

# Along Arc Petrochemical Variations in the Southernmost Andean SVZ (43.5-46°S): Implications for Magma Genesis

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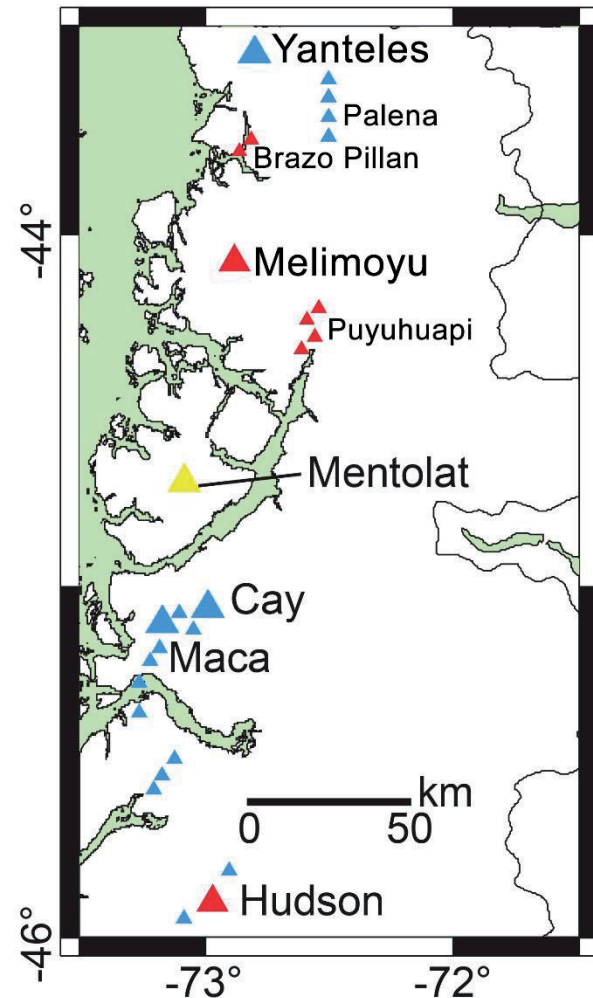
**Abstract.** The southernmost Andean SVZ (43.5-46°S) consists of six stratovolcanoes (Yanteles, Melimoyu, Mentolat, Macá, Cay, Hudson). Hudson and Melimoyu are high-K ( $K_2O > 1$  wt% at 50 wt%  $SiO_2$ ), high incompatible element abundance (HA) types. Macá and Cay are low-K, low incompatible element abundance (LA) centers, while Mentolat has very low K, Rb and other incompatible element contents (VLA), similar to Huequi, Calbuco and Nevados de Longaví further north. Such differences have been attributed to differences in degree of mantle partial melting due to variability in the extent of contamination of the mantle source region by hydrous fluids and/or melts derived from subducted oceanic lithosphere, possibly as a result in down-dip temperature changes at the top of the subducted slab. VLA magmas, which generally contain amphibole as a phenocryst phase, are attributed to high water contents and high degree of mantle partial melting, while HA magmas are attributed to lower water and lower degrees of mantle partial melting. However, the HA volcanoes Melimoyu (which also contains amphibole) and Hudson (for which cryptic amphibole fractionation has been proposed) both occur along the volcanic front and are the largest centers, while VLA volcano Mentolat is the smallest volcano in the SSVZ, inconsistent with these models.

**Keywords:** Andean volcanism, magma genesis

## 1 Introduction

The southernmost Andean SVZ (43.5-46°S) consists of six stratovolcanoes (Fig. 1; Yanteles, Melimoyu, Mentolat, Macá, Cay and Hudson; Stern, 2004; Völker et al., 2011), as well as numerous minor eruptive centers (MEC; López et al., 1995a; Gutiérrez et al., 2005; Vargas et al., 2013), located both along the arc-parallel Liquiñe-Ofqui Fault system (LOFZ; Cembrano et al., 1996) or associated with the larger stratovolcanoes along the volcanic front. Previous studies of these centers have demonstrated significant variability. For the stratovolcanoes, Melimoyu (López et al., 1993; Naranjo and Stern, 2004) and Hudson (Futa and Stern, 1988; D'Orazio et al., 2003; Gutiérrez et al., 2005; Kratzmann et al., 2010) have erupted high-K, high incompatible element abundance (HA) type magmas (Fig. 2), Macá, Cay and Yanteles lower K, lower incompatible element abundance (LA) type magmas, and Mentolat very low K and incompatible element abundances (VLA) similar to Huequi (Watt et al., 2011), Calbuco (López et al., 1995b) and Nevado de Longaví

(Sellés et al., 2004) further to the north. Among the smaller MEC, the Puyuhuapi group are HA type basalts (Fig. 2; López et al. 1995a). In contrast, the Palena group just to the north of are LA type basalts (Fig. 2; Watt et al., 2013), as are all other MEC cones further to the south in the SSVZ. This paper addresses these regional variations in magma types along and across the SSVZ arc.



