T. A., Smith, V. C., Fontijn, K., Lachowycz, S. M., & Naranjo, J. A. (2016). The magmatic and eruptive response of arc volcanoes to deglaciation: Insights from southern Chile. Geology, 44(4), 251-254.

Roduit, N. (2005). Two complementary efficient methods to quantify porosity types in digital images of thin sections with the software JMicroVision. In Abstract, Scenic Sedimentology, 24th IAS Meeting.

Roedder, E. (1979). Origin and significance of magmatic inclusions. Bulletin de Mineralogie, 102(5), 487-510.

Roeder, P. L., & Emslie, R. (1970). Olivine-liquid equilibrium. Contributions to Mineralogy and Petrology, 29(4), 275-289.

Roggensack, K., Hervig, R. L., McKnight, S. B., & Williams, S. N. (1997). Explosive basaltic volcanism from Cerro Negro volcano: influence of volatiles on eruptive style. Science, 277(5332), 1639-1642.

Ruth, D. C., Costa, F., De Maisonneuve, C. B., Franco, L., Cortés, J. A., & Calder, E. S. (2018). Crystal and melt inclusion timescales reveal the evolution of magma migration before eruption. Nature Communications, 9(1), 1-9.

Ruth, D. C., Cottrell, E., Cortés, J. A., Kelley, K. A., & Calder, E. S. (2016). From passive degassing to violent Strombolian eruption: the case of the 2008 eruption of Llaima volcano, Chile. Journal of Petrology, 57(9), 1833-1864.

Sadofsky, S. J., Portnyagin, M., Hoernle, K., & van den Bogaard, P. (2008). Subduction cycling of volatiles and trace elements through the Central American volcanic arc: evidence from melt inclusions. Contributions to Mineralogy and Petrology, 155(4), 433-456.

Sánchez, P., Pérez-Flores, P., Arancibia, G., Cembrano, J. & Reich, M. (2013). Crustal deformation effects on the chemical evolution of geothermal systems: the intra-arc Liquiñe–Ofqui fault system, Southern Andes. International Geology Review 55(11), 1384-1400.

Schleicher, J. M., Bergantz, G. W., Breidenthal, R. E., & Burgisser, A. (2016). Time scales of crystal mixing in magma mushes. Geophysical Research Letters, 43(4), 1543-1550.

Segovia, M. J., Diaz, D., Slezak, K., & Zuñiga, F. (2021). Magnetotelluric study in the Los Lagos Region (Chile) to investigate volcano-tectonic processes in the Southern Andes. Earth, Planets and Space, 73(1), 1-14.

Sellés, D., Rodríguez, A.C., Dungan, M. A., Naranjo, J. A., & Gardeweg, M. (2004). Geochemistry of Nevado de Longaví Volcano (36.2 S): a compositionally atypical arc volcano in the Southern Volcanic Zone of the Andes. Revista Geológica de Chile, 31(2), 293-315.

Sellés, D., & Moreno, H. (2011) Geología del Volcán Calbuco, Región de Los Lagos. Carta Geológica de Chile. Serie Geológica Básica, No. 130. Escala 1:50.000.

SERNAGEOMIN–OVDAS (2017a). Reporte Especial de Actividad Volcánica (REAV) — Región de los Lagos, volcán Osorno 2017, diciembre 19 —18:30 (local time).

SERNAGEOMIN–OVDAS (2017b). Red Nacional de Vigilancia Volcánica, Volcán Calbuco. https://rnvv.sernageomin.cl/volcan-calbuco/. Accessed 26 September 2022.

SERNAGEOMIN–OVDAS (2018a). Reporte especial de actividad volcánica (REAV) — Región de los Lagos, volcán Osorno 2018, junio 23 —11:00 (local time).

SERNAGEOMIN–OVDAS (2018b). Reporte especial de actividad volcánica (REAV) — Región de los Lagos, volcán Osorno 2018, agosto 5 —11:47 (local time).

SERNAGEOMIN–OVDAS (2018c). Reporte Especial de Actividad Volcánica (REAV) — Región de los Lagos, volcán Osorno 2018, abril 14 —14:30 (local time).

SERNAGEOMIN–OVDAS (2019). Reporte de actividad volcánica (RAV) — Región de los Lagos, volcán Osorno, febrero 2019.

