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Key Points:

- The composition of continental arc magmas is conditioned by the architecture, constitution and reshaping of the continental crust
- Tracking magmatic components needs the integration of different isotopic systems
- Four main components determine the composition of Andean arc magmas in Central Chile

Supporting Information:

Supporting Information may be found in the online version of this article.

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Resolving Crustal and Subcrustal Dynamic Sources in Continental Arc Magmas: The Cenozoic Andean Arc of Central Chile

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Abstract The Andean margin of Central Chile (~32°40'–34°30'S) records abundant Cenozoic arc magmatic activity with variable compositional characteristics. This is examined through the analysis of an extensive database of new and published whole-rock geochemistry and Sr-Nd isotopic compositions, in addition to zircon Hf and O isotopic compositions. The whole-rock data record an increasing assimilation of continental crust material that developed through the compressional regime set in the margin in the Early Miocene that led to the construction of the modern Andes. The same is recorded by the Hf and O isotopic compositions, but these also allow identification of components involved in the magma genesis: (a) the sub arc mantle derived primary magmas, (b) a late Paleozoic—Early Triassic crystalline component, as that currently outcropping immediately to the east of the study area, (c) a deep enriched component, which likely corresponds to the Cuyania terrane, a Grenville age basement recognized further east in this Andean region, and (d) a deep juvenile low- $\delta^{18}\text{O}$ component, interpreted here as basement with oceanic crust affinities. This latter component reveals a possible composite nature for the Chilenia terrane, the postulated Grenville age basement in the region. The Cenozoic Andean arc magmas correspond to the differentiated products of an extensive intra-crustal re-working, taking place along tens of kilometers below their emplacement level, and whose main imprint is on the magmatic isotopic composition. Our results document the role of the continental crust, particularly regarding its evolving architecture and constitution, over the composition of arc magmas.

Plain Language Summary The western Andes cordillera in Central Chile (~32°40'–34°30'S) is composed of abundant igneous rocks derived from magmatic processes related to subduction from ~43 Ma to present. These rocks show variable compositional characteristics according to their location and age, which can be used as a tool for unraveling the evolution of the associated magmas in their transit from the mantle through the overlying crust to sub- surficial levels (<5 km). The results from this work show that these magmas are sourced mainly from the mantle, yet their original composition is strongly modified by their interaction with materials from the crust throughout their ascension. Three major crustal domains of different compositions have been identified, which are inherited from an earlier evolution of the region prior to the formation of the Andes cordillera. The studied Andean igneous rocks document the major role of the continental crust in modulating the composition of magmas in these settings.

1. Introduction

Continental arc magmas are chemical systems derived from multi-stage and multi-component processes. They originally form from the melting of the subduction-modified subcontinental mantle, but upon reaching the overlying crust diverse contaminants can variably modify their primary composition. It is problematic to resolve crustal and subcrustal magmatic arc components. Principally, because crustal contaminants can be incorporated both in the asthenospheric source and in the crust itself, in addition to the large compositional diversity hosted in a continental crust reservoir. In a wider frame, this blurs our ability to use arc magmas as proxies for the major tectonic processes that determine the composition of the subarc mantle and the continental crust, and their

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variations in time. Such is the case for the Cenozoic arc magmatism of southwestern South America, where a long-standing debate on magmatic arc sources is ongoing. Focusing on the currently active Andean volcanic arc, the outstanding early works of Hildreth & Moorbath (1988) and Stern (1991a) initiated the grounds for the debate, each putting forward contrasting hypotheses about crustal versus subcrustal incorporation of crustal material in the genesis of Andean magmas in thickened orogen areas (see also Hildreth & Moorbath, 1991; Stern, 1991b). Hildreth and Moorbath (1988) argued for a dominant crustal control conceptualized in the MASH model (*melting, assimilation, storage, homogenization*). In this model, asthenospheric-derived primary magmas ascend until reaching a MASH zone at the base of the overlying crust, a domain where they stall and compositionally homogenize. They then continue to ascend carrying the imprint of these base-level isotopic and chemical characteristics. In contrast, for mostly the same area, Stern (1991a) postulated a subcrustal control via subduction erosion. In this model, the scrapping off of the continental crust by the subducting oceanic lithosphere would be responsible for the incorporation of crustal material in the asthenospheric source and, therefore, for the crustal signal carried by the ascending arc magmas. These hypotheses have endured as two contrasting models to explain the composition of arc rocks.

A key area for such discussion is the northern segment of the Andean Southern Volcanic Zone, also called the Northern Southern Volcanic Zone (NSVZ; see Stern et al., 2007 for reviews). This corresponds to the currently active arc that distributes along the central Chile-Argentina Andean drainage divide, between $\sim 33^\circ$ and $34^\circ 30'S$ (Figures 1a and 1b), and the volcanic products show compositional characteristics indicating an important incorporation of crustal material (e.g., Hildreth & Moorbath, 1988; Hickey-Vargas, Holbik, et al., 2016; Stern, 1991a; Stern et al., 2007). In this area, the arc overlays a ~ 50 – 60 km thick crust (Figure 1c; Hickey-Vargas, Holbik, et al., 2016; Tassara et al., 2006), mostly old late Paleozoic-Early Triassic basement as a potential contaminant is exposed both near the arc region and along the coast (Figure 1b), and evidence for subduction erosion processes along the margin have been presented for Neogene times (Kay et al., 2005). The debate about crustal versus subcrustal controls over NSVZ compositions has, in addition, extended to and nourished from considering the protracted history of Cenozoic magmatism in the region (Kay et al., 2005; Muñoz et al., 2013; Stern, 1989, 2020; Stern & Skewes, 1995; Stern, Skewes, & Arévalo, 2011; Stern et al., 2019), of which the current arc is only the latest episode. This magmatism was initially framed by an Oligocene-Early Miocene extensional event, characterized by an intra-arc rift system developed over a thin crust (~ 35 km; Charrier et al., 2002, 2007; Nyström et al., 2003; Kay et al., 2005). The system was then inverted in the Early Miocene under a compressional regime, active until today and responsible for the constructional processes of the modern Andes in the region (e.g., Farías et al., 2010; Giambiagi & Ramos, 2002). Arc igneous rocks accompanying this evolution show compositional variations marked by an increasing crustal signal, yet the relative crustal versus subcrustal control on such variations remains debated (Kay et al., 2005; Muñoz et al., 2013; Nyström et al., 2003; Stern, 2020; Stern et al., 2019).