**Figure 1.** Map of the southernmost part of the Andean Southern Volcanic Zone (SSVZ; modified after Watt et al., 2011) showing the location of the major stratovolcanoes and some of the minor eruptive centers addressed in this abstract. Volcanoes that erupt HA type magmas shown in red, LA type magmas in blue, and VLA type magmas (Mentolat) in yellow.

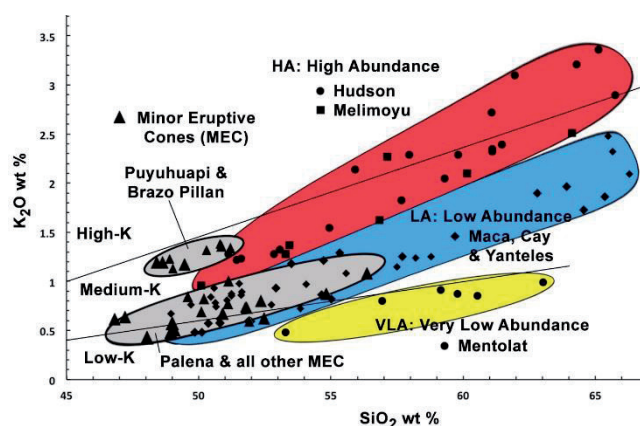


Fig. 2. Plot of  $\text{SiO}_2$  versus  $\text{K}_2\text{O}$  for samples of lavas and tephra from the Yanteles, Melimoyu, Mentolat, Macá, Cay and Hudson volcanoes (Futa and Stern, 1988; López et al., 1993; Naranjo and Stern, 1998, 2004; D’Orazio et al., 2003; Gutiérrez et al., 2005; Kratzmann et al., 2010; Weller et al., 2014), and MEC cones (López et al., 1995a, Watt et al., 2013; our new data), illustrating the various fields for HA, LA and VLA magma types. Puyuhuapi and Brazo Pillán MEC are HA types and Palena and all other MEC in the SSVZ are LA types.

## 2 Methods, Samples, Results

Samples of tephra derived from Melimoyu (MEL1 and MEL2 (Naranjo and Stern, 2004) and Mentolat (MEN1; Naranjo and Stern, 2004), and both scoria and lavas from small mafic monogenic cones in Brazo Pillán fjord north of Melimoyu, as well as near both Puyuhuapi and Palena (Fig. 1), were analysed for mineral chemistry, major and trace-element compositions, and Sr-, Nd- and Pb isotopic ratios. The new data are consistent with previously published data that indicate that Melimoyu and Hudson volcanoes and the Puyuhuapi group cones have erupted HA type magmas, as have the small cones along the volcanic front in Brazo Pillán fjord just north of Melimoyu. Macá, Cay, Yanteles and Palena group MEC, as well as all other MEC in the southernmost SSVZ, are LA type centers (Figs. 1 and 2). Mentolat in contrast is a VLA center similar to Huequi (Watt et al. 2011), Calbuco (López et al., 1995b) and Nevado de Longaví (Sellés et al., 2004) further to the north along the volcanic front. Mentolat, as well as Melimoyu and Cay, have amphibole as a phenocryst phase. Pb isotopes for all these centers fall along a mixing line between South Atlantic Mid Ocean-Ridge Basalt (MORB) source and a slab component derived from subducted Chile trench sediments and altered oceanic crust, similar to other SVZ magmas (Jacques et al., 2013). Sr and Nd isotopes also fall within the same range as for other SVZ and back-arc basalts and South Atlantic MORB, although Hudson has slightly elevated  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70444$  for both mafic and felsic eruptive products (Weller et al., 2014). All the isotopic ratios from the other volcanoes are also independent of  $\text{SiO}_2$  content, which argues against crustal contamination

as a significant processes in the generation of any of these magmas.