SERNAGEOMIN–OVDAS (2022). Reporte Especial de Actividad Volcánica (RAV) — Región de los Lagos, volcán Osorno, septiembre 2022.

Shaw, A. M., Hauri, E. H., Fischer, T. P., Hilton, D. R., & Kelley, K. A. (2008). Hydrogen isotopes in Mariana arc melt inclusions: Implications for subduction dehydration and the deep-Earth water cycle. Earth and Planetary Science Letters, 275(1-2), 138-145.

Shejwalkar, A. & Coogan, L.A. (2013). Experimental calibration of the roles of temperature and composition in the Ca-in-olivine geothermometer at 0.1 MPa. Lithos 177, 54-60.

Simakin, A. G., Salova, T. P., Shaposhnikova, O. Y., Isaenko, S. I., & Nekrasov, A. N. (2021). Experimental Study of Interaction of Carbonic Fluid with Cumulus Minerals of Ultrabasic Intrusions at 950 °C and 200 MPa. Petrology, 29(4), 371-385.

Simkin, T., & Smith, J. V. (1970). Minor-element distribution in olivine. The Journal of Geology, 78(3), 304-325.

Sinton, C. W., Christie, D. M., Coombs, V. L., Nielsen, R. L., & Fisk, M. R. (1993). Near-primary melt inclusions in anorthite phenocrysts from the Galapagos Platfor m. Earth and Planetary Science Letters, 119(4), 527-537.

Smith, I.E.M. & Németh, K. (2017). Source to surface model of monogenetic volcanism: a critical review. Geological Society, London, Special Publications 446(1), 1-28.

Stern, C.R. (2004). Active Andean volcanism: its geologic and tectonic setting. Revista Geológica de Chile 31(2), 161-206.

Stern, C.R., Moreno, H., López-Escobar, L., Clavero, J.E., Lara, L.E., Naranjo, J.A., Parada, M.Á. & Skewes, M.A. (2007). Chilean Volcanoes. In: Moreno, T., Gibbons, W. (eds) The Geology of Chile, Geological Society of London, London, 149-180.

Stormer, J.C. (1983). The effects of recalculation on estimates of temperature and oxygen fugacity from analyses of multicomponent iron–titanium oxides. American Mineralogist 68, 586–594.

Sun, S.S. & McDonough, W.S. (1989). Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Geological Society, London, Special Publications 42(1), 313-345.

Tagiri, M., Moreno, H., López-Escobar, L. & Notsu, K. (1993). Two magma types of the high-alumina basalt series of Osorno Volcano, Southern Andes (41º06’S) – plagioclase dilution effect. Journal of Mineralogy, Petrology, and Economic Geology 88, 359-371.

Takada, A. (1994). The influence of regional stress and magmatic input on styles of monogenetic and polygenetic volcanism. Journal of Geophysical Research: Solid Earth 99(B7), 13563-13573.

Tassara, S., Reich, M., Cannatelli, C., Konecke, B. A., Kausel, D., Morata, D., ... & Leisen, M. (2020). Post-melting oxidation of highly primitive basalts from the southern Andes. Geochimica et Cosmochimica Acta, 273, 291-312.

Tatsumi, Y., Takahashi, T., Hirahara, Y., Chang, Q., Miyazaki, T., Kimura, J. I., Ban, M. & Sakayori, A. (2008). New insights into andesite genesis: the role of mantle-derived calc-alkalic and crust-derived tholeiitic melts in magma differentiation beneath Zao Volcano, NE Japan. Journal of Petrology, 49(11), 1971-2008.

Taylor Jr, H. P. (1980). The effects of assimilation of country rocks by magmas on 18O/16O and 87Sr/86Sr systematics in igneous rocks. Earth and Planetary Science Letters, 47(2), 243-254.

Tilling, R. I. (2008). The critical role of volcano monitoring in risk reduction. Advances in Geosciences 14, 3-11.

Tobelko, D. P., Portnyagin, M. V., Krasheninnikov, S. P., Grib, E. N., & Plechov, P. Y. (2019). Compositions and formation conditions of primitive magmas of the Karymsky volcanic center, Kamchatka: evidence from melt inclusions and trace-element thermobarometry. Petrology, 27(3), 243-264.

Toplis, M. J. (2005). The thermodynamics of iron and magnesium partitioning between olivine and liquid: criteria for assessing and predicting equilibrium in natural and experimental systems. Contributions to Mineralogy and Petrology, 149(1), 22-39.