In this work, we address the crustal versus subcrustal control on arc magmas in the Cenozoic arc of Central Chile, between $\sim 32^\circ 40'$ – $34^\circ 30'S$ (Figure 1). We base our study on new and published: (a) whole-rock geochemistry and Nd and Sr isotopic composition, (b) Hf and O isotopic composition mostly from single zircon crystal analyses, and (c) radiometric ages. The results allow us to identify four major components involved in the arc magma genesis, to resolve to a significant extent the different crustal versus subcrustal sources, and to track source dynamic variations linked to the continental margin evolution during the Cenozoic.

2. Geological Background

The Chilean Andes margin corresponds to a continental margin setting characterized, in most of its length, by the eastward subduction of the Nazca oceanic plate underneath the South America continental plate (Figure 1a). Such a process occurs with a convergence rate of ~ 7 cm/yr, an obliquity of $\sim 20^\circ$ (Somoza & Ghidella, 2005), and a subduction dip angle of $\sim 27^\circ$; excepting a flat slab subduction segment (27° – $33^\circ S$; Pardo et al., 2002). The study area is in Central Chile between $\sim 32^\circ 40'$ – $34^\circ 30'S$, in the northern part of the Southern Central Andes ($\sim 33^\circ$ – $46^\circ S$), where the margin is composed of several NS-trending geological units (Figure 1b). The coastal region mostly exposes Paleozoic plutonic rocks, grouped as the Coastal Batholith, and subordinate Mesozoic plutonic rocks and metasedimentary units. These are flanked to the east by Jurassic-Cretaceous intrusive rocks and stratified sequences that comprise the Coastal Cordillera. The Central Depression develops between the latter and the western main Andes Cordillera and accumulates Pliocene-Quaternary sedimentary fill. The main Andes Cordillera is a doubly vergent deformed and uplifted area and, from west to east, is composed of (Figure 1b):