## 3 Discussion and Conclusions

Relative to LA type magmas, HA magmas have both higher incompatible element contents and light to heavy REE ratios ( $\text{La}/\text{Yb}$ ), but lower ratios of soluble to insoluble elements ( $\text{Ba}/\text{La}$  for example). West-to-east across arc differences between LA and HA magma types were first documented in the SVZ by Hickey et al. (1986, 1989), Futa and Stern (1988) and Stern et al. (1990). They were attributed to a decrease of slab-derived hydrous fluids and dissolved solids, causing decreasing  $\text{Ba}/\text{La}$  as a result of progressive down-dip slab dehydration, which also resulted in an across arc decrease in mantle partial melting, causing higher incompatible element contents and  $\text{La}/\text{Yb}$  ratios. New trace-element and isotopic data for central SVZ volcanoes and back-arc basalts confirm these trends (Jacques et al., 2013). Watt et al. (2013) recently concluded that that increasing slab-surface temperatures cause the sub-arc slab flux to become both less water-rich and increasingly dominated by hydrous melts rather than fluids over a distance of a few kilometers behind the arc front, resulting in across arc variations from lower to higher abundance magmas.

López et al. (1995a, 1995b) showed that these differences also occurred among MEC centers. López et al. (1995b) attributed differences among LA type stratovolcanoes and HA type MEC to different degrees of partial melting in their mantle sources. Hickey et al. (2002) also identified HA type basalts erupted from MEC and concluded that these had either lost soluble components during solidification, or were derived from hotter (but not wetter) regions of the mantle.

López et al. (1995b) documented Calbuco volcano as having unusual low abundance (VLA) of incompatible trace elements relative to other SVZ centers. They attributed this to fractionation of amphibole that occurred at Calbuco as a phenocryst phase and not at other SVZ centers. More recently, Sellés et al. (2004) and Watt et al. (2012) described similar very low incompatible element magmas from Nevado de Longaví and Huequi volcanoes, respectively, both of which also contain amphibole as a phenocryst phase as does Mentolat in the SSVZ. They attributed the low incompatible element concentrations and presence of amphibole to relative high degrees of mantle partial melting as a result of enhanced water in the mantle, in the case of Nevado de Longaví possibly as a result of the subduction of the Mocha Fracture Zone which projects below this volcano.

Futa and Stern (1988) and López et al. (1993) identified differences between LA and HA type volcanoes north-to-south along the volcanic front of the arc in the SSVZ,

differences further elaborated on by Naranjo and Stern (1998, 2004) and Watt et al. (2012). These studies have demonstrated that both Hudson and Melimoyu volcanoes are HA types, Yanteles, Maca and Cay are LA type, and Huequi and Mentolat are VLA type centers (Figs 1 and 2).

However, a number of first order inconsistencies occur in the along strike chemical variations among the volcanoes in the SSVZ and the proposed models for the generation of LA, HA and VLA magmas. One is that Mentolat, the one VLA center, presumably generated by relative high degrees of partial melting of a relatively water-rich mantle, is the smallest volcano in the SVZ (36 km<sup>3</sup>; Völker et al., 2011), while Hudson and Melimoyu, the HA type centers presumably generated by lower degrees of partial melting of a relatively dry mantle, are the largest centers (147 and 142 km<sup>3</sup>, respectively). Both of these latter two centers have had multiple large explosive eruptions, so that even these volumes, which do not include pyroclastic material, are minimum estimates. Weller et al. (2014) suggested that Hudson had erupted over 50 km<sup>3</sup> of pyroclastic material since the Last Glacial Maximum which would make it volume >200 km<sup>3</sup>. Maca, Cay and Yanteles, the LA type centers, are more similar in volume (40 to 90 km<sup>3</sup>) to average Andean volcanoes.

Another anomaly is that Mentolat contains amphibole, as do other VLA centers further north in the Andes, but so do samples from the HA center Melimoyu, and cryptic fractionation of amphibole has been invoked to explain the chemistry of the HA Hudson volcano (Kratzmann et al., 2010), although no amphibole has been found in any Hudson lava or tephra sample. Cay, an LA center east of the volcanic front (Figs. 1 and 2), also has amphibole as a phenocrysts (Stern et al., 1976; Futa and Stern, 1988).

Mentolat may occur above the down-dip projection of the Guablin fracture zone (D'Orazio et al., 2003), but LA center Yanteles also sits above the projection of the Guafó F.Z., and HA center Hudson above the Darwin (Gutiérrez et al., 2005) and/or the Taitao F.Z (D'Orazio et al., 2003), so there is no clear relation between fracture zone subduction and VLA, LA or HA volcanism in the SSVZ.