Tormey, D.R., Hickey-Vargas, R., Frey, F.A. & López-Escobar, L. (1991). Recent lavas from the Andean volcanic front (33 to 42 S); interpretations of along-arc compositional variations. Andean magmatism and its tectonic setting: Geological Society of America Special Paper 265, 57-77.

Vander Auwera, J., Namur, O., Dutrieux, A., Wilkinson, C.M., Ganerød, M., Coumont, V. & Bolle, O. (2019). Mantle melting and magmatic processes under La Picada stratovolcano (CSVZ, Chile). Journal of Petrology 60(5), 907-944.

Völker, D., Kutterolf, S., & Wehrmann, H. (2011). Comparative mass balance of volcanic edifices at the southern volcanic zone of the Andes between 33 S and 46 S. Journal of Volcanology and Geothermal Research, 205(3-4), 114-129.

Wan, Z., Coogan, L. A., & Canil, D. (2008). Experimental calibration of aluminum partitioning between olivine and spinel as a geothermometer. American Mineralogist, 93(7), 1142-1147.

Watson, E.B. & Müller, T. (2009). Non-equilibrium isotopic and elemental fractionation during diffusion-controlled crystal growth under static and dynamic conditions. Chemical Geology 267(3-4), 111-124.

Watt, S.F., Pyle, D.M. & Mather, T.A. (2009). The influence of great earthquakes on volcanic eruption rate along the Chilean subduction zone. Earth and Planetary Science Letters 277(3-4), 399-407.

Watt, S. F., Pyle, D. M., Mather, T. A., & Naranjo, J. A. (2013). Arc magma compositions controlled by linked thermal and chemical gradients above the subducting slab. Geophysical Research Letters, 40(11), 2550-2556.

Weis, D., Kieffer, B., Maerschalk, C., Pretorius, W., & Barling, J. (2005). High- precision Pb- Sr- Nd- Hf isotopic characterization of USGS BHVO- 1 and BHVO- 2 reference materials. Geochemistry, Geophysics, Geosystems, 6(2).

Weller, D. J., & Stern, C. R. (2018). Along-strike variability of primitive magmas (major and volatile elements) inferred from olivine-hosted melt inclusions, southernmost Andean Southern Volcanic Zone, Chile. Lithos, 296, 233-244.

Werner, C., Rasmussen, D. J., Plank, T., Kelly, P. J., Kern, C., Lopez, T., Gliss, J., Power, J.A., Roman, D. C., Izbekov, P., & Lyons, J. (2020). Linking subsurface to surface using gas emission and melt inclusion data at Mount Cleveland volcano, Alaska. Geochemistry, Geophysics, Geosystems, 21(7), e2019GC008882.

Workman, R.K. & Hart, S.R. (2005). Major and trace element composition of the depleted MORB mantle (DMM). Earth and Planetary Science Letters 231(1-2), 53-72.

Zindler, A. & Hart, S. (1986). Chemical geodynamics. Annual Review of Earth and Planetary Sciences 14(1), 493-571.

Zimmer, M. M., Plank, T., Hauri, E. H., Yogodzinski, G. M., Stelling, P., Larsen, J., Singer, B., Jicha, B., Mandeville, C., & Nye, C. J. (2010). The role of water in generating the calc-alkaline trend: new volatile data for Aleutian magmas and a new tholeiitic index. Journal of Petrology, 51(12), 2411-2444.

Zhang, Y., & Gan, T. (2022). Diffusion in melts and magmas. Reviews in Mineralogy and Geochemistry, 87(1), 283-337.

Zhang, Y., & Ni, H. (2010). Diffusion of H, C, and O components in silicate melts. Reviews in Mineralogy and Geochemistry, 72(1), 171-225.

Zhang, Y., Ni, H., & Chen, Y. (2010) Diffusion data in siliate melts. Reviews in Mineralogy and Geochemistry, 72(1), 311-408.

Zhang, Y., Xu, Z., Zhu, M., & Wang, H. (2007). Silicate melt properties and volcanic eruptions. Reviews of Geophysics, 45(4).

Figure 1. a) Location of the different volcanic zones of the Andes. b) Location of the four subdivisions of the Southern Volcanic Zone. c) The Central Southern Volcanic Zone and location of stratovolcanoes and the Liquiñe-Ofqui Fault Zone (LOFZ). Location of the LOFZ (solid and dashed lines) inferred from Cembrano et al. (1996) and Cembrano and Lara (2009).