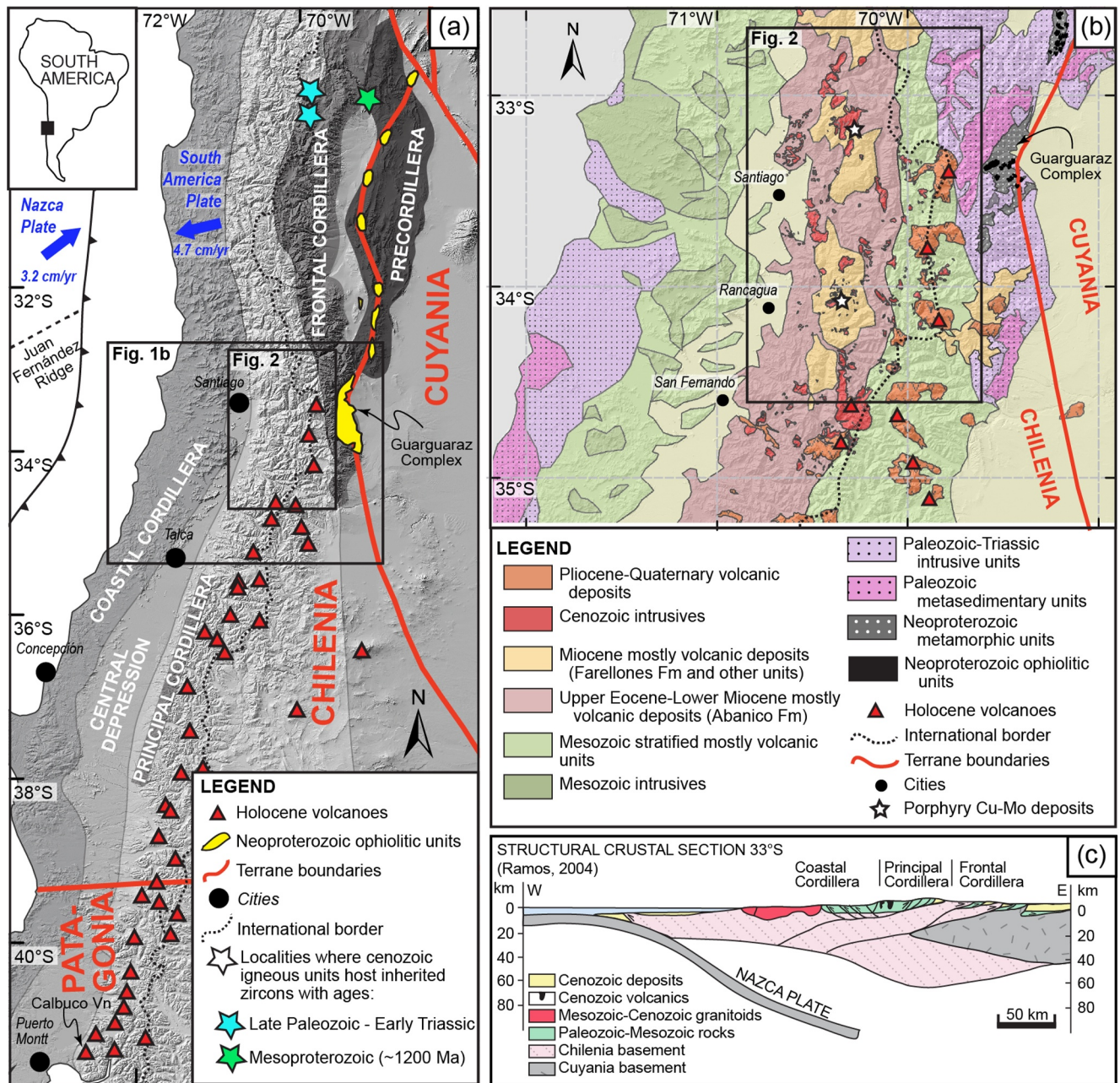


Figure 1. Main tectonic and geologic features of the Andean margin of central Chile-Argentina. (a) Map displaying the tectonic configuration of the margin regarding characteristics of the plate convergence (in blue) and the distribution of the main morphostructures (areas in grayscale), Holocene volcanic centers, the different terranes accreted to western Gondwana during the Paleozoic (in red; Ramos, 2004), and ophiolitic units in westernmost Argentina (in yellow; Boedo et al., 2016). The study area lies within the black rectangle indicated as Figure 2. (b) Simplified regional geologic map of the Andean margin where the study area is located (black rectangle). Compiled from Thiele (1980), Sernageomin (2003), Farías et al. (2010), Ramos et al. (2010), and Lavandaio et al. (2023). (c) Structural cross-section of the Andean margin at 33°S highlighting the crustal architecture and major units composing the basement in the region as proposed by Ramos (2004).

(a) Western Principal Cordillera, a fault-bounded block of Eocene to Miocene series composed of up to ~5,500 m thick igneous and minor sedimentary rocks; (b) Eastern Principal Cordillera, a series of sedimentary and minor volcanic Mesozoic series that are involved in east vergent thin- and thick-skinned fold and thrust belts near the Chilean-Argentinean border; (c) Frontal Cordillera, in westernmost Argentina, a thick eastwardly thrust block of upper Paleozoic-Triassic crystalline rocks in addition to subordinate Paleozoic metasedimentary units and Neoproterozoic metamorphic units which include ophiolitic sequences. The margin configuration is completed to

the east by the Andean foreland in Argentina and the currently active volcanic arc distributed along the Eastern Principal Cordillera (Figure 1b).

The Cenozoic evolution of Central Chile is well documented by the continental and mainly volcanic series exposed in the eastern portion of the Central Depression and the Western Principal Cordillera, in addition to numerous intrusive units in those areas and also in the Eastern Principal Cordillera (Figures 1b and 2). Along with the Quaternary volcanic deposits, these units constitute an almost continuous arc record from the middle Eocene to the present. The early stage is dominated by an extensional regime represented in an at least ~1,000 km long margin parallel rift system known as the Abanico basin (e.g., Charrier et al., 2002). More than 3,000 m of volcanic and subordinated sedimentary continental deposits accumulated in this system in an intra arc setting over a ~35 km thick crust (e.g., Charrier et al., 2002, 2007; Kay et al., 2005; Nyström et al., 2003). The great thickness of those deposits in addition to the high heat flow conditions prompted the widespread development of low-grade metamorphism in the basin (e.g., Aguirre et al., 2000; Fuentes, 2004; Muñoz et al., 2010). In the study region, the extensional episode extended from at least the middle Eocene to Oligocene times (e.g., Charrier et al., 2002, 2007; Kay et al., 2005; Muñoz-Gómez, Fuentes, et al., 2020; Muñoz et al., 2006; Nyström et al., 2003) and the maximum crustal thinning in the basin was recorded in the middle Oligocene (Muñoz-Gómez, Fuentes, et al., 2020). A contractional regime occurred in the margin in the Early Miocene and was responsible for the basin inversion and the shortening, thickening and uplifting processes leading to the construction of the modern Andes cordillera (e.g., Charrier et al., 2002, 2007; Farías et al., 2010; Fock et al., 2006; Giambiagi & Ramos, 2002; Jara & Charrier, 2014; Kay et al., 2005; Nyström et al., 2003). This stage was also characterized by a progressive eastward migration of both the volcanic arc loci, whose current position is nearly 80 km eastwards from the Oligocene frontal arc deposits, and the deformation. The current crustal thickness in the region reaches up to ~60 km under the mountain range axis, which hosts the active NSVZ arc, and up to ~50 km under the Western Principal Cordillera (Figure 1c; Tassara et al., 2006). The latter value therefore records at least ~15 km of crustal thickening since the development of the Abanico basin stage in that area. Throughout the described evolution, in the Late Miocene, the Western Principal Cordillera area also hosted formation of giant porphyry Cu-Mo deposits, among which El Teniente and Río Blanco—Los Bronces stand out as among the most highly endowed deposits in the world (e.g., Camus, 2003; Sillitoe, 2010; see locations in Figure 2).