With regard to the MEC magmas, there is also notable along-strike variability just in the short section between Puyuhuapi and Palena. Watt et al. (2014) outline a model of magma genesis for Palena group basalts which places them above a relatively deep (135-140 km) and hot (870°C) slab from which water-poor slab melts are added to and cause melting in the overlying mantle wedge. However, their estimate of slab-depth below Palena is based on a southward extrapolation of the interpretation by Lange et al. (2007, 2008) of the slab geometry from north of 42.5°S. In contrast, according to Tassara et al. (2006) and Völker et al. (2011), depth to the subducted slab below the volcanic front decreases southwards in the SSVZ south of 42.5°S as the age of the subducted slab

decreases, and the Melimoyu volcano and Brazo Pillán cones along volcanic front occur over a region where the subducted slab is at a depth of ≤90 km, and the slab depth below Palena may be only as deep as 110 km. Ignoring these uncertainties in slab depth below the volcanic front and back-arc MEC in this region of the SSVZ, it is still clear that the LA Palena group basalts occur at about the same distance behind the volcanic front and at the very same depth above the subducted slab as the HA Puyuhuapi cones to the south. Therefore simple across arc changes in temperature and the character of slab-derived fluids and/or melts alone cannot account for these difference in the chemistry of the overlying MEC volcanoes. Furthermore the Melimoyu and Brazo Pillán centers along the volcanic front west of Palena erupted HA type magmas, typically explained by low slab-derived flux and low degrees of mantle partial melting in the back-arc region, while the Palena group behind the arc front are LA type basalts.

In summary, some of the previous explanation of across-arc variations in trace-element abundances and ratios are inconsistent with similar variation observed north-to-south along-the-arc in the SSVZ, and are not simply applicable as explanations of these differences.

Differences between HA and LA type basaltic magmas in the SSVZ may instead reflect transit time from their formation above the slab to their eruption at the surface. Hickey et al. (2002) suggest that, in the central SVZ, LA magmas erupted above areas with shorter transit times, and HA type magmas erupted above areas with longer transit times, causing them to lose volatiles and fluid-mobile elements relative to more immobile dissolved solids during solidification. Different ascent rates of magmas in the SSVZ may reflect in part the complexities in the subduction process associated with the subduction of the younger and more fractured oceanic crust just north of the Chile Rise, or they may result, as in the southern part of the Central Andes (Naranjo et al., in press), from differences in stress and/or the density of the continental crust and underlying mantle lithosphere as a function of the degree to which it is fractured by the Liquiñe-Ofqui Fault system. For instance MEC basalts are generally located along the LOFZ, but their occurrence is not continuous and their chemistry is variable, possibly indicating different degrees of transpression or transtension affecting the ability of magmas to transverse the lithosphere from above the subducted slab.

## References

- Cembrano, J., Hervé, F., Lavenu, A., 1996. The Liquiñe Ofqui fault zone: a long-lived intra-arc fault system in southern Chile. *Tectonophysics* 259: 55-66.
- D'Orazio, M.; Innocenti, F.; Manetti, P.; Tamponi, M.; Tonarini, S.; González-Ferrán, O.; Lahsen, A.; Omarini, R. 2003. The Quaternary calc-alkaline volcanism of the Patagonian Andes close to the Chile triple junction: geochemistry and