Figure 2. (a) Location of the Osorno volcano in Chile. (b) Location of Osorno, La Picada, Puntiagudo, and Calbuco volcanoes and Cordón Cenizos volcanic chain, La Viguería cone, and the Liquiñe-Ofqui Fault Zone (LOFZ, white dashed line). The alignment of Osorno, La Picada, Puntiagudo and Cordón Cenizos is represented by a yellow, dashed line. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) image was obtained via EarthExplorer, USGS (http://earthexplorer.usgs.gov).

Figure 3. Osorno volcano and the deposits of the first and second stages of the 1835 eruption. Yellow stars represent locations where samples are collected from a lava flow, whereas lapilli sample locations are represented by red stars. Locations and dates of the lava flows and fall deposits are based on Moreno et al. (2010) and Lara et al. (2012). ASTER–GDEM image from EarthExplorer, USGS (http://earthexplorer.usgs.gov).

Figure 4. (a) Backscatter electron (BSE) images of an isolated plagioclase phenocryst where different compositional zones are found. Brighter greyscale colours are correlated to higher density. (b) The arrow represents the profile measured by electron probe micro-analysis (EPMA) and its direction. (c) Relation and coefficient of determination (r^2) between BSE greyscale profile and the measured anorthite content (An = 100×Ca/(Ca+Na+K); in molar proportions). “An” is a representative description of the composition of plagioclase because in all crystals the K content remains constant throughout (details in Supplementary Data 2). (d) Anorthite profile composition (An) by EPMA of the measured profile (circles) coupled with the BSE profile based on greyscale values calibrated with the composition measured by electron microprobe (solid line).

Figure 5. (a) Olivine-hosted melt inclusion of ~110 μm diameter. (b) Resorption feature (embayment) in olivine phenocryst with glass and plagioclase microlites. The yellow dashed line represents the olivine grain boundary.

Figure 6. (a) BSE image of a crystal clot of olivine grains. (b) Zoom of the BSE image, which shows interstitial glass between the crystals constituting the clot. (c) EBSD map represents the diversity of olivine crystal orientations, consistent with the observation that the glasses are interstitial and are not melt inclusions.

Figure 7. Total alkali versus silica (Le Bas et al., 1986) plots of the Osorno 1835 volcanic products (grey squares), the modified composition of Os-144 (Os-144*, yellow star), melt inclusions (Group 1 of glass, red field), and glass from groundmass (Group 2 glass, green

field), La Viguería cone products (pink triangles), La Picada volcanic products (Vander Auwera et al., 2019, blue field), and Calbuco 2015 volcanic products (Morgado et al., 2019a, yellow squares).

Figure 8. (a) Variations of Ni ($\mu g \cdot g^{-1}$) versus SiO_2 (wt. %), (b) K_2O (wt. %) versus SiO_2 (wt. %), (c) FeO*/MgO versus SiO_2 (wt. %), (d) K_2O (wt. %) versus MgO (wt. %), (e) CaO (wt. %) versus MgO (wt. %), and (f) Al_2O_3 (wt. %) versus MgO (wt. %) of Holocene erupted products from Calbuco volcano (Castruccio et al., 2016; Morgado et al., 2019a; Arzilli et al., 2019; Namur et al., 2020), Osorno volcano (Tagiri et al., 1993; Moreno et al., 2010; Bechon et al., 2022; this study), and Cayutué-La Viguería field (López-Escobar et al., 1995a; this study).

Figure 9. (a) Primitive mantle-normalised (Sun and McDonough, 1989) incompatible trace element diagram for Calbuco erupted products, taken from López-Escobar et al. (1995b) Morgado et al. (2019a). Major and trace element concentrations from Osorno and La Viguería are available in Table 2. (b) REE patterns of bulk rock samples from volcanic systems of the region (La Viguería, Osorno, Calbuco, and La Picada volcanoes).

Figure 10. (a) $^{144}Nd/^{143}Nd$ versus $^{87}Sr/^{86}Sr$ of volcanic products of Osorno, Calbuco, sediments from the CSVZ trench, granulite xenoliths, gabbro xenoliths and from the basement, and granitoids from basement. (b) Comparison of $^{144}Nd/^{143}Nd$ versus $^{87}Sr/^{86}Sr$ with other volcanic zones from the SVZ (from Hickey-Vargas et al., 2016 and references therein).