The arc igneous rocks of the Andean margin show important variations throughout the Cenozoic, which constitute fundamental tools in tracking the geologic evolution of the region. The earliest record is scarce and only represented by the middle Eocene Estratos del Cordón de los Ratones Unit (ECLR; Figure 2), a 450 m thick mainly volcanic series hosting numerous coeval subvolcanic intrusions (Fock, 2005; Muñoz-Gómez, Fuentes, et al., 2020; Sellés & Gana, 2001). This unit is a bimodal arc suite, with calc-alkaline affinities, juvenile isotopic signatures, and compositional characteristics that indicate a thicker crust (~35–45 km) with respect to that recorded by the ensuing Oligocene magmas (Muñoz-Gómez, Fuentes, et al., 2020). In a wider context, the ECLR is a unit that marks the change from the preceding neutral tectonic conditions, recorded in the region from the latest Cretaceous to mid-Eocene (e.g., Balgord, 2016; Horton & Fuentes, 2016), and the subsequent Oligocene extension (Muñoz-Gómez, Fuentes, et al., 2020). The following period, to present, is widely and well represented by numerous units present in the region. The continental and mainly volcanic series grouped in the Abanico Formation (late Eocene—earliest Miocene; ~3,000 m thick) and the Farellones Formation (Early Miocene; ~2,500 m thick; Figure 2; Thiele, 1980), respectively record the development of an extensional regime followed by a compression. This record is complemented with numerous dispersed Cenozoic intrusive units (Figure 2). Igneous products of the Abanico Formation show a high proportion of undifferentiated and unfractionated compositions, tholeiitic to calc-alkaline affinities, and juvenile isotopic signatures (e.g., Fuentes, 2004; Kay et al., 2005; Nyström et al., 2003; Sellés, 1999). In turn, for the Farellones Formation a progressive change in these characteristics is observed with an increasingly stronger crustal signature, namely a higher proportion of differentiated and fractionated compositions, stronger calc-alkaline affinities and more enriched isotopic compositions (e.g., Fuentes, 2004; Kay et al., 2005; Nyström et al., 2003; Sellés, 1999). Subsequently, the stronger crustal signature variably increases to present as evidenced by the later Late Miocene to Pleistocene intrusives and dispersed volcanic deposits and the current NSVZ deposits (Kay et al., 2005). In addition to these changes, the arc evolution also shows a waning of volcanic activity, with decreases in both the volume and area extent of the associated deposits after the Oligocene (Abanico Formation; Figure 2).

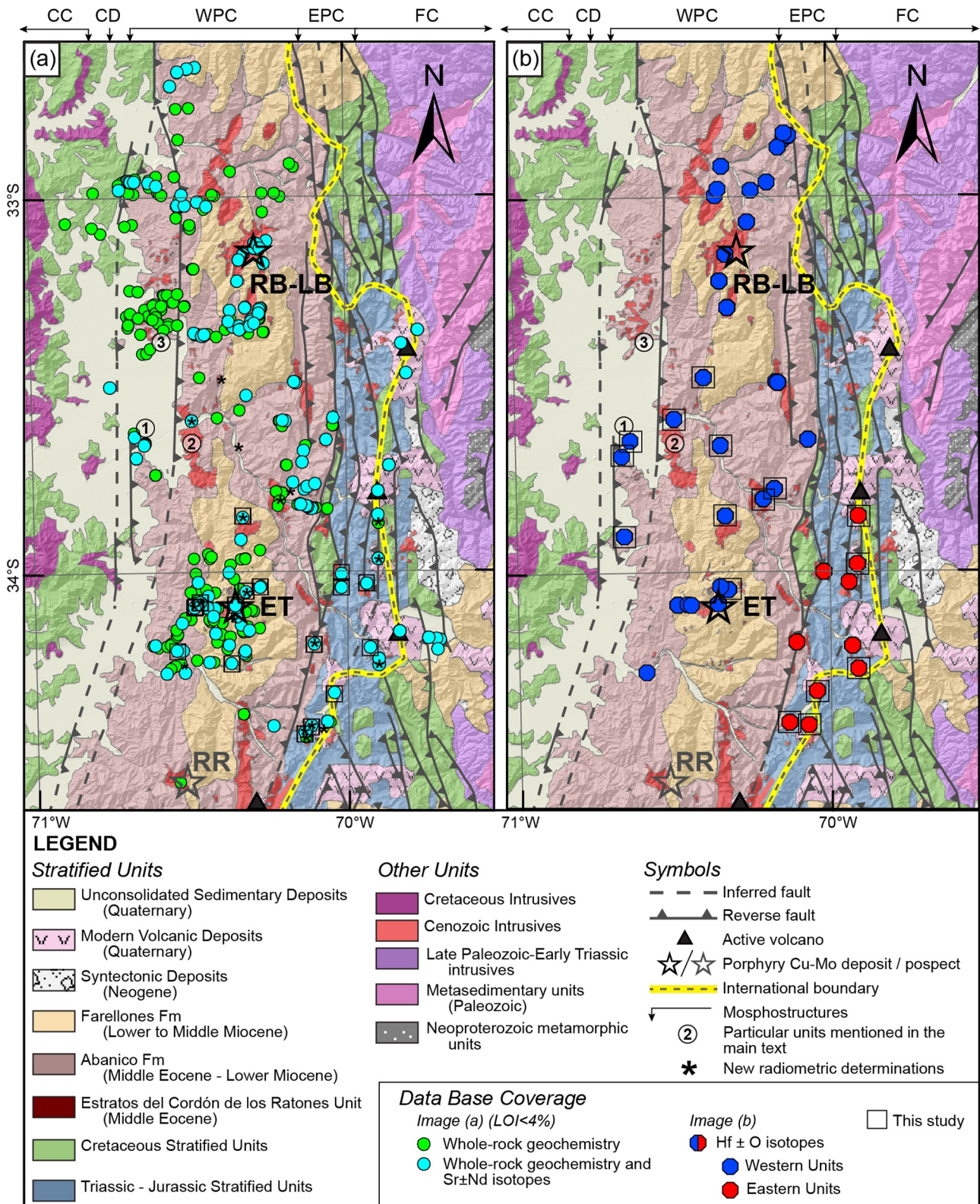


Figure 2.

3. Methods

This study is based on field and analytical work that our research group has developed for more than a decade in Cenozoic units of the Central Chile region. The data presented and analytical methods are included in the Supporting Information S1 and can also be accessed through an online repository (see below the Open Research section). The data include a variety of geochemical, isotopic and radiometric determinations performed in igneous intrusive and extrusive rocks. Detailed analytical methods are presented in the Text S1 in Supporting Information S1.