- petrogenesis of volcanic rocks from the Cay and Maca volcanoes (~45°S, Chile). *Journal of South American Earth Sciences* 16: 219-242.
- Futa, K.; Stern, C.R. 1988. Sr and Nd isotopic and trace element compositions of orogenic Quaternary volcanic centers of the southern Andes. *Earth and Planetary Science Letters* 88: 253-262.
- Gutiérrez, F.; Gioncada, A.; Gonzalez-Ferran, O.; Lahsen, A.; Mazzuoli, R. 2005. The Hudson volcano and surrounding monogenetic centres (Chilean Patagonia): an example of volcanism associated with ridge-trench collision environment. *Journal of Volcanology and Geothermal Research* 145: 207-233.
- Hickey, R.L.; Frey, F.A.; Gerlach, D.C. 1986. Multiple sources for basaltic arc rocks from the Southern Volcanic Zone of the Andes (34-41°S): Trace element and isotopic evidence for contributions from subducted oceanic crust, mantle, and continental crust. *Journal of Geophysical Research* 91: 5963-5983.
- Hickey-Vargas, R.L.; 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: 361-386.
- Hickey-Vargas, R.L.; 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.
- Jacques, G.; Hoernle, K.L.; Gill, J.; Hauff, F.; Wehrmann, H.; Garbe-Schönberg, D.; van den Bogaard, P.; Bindeman, I.; Lara, L.E. 2013. Across-arc geochemical variations in the Andean Southern Volcanic Zone, Chile (34.5-38.0°S): Constraints on mantle wedge and slab input compositions. *Geochimica et Cosmochimica Acta* 123: 218-243.
- Kratzmann, D.J.; Carey, S.; Scasso, R.A.; Naranjo, J.A. 2010. Role of cryptic amphibole crystallization in magma differentiation at Hudson volcano, Southern Volcanic Zone, Chile. *Contributions to Mineralogy and Petrology* 159: 237-264.
- Lange, D.; Rietbrock, A.; Haberland, C.; Bataille, K.; Dahm, T.; Tilmann, F.; Flüh, E.R. 2007. Seismicity and geometry of the south Chilean subduction zone (41.5°S-43.5°S): Implications for controlling parameters. *Geophysical Research Letters* 34: L06311.
- Lange, D.; Cembrano, J.; Rietbrock, A.; Haberland, C.; Dahm, T.; Bataille, K. 2008. First seismic record for intra-arc strike-slip tectonics along the Liquiñe-Ofqui fault zone at the obliquely convergent plate margin of the southern Andes. *Tectonophysics*, 455, 14-24.
- López-Escobar, L.; Kilian, R.; Kempton, P.; Tagiri, M. 1993. Petrology and geochemistry of Quaternary rocks from the southern volcanic zone of the Andes between 41°30' and 46°00'S, Chile. *Revista Geológica de Chile* 20: 33-55.
- López-Escobar, L.; Cembrano, J.; Moreno, H. 1995a. Geochemistry and tectonics of the Chilean Southern Andes basaltic Quaternary volcanism (37°-46°S). *Revista Geológica de Chile* 22: 219-234.
- López-Escobar, L.; Parada, M.A.; Hickey-Vargas, R.; Frey, F.A.; Kempton, P.D.; Moreno, H. 1995b. Calbuco Volcano and minor eruptive centres 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: 345-361.
- Naranjo, J.A.; Stern, C.R. 1998. Holocene explosive activity of Hudson Volcano, southern Andes. *Bulletin of Volcanology* 59: 291-306.
- Naranjo, J.A.; Stern, C.R. 2004. Holocene tephrochronology of the southernmost part (42-45°S) of the Andean Southern Volcanic Zone. *Revista Geológica de Chile* 31(2): 225-240.
- Naranjo, J., Villa, V., Ramírez, C.A., Pérez de Arce, C., (in press). Oligo-Holocene evolution of the southern part of the Central Andes: volcanism and tectonic. *Jornadas Geológicas SDNG, Servicio Nacional de Geología y Minería*
- Sellés, D.; Rodríguez, A.C.; Dungan, M.A.; Naranjo, J.A.; Gardeweg, M. 2004. Geochemistry of Nevados de Longaví volcano (36.2°S): a compositionally atypical arc volcano in the Southern Volcanic Zone of the Andes. *Revista Geológica de Chile* 31: 293-315.
- Stern, C.R. 2004. Active Andean Volcanism: its geologic and tectonic setting. *Revista Geológica de Chile* 31(2): 161-206.
- Stern, C.R.; Skewes, M.A.; Duran, M. 1976. Volcanismo orogenico en Chile austral. *In Congreso Geológico Chileno, No. 1, Actas* 2: 195-212. Santiago.
- Stern, C.R., F.A. Frey, K. Futa, R.E. Zartman, Z. Peng and T.K. Kyser 1990. Trace-element and Sr, Nd, Pb, and O isotopic composition of Pliocene and Quaternary alkali basalts of the Patagonian plateau lavas of southernmost South America. *Contributions to Mineralogy and Petrology* 104: 294-308.
- Tassara, A.; Götze, H.J.; Schmidt, S.; Hackney, R. 2006. Three dimensional density model of the Nazca plate and the Andean continental margin. *Journal of Geophysical Research* 111: B09404.
- Vargas, G.; Rebolledo, S.; Sepúlveda, S.A.; Lahsen, A.; Thiele, R.; Townley, B.; Padilla, C.; Rauld, R.; Herrera, M.J.; Lara, M. 2013. Submarine earthquake rupture, active faulting and volcanism along the major Liquiñe-Ofqui Fault Zone and implications for seismic hazard assessment in the Patagonian Andes. *Andean Geology* 40: 141-171.
- 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: 114-129.
- Watt, S.F.L.; Pyle, D.M.; Mather, T.A. 2011. Geology, petrology and geochemistry of the dome complex of Huequi volcano, southern Chile. *Andean Geology* 38(2): 335-348.
- Watt, S.F.L.; 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.
- Weller, D.; Miranda, C.G.; Moreno, P.I.; Villa-Martínez, R.; Stern, C.R. 2014. A very large (>20 km<sup>3</sup>) late-glacial eruption (Ho) of the Hudson volcano, southern Chile. *Bulletin of Volcanology* 76: 831-849.