Figure 11. Olivine core compositions ($X_{ol}(Fe^{2+}/Mg)$ vs $X_{melt}(Fe^{2+}/Mg)$) for products of the 1835 Osorno eruption. Most of the olivine compositions from group 1 ($Fo_{76\text{-}79}$) are in equilibrium with the hosted melt inclusions, whereas the two olivine crystals from group 2 ($Fo_{69–73}$) are in equilibrium with the hosted melt inclusions. The Fe^{2+} in the melt is calculated using the olivine-hosted spinel inclusions Fe^{2+}/Fe^{3+}. We calculate the equilibrium lines as $X_{ol}(Fe^{2+}/Mg) = K_D \times X_{melt}(Fe^{2+}/Mg)$, where K_D is calculated via the Toplis (2005) procedure. Dashed lines represent the uncertainty of the Toplis (2005) method.

Figure 12. (a) BSE image of an olivine phenocryst and melt inclusions. (b) Zoom of the BSE image, which shows the EPMA profiles in olivine and large melt inclusion. (c) Mg# composition of olivine phenocryst traverse, which is flat (showing the absence of disequilibrium), (d) MgO (wt. %) composition profiles of the melt inclusion shown in b), which show depletion towards the rim. That depletion represents diffusion and the related timescales are a few minutes.

Figure 13. Evolution of plagioclase phenocrysts zoning over time: first event (I) is nucleation and growth of plagioclase phenocryst cores (Zone 1 composition); after that (II), growth of plagioclase phenocryst rims and nucleation and growth of new plagioclase phenocrysts

occurred (Zone 2 composition). These two first crystallization events occurred during the crystal mush formation. After the crystal mush building, another process generating plagioclase-melt disequilibrium and resorption (we suggest volatile additions or heating) occurred (III), and finally (IV), a last growth event occurred. We infer that the last growth event occurred before or during the eruption triggering.

Figure 14. Plots of fluid mobile/immobile elements of Holocene volcanic samples of the region: (a) Ba/La versus Rb/La and (b) plot of Ba/Nd versus Rb/Nd. (c) plot of La/Yb versus SiO_2. (d) plot of Ni ($\mu g \cdot g^{-1}$) versus Cr ($\mu g \cdot g^{-1}$). (e) plot of Rb ($\mu g \cdot g^{-1}$) versus Mg#. In a) and b) the arrows represent the direction in which the fluid component in the source is increasing. In c) the arrow represents the direction in which partial melting degree of the source is increasing. The arrows in d) and e) represent the direction in which the products are more primitive. We calculated Mg# assuming $Fe^{2+}/Fe^{3+} \approx 3$ (the same ratio we reported in this article via titration) in those samples from studies in which only $Fe_2O_{3(t)}$ is reported (Moreno et al., 2010; Bechon et al., 2022).

Figure 15. $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ of whole-rock compositions of the samples from the regional crustal rocks (granulite, gabbro, and granitoids; Hickey-Vargas et al., 1995; Aragón et al., 2011), Calbuco and Osorno stratovolcanoes, La Viguería small eruptive centre, and samples representing mantle compositions (DMM and EM-I; Workman and Hart, 2005; Garapić et al., 2015) and mixing lines showing possible fluid composition supplies considering the ranges of $^{87}Sr/^{86}Sr$ ratio and $^{143}Nd/^{144}Nd$ for trench sediments in Kilian and Behrmann (2003). The sediment compositional end-members are modelled in a) and b), respectively. The mixing lines are built according to the isotopic values presented in Table 3.

Figure 16. Schematic representation of the evolution of the shallow reservoir beneath Osorno volcano before the 1835 eruption. Figure (a) shows the initial crystal mush, which is perturbed (by heating and/or volatile addition), as represented in Figure (b). Figure (c) shows how crystals are disaggregated from the crystal mush and incorporated to the eruptible magma. Figure (d) shows when the eruption is triggered, it occurs in the main crater as well as the parasitic cones (image not to scale). The main crater and parasitic cones erupt lava flows and fall deposits. The sequence occurred for both eruptive events: January-February 1835 and November 1835-January 1836. Volatile accumulation events during magma evolution and their subsequent release could have triggered the relatively explosive first event in January 1985.