A total of 23 whole-rock geochemical analyses by ICP-AES (major elements) and ICP-MS (trace elements) were performed at the Departamento de Geología—Universidad de Chile and the Laboratoire des Mécanismes et Transferts en Géologie, Université Paul Sabatier, respectively (Table S1 in Supporting Information S1). For 21 of these samples whole-rock Sr-Nd isotopic composition by ICP-MS was performed at the latter facility (Table S1 in Supporting Information S1). Analyses in zircon crystals for U-Pb ages, and Hf and O isotopic compositions were performed in several samples at different facilities. A total of 15 samples were analyzed at the Research School of Earth Sciences—Australian National University for coupled U-Pb ages by SHRIMP (Table S2 in Supporting Information S1) and O and Hf isotope composition, respectively, by SHRIMP (Table S3 in Supporting Information S1) and LA-ICP-MS (Table S4 in Supporting Information S1). For completing previously published determinations from the same facility (Muñoz et al., 2013; Muñoz-Gómez, Fuentes, et al., 2020), 1 Hf and 6 O isotope analyses by the same methods were performed in addition (Tables S3 and S4 in Supporting Information S1). Hf isotopic composition was also analyzed at the Centro de Geociencias—Universidad Autónoma de México in 3 samples with previously published U-Pb ages from the same facility (Muñoz-Gómez, Fuentes, et al., 2020; Table S5 in Supporting Information S1). We also present 7 new ^{39}Ar - ^{40}Ar radiometric ages in mineral concentrates (plagioclase, biotite, amphibole; Table S6 in Supporting Information S1) performed at the Oregon State University (Corvallis).

As will be presented and discussed in the following sections, U-Pb ages in single zircon crystals have revealed the presence of inherited material in several igneous units of the Cenozoic Andean arc. Such material shows mainly late Paleozoic-Early Triassic ages, subordinated Cenozoic ages, and scarce Mesozoic ages (Muñoz et al., 2013; this work). To evaluate its role in contaminating Cenozoic arc magmas, we have used the U-Pb data coupled with the Hf and O isotopic compositions. In the case of the O data, this is made by directly using the $\delta^{18}\text{O}_{\text{Zrc}}$ values, but in the case of the Hf isotopic data, a recalculation of the zircon ϵHf values is needed. The latter follows from considering time corrections and zircon Hf isotope systematics. Regarding time corrections, as the rocks studied are Cenozoic in age, the use of present values for the Hf isotopic composition is a reasonable approximation at the time of contamination. There is a negligible time correction for the initial Hf isotopic composition due to the minimal decay of ^{176}Lu into ^{177}Hf (Soderlund et al., 2004). Regarding the zircon Hf isotope systematics, as at the time of crystallization this mineral phase will incorporate almost no Lu its $^{176}\text{Hf}/^{177}\text{Hf}$ will remain nearly unchanged in time (Figure 3). However, the whole rock Hf isotopic composition, which is the actual contaminant of interest, will follow a path of increasing $^{176}\text{Hf}/^{177}\text{Hf}$ depending on the Lu concentration (Figure 3). Taking these considerations into account, in order to estimate the Hf isotopic signature of such rock contaminants projected at the time of contamination, we have defined the parameter $\epsilon\text{Hf}^{\text{C}}$. This is a standard calculation of the ϵHf parameter on a forward projection to today from initial zircon $^{176}\text{Hf}/^{177}\text{Hf}$ values using a Bulk Earth $^{176}\text{Lu}/^{177}\text{Hf}$ of 0.015, the latter as representative of the whole rock system (Figure 3; Goodge & Vervoort, 2006).

Figure 2. Distribution of the sampling sites that provided the chemical and isotopic databases discussed in the main text over the geological map of the study area. Particular units signaled in the maps correspond to (1) Estratos del Cordón de Los Ratones (ECLR), (2) La Obra pluton and (3) Manquehue stock. Morphostructural units correspond to CC: Coastal Cordillera, CD: Central Depression, WPC: Western Principal Cordillera, EPC: Eastern Principal Cordillera, FC: Frontal Cordillera. Porphyry Cu-Mo deposits correspond to RB-LB: Río Blanco—Los Bronces, ET: El Teniente, RR: Rosario de Rengo. LOI: loss on ignition. Base geology was compiled from Thiele (1980), Sernageomin (2003), Farías et al. (2010), and Lavandaio et al. (2023). Geochemical data taken from the following studies: (i) Eocene to early Pleistocene rocks from Stern & Skewes (1995), Sellés (1999, 2000), Reich (2001), Oliva (2002), Nyström et al. (2003), Fuentes (2004), Kay et al. (2005), Hollings et al. (2005), Muñoz et al. (2006), Vidal (2007), Montecinos et al. (2008), Deckart et al. (2010), Stern, Skewes, and Arévalo (2011), Stern, Floody, and Espiñeira (2011), Muñoz-Gómez, Fuentes, et al. (2020), Muñoz-Gómez, Payacán, et al. (2020), and (ii) Late Pleistocene to Holocene rocks (NSVZ) from Stern et al. (1984), Hickey et al. (1986), Futa and Stern (1988), Hildreth & Moorbath (1988), Stern (1988), Godoy and Hildreth (2001), Sruoga et al. (2005, 2012), Holm et al. (2014), Hickey-Vargas, Holbik, et al. (2016), and Muñoz-Gómez, Payacán, et al. (2020).

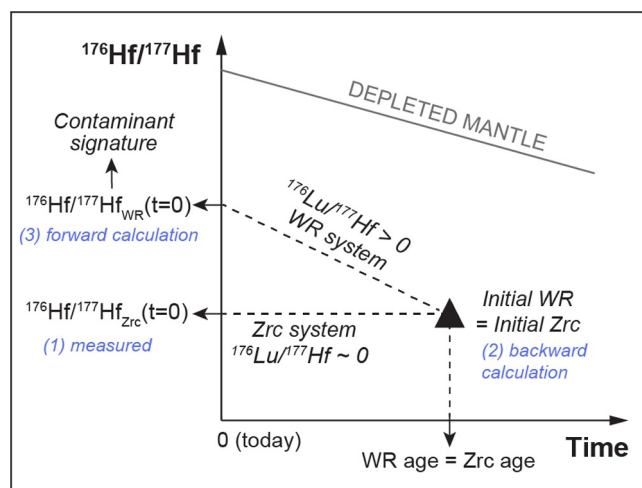


Figure 3. Schematic illustration of the $^{176}\text{Hf}/^{177}\text{Hf}$ isotopic systematics in zircon (Zrc) and the whole rock containing it (WR). The EHf^C parameter discussed in the main text is calculated from the $^{176}\text{Hf}/^{177}\text{Hf}_{\text{WR}}(t=0)$ illustrated in the figure. The latter corresponds to a forward calculation to today from the initial $^{176}\text{Hf}/^{177}\text{Hf}_{\text{Zrc}}$ using a $^{176}\text{Lu}/^{177}\text{Hf}$ of 0.015 as that of the whole rock system (Bulk Earth value; Goodge & Vervoort, 2006). For further discussion see Section 3 Methods in the main text.

4. Results

The new data presented in this work are discussed in the following, integrated with previously published geochemical and isotopic determinations in Cenozoic igneous rocks from Central Chile between $\sim 32^\circ 40' - 34^\circ 30' \text{S}$ (Figure 1). These data allow an extensive compositional characterization of the evolution of a nearly ~ 150 km long arc segment over the last ~ 43 Ma (Figure 2). For the whole-rock analyses, we provide a composite data set of the new data together with the numerous previous analyses of chemical composition (582 analyses), Sr isotopic composition (216 analyses) and Nd isotopic composition (176 analyses; Figure 2; Table S7 in Supporting Information S1; see references for previous analyses in Figure 2). The new whole-rock data include intrusive and extrusive igneous rocks (see sample locations in Figure 2), display a silica range between 51% and 69% and LOI values between 0.4% and 2.0% (Table S1 in Supporting Information S1), and show compositional characteristics within those described by the coeval igneous rocks included in the composite data set (see the following). In order to accurately consider these rocks in time, new radiometric determinations were performed for most of them and these provide ages between 0.4 and 23 Ma (Table 1; see sample locations in Figure 2). The new zircon Hf and O isotopic data presented correspond to igneous intrusive and extrusive rocks, covering an age range between ~ 0.4 and 42 Ma. Most of these rocks also have geochemical determinations from this or previous works. The Hf and O isotopic data are also assessed in the following sections integrated with

previously published determinations, providing a good spatial coverage for the discussed Cenozoic arc segment (see sample locations in Figure 2). For the new results, Hf isotopic compositions show a range of $^{176}\text{Hf}/^{177}\text{Hf}$ values between 0.282432 and 0.283122, with corresponding EHf values between -12 and $+11$ and $\text{EHf}(i)$ values between -10 and $+12$. The O isotopic compositions record a range in $\delta^{18}\text{O}_{\text{Zrc}}$ between $\sim +3.3$ to $+8.2$.

5. Discussions of the Integrated Cenozoic Arc Data

5.1. Geochemical and Isotopic Characteristics

5.1.1. Whole-Rock Geochemistry and Sr-Nd Isotopic Composition

The Cenozoic arc rocks show mainly a subalkaline character with a continuous silica range between 47% and 78% (Figure 4a; all analyses treated in anhydrous basis and filtered for volatiles values lower than 4%). In terms of age groups, the middle Eocene rocks are notable for displaying a silica gap between 54% and 64%, thus recording a bimodal suite. As seen in many chemical parameters, there are temporal variations which markedly correlate with the major tectonic episodes identified in the region. Calc-alkaline affinities are recorded initially in the middle Eocene (extensional stage initiation), shifting to tholeiitic in the Oligocene-earliest Miocene (extensional stage) and to calc-alkaline from the Early Miocene onwards (compressional stage). Notably, the last stage also shows progressively stronger calc-alkaline signatures toward younger units (Figure 4b). The described evolution is also recorded in parameters such as the FeO_T contents (total iron; Figures 4c and 5b), in addition to TiO_2 and MnO (not shown), which display an increase in the maximum contents from the middle Eocene and through the Oligocene-earliest Miocene, and then continuously decrease to the present (Figure 5b). In agreement with these variations, the less evolved arc compositions occur in the Oligocene-earliest Miocene, this is during the extensional stage, with higher MgO contents at the earliest stages of differentiation (low SiO_2 contents; Figure 4c). A last characteristic that stands out in major element basis corresponds to variations of SiO_2 and K_2O concentrations in time, for which Cenozoic arc rocks display variable and similar values within a range throughout the entire time span considered (Figures 5a and 5c). However, it is evident that minimum concentrations increase progressively toward younger units from the Oligocene-earliest Miocene in the case of SiO_2 and at least since the Late Miocene (~ 8 Ma) in the case of K_2O (Figures 5a and 5c). As these elements are incompatible through most of the magmatic differentiation path, such a pattern indicates that comparatively less evolved/enriched magmas did not reach upper crustal levels during the last stages of the Cenozoic arc. These stages developed through the compressional period since the Early Miocene and coincide well with the main uplifting event of the Andes in the region.

Table 1
Summary of New Radiometric Determinations Presented in This Study

Unit	Sample	Lithology	Location ^a	Age $\pm 2\sigma$ [Ma] ^b	Method ^c (system ^d)
Abanico Fm	ETY-03	lapilli tuff	33.667°S–70.344°W	21.34 $\pm$ 0.25	U-Pb SHRIMP (Zrc)
Abanico Fm	MF-15	lapilli crystalline tuff	33.784°S–70.174°W	20.38 $\pm$ 0.22	U-Pb SHRIMP (Zrc)
Arriaza stock	MLL9	clinopyroxene diorite	34.414°S–70.071°W	1.68 $\pm$ 0.04	U-Pb SHRIMP (Zrc)
Blancos de Las Leñas dikes	MM16	dacitic dike	34.407°S–70.132°W	12.70 $\pm$ 0.11	U-Pb SHRIMP (Zrc)
Cachapoal stock	MM18	amphibole quartz diorite	34.323°S–70.043°W	12.19 $\pm$ 0.11	U-Pb SHRIMP (Zrc)
Cachapoal Stock	MM18	amphibole quartz diorite	34.323°S–70.043°W	11.92 $\pm$ 0.83	⁴⁰ Ar– ³⁹ Ar SH (Pl)
Carlota stock	MM3	clinopyroxene diorite	33.855°S–70.331°W	9.90 $\pm$ 0.09	U-Pb SHRIMP (Zrc)
Cerro Castillo volcanic series	MM5	orthopyroxene rhyolite	33.986°S–69.911°W	$\sim$ 0.688 $\pm$ 0.090 ^e	U-Pb SHRIMP (Zrc)
Cerro Catedral Stock	MM15	biotite granodiorite	34.193°S–70.107°W	3.08 $\pm$ 0.05	⁴⁰ Ar– ³⁹ Ar SH (Bt)
Cerro Listado volcanic series	MM14	biotite rhyolite	34.264°S–69.910°W	0.434 $\pm$ 0.031	U-Pb SHRIMP (Zrc)
Farellones Fm ^f (Cerro Minero Lavas)	MT1	two pyroxene andesite	34.092°S, 70.486°W	7.04 $\pm$ 0.13	⁴⁰ Ar– ³⁹ Ar SH (Pl)
Farellones Fm ^f (Cerro Minero Lavas)	MT2	two pyroxene andesite	34.081°S–70.470°W	8.30 $\pm$ 0.11	⁴⁰ Ar– ³⁹ Ar SH (Pl)
Estero Crucero Stock	MLL3	amphibole monzogranite	34.427°S–70.139°W	9.64 $\pm$ 0.39	⁴⁰ Ar– ³⁹ Ar SH (Amph)
Estero Crucero Stock	MM17	amphibole tonalite	34.410°S–70.119°W	9.76 $\pm$ 0.06	⁴⁰ Ar– ³⁹ Ar SH (Bt)
Farellones Fm	SRA-02	lapilli tuff	33.486°S–70.396°W	22.47 $\pm$ 0.18	U-Pb SHRIMP (Zrc)
Farellones Fm	MCh2	two pyroxene dacite	34.235°S–70.518°W	14.12 $\pm$ 0.20	⁴⁰ Ar– ³⁹ Ar SH (Pl)
La Huifa stock	MT9	amphibole granodiorite	34.052°S–70.323°W	7.21 $\pm$ 0.16	U-Pb SHRIMP (Zrc)
La Obra Batholith	MF-08	granodiorite	33.595°S–70.490°W	20.96 $\pm$ 0.24	U-Pb SHRIMP (Zrc)
Paso Colina stock	MM4	amphibole diorite	33.858°S–69.906°W	1.21 $\pm$ 0.06	U-Pb SHRIMP (Zrc)
San Gabriel Pluton	MF-12	granodiorite	33.810°S–70.210°W	12.26 $\pm$ 0.09	U-Pb SHRIMP (Zrc)
San Gabriel Pluton	MF-13	granodiorite	33.810°S–70.209°W	12.19 $\pm$ 0.18	U-Pb SHRIMP (Zrc)

^aSee Figure 2 for sample locations. ^bFull data given in the Supporting Information S1. ^cSHRIMP: Sensitive High Resolution Ion Microprobe, SH: Step Heating. ^dZrc: Zircon; Pl: Plagioclase; Bt: Biotite; Amph: Amphibole. ^eWeighted average that considers the three youngest spot ages in the sample. ^fIn the El Teniente area (porphyry Cu-Mo deposit, $\sim$ 34°S; see Figure 2), these units have been grouped under the informal unit Teniente Volcanic Complex (e.g., Kay et al., 2005).

According to reconstructions, such an event corresponded to a rapid and high magnitude regional uplift (of between 1.5 to at least 2.5 km), in response to crustal thickening processes that was completed by $\sim$ 7–4 Ma, when the Andes reached the current configuration (Fariás et al., 2008).

The main observations described above in the major element basis agree with those recorded by numerous trace elements. For compatible elements such as Sc (Figure 5d) and V (not shown) the Cenozoic arc rocks show an increase in maximum values from the middle Eocene to the Oligocene-earliest Miocene, then decrease continuously from Early Miocene to the present. In turn, for incompatible elements such as Zr, Hf, Ba, Ta, Nb, Th, U, and the LREE (light rare earth elements), minimum values variably increase from either the Early Miocene or Late Miocene onwards (for Ba, Th, and La see Figures 5e–5g). In agreement with above, these patterns record a higher proportion of less evolved rocks during the extensional stage, with a progressive waning of such compositions through the compressional stage, in contrast to comparatively more evolved/enriched compositions. Further, for the elements Th, Rb and the LREE there is an overall increase in maximum values for the same time span (for Th and La see Figures 5f and 5g). Such characteristics signal, in particular, the more enriched nature of magmas formed through the compressional stage.

It is important to highlight that the patterns described above do not change significantly when the study is restricted to less evolved rocks such as basalt and basaltic andesite compositions. This indicates that: (a) the previous discussions are not biased by an over representation of evolved compositions in specific age ranges, and (b) the variations described are present from the earliest stages of differentiation that can be traced in these arc rocks (basalts with SiO₂ > 47%; Figure 4a).

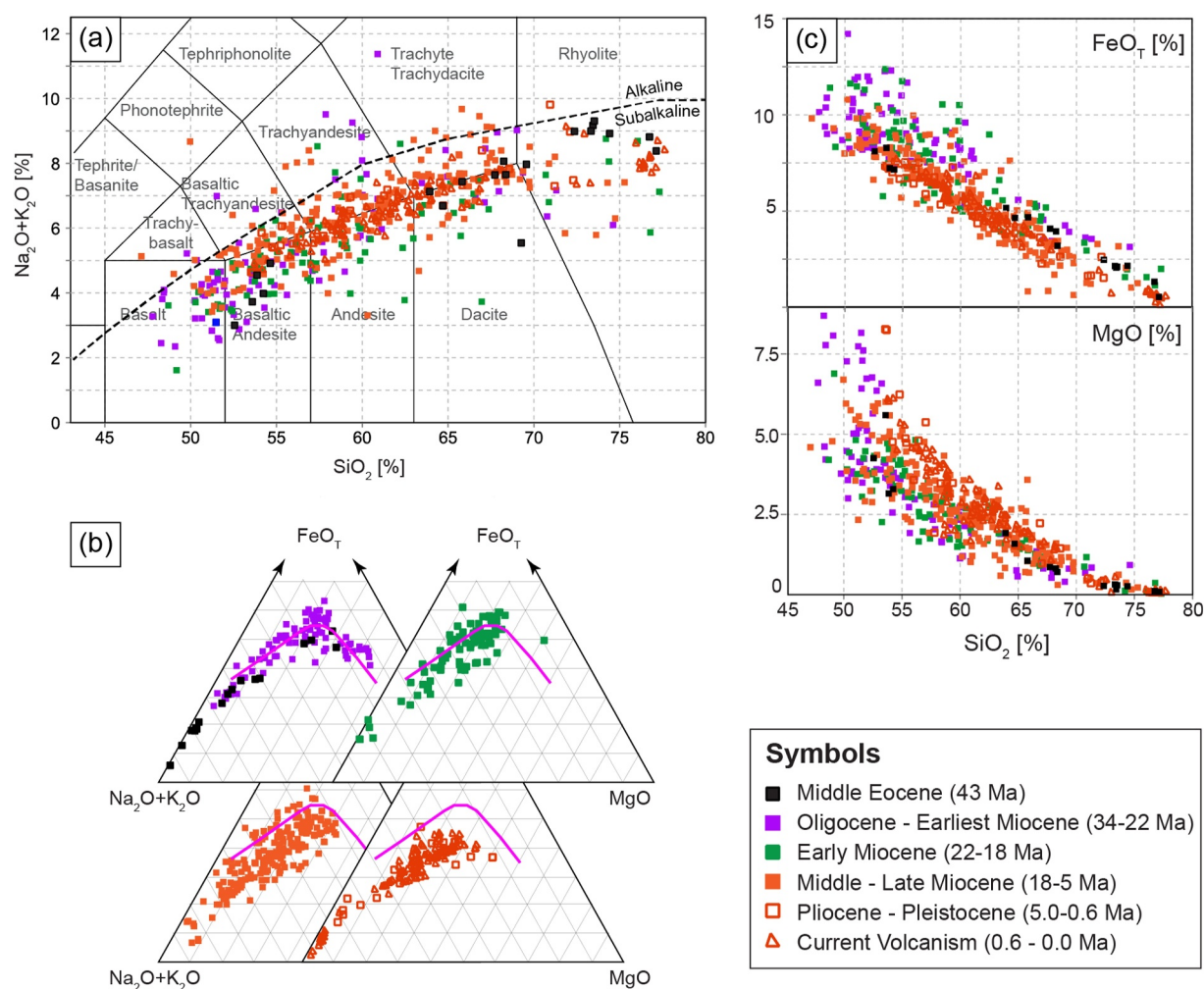


Figure 4. Main compositional characteristics of the studied rocks in major elements basis. (a) Volcanic TAS diagram (Le Maitre, 1989) with the Alkaline-Subalkaline classification after Irvine & Baragar (1971). (b) AFM diagrams with the Tholeiitic—Calc-alkaline subdivision after Irvine & Baragar (1971). (c) Selected Harker diagrams of FeO_T and MgO .

The rocks studied comprise variable numbers of the common major mineral phases: plagioclase, pyroxene, olivine and amphibole, plus iron oxides. As expected, these have been invoked as the main fractionating phases through differentiation (see references in Figure 2). In addition, the increasing involvement in the petrogenetic processes of pressure sensitive minerals, such as garnet and amphibole, from the early stages of differentiation has also been inferred for the compressional stage (e.g., Fuentes, 2004; Kay et al., 2005; Nyström et al., 2003). This is recorded in common geochemical proxies such as La/Yb and Sr/Y ratios, whose values progressively increase from the Early Miocene (Figures 6b and 6c) resulting from the combination of several characteristics as follows. First, the concentrations of Y and the HREE (heavy rare earth elements) systematically decrease during this time span in the Cenozoic arc rocks (for Y see Figure 5h). In addition, this is accompanied by a significant decrease in the concentration of those elements, which probably accounts for the increasing involvement of garnet in particular (Figure 5h). In the case of La/Yb ratios, the values are also controlled by the progressive enrichment recorded through the Early Miocene and evidenced in the progressive increase in La/Sm ratios (Figure 6d). Within the evolution tracked by these proxies, two notable anomalies stand out at ~ 7 – 5 Ma and at ~ 18 Ma, when particularly high Sr/Y and La/Yb ratios (Figures 6b and 6c) are observed due to low Y and Yb concentrations (Figure 5h). These anomalies correspond to the presence of adakite-like intrusions at the El Teniente porphyry Cu-Mo mega deposit (Kay et al., 2005) and among the Manquehue hill stocks (Sellés, 1999; see locations in Figure 2). Several hypotheses have been proposed to explain these singular magmas within the evolving frame of the Cenozoic arc. For the El Teniente intrusions, Stern, Skewes, and Arévalo (2011) postulated that such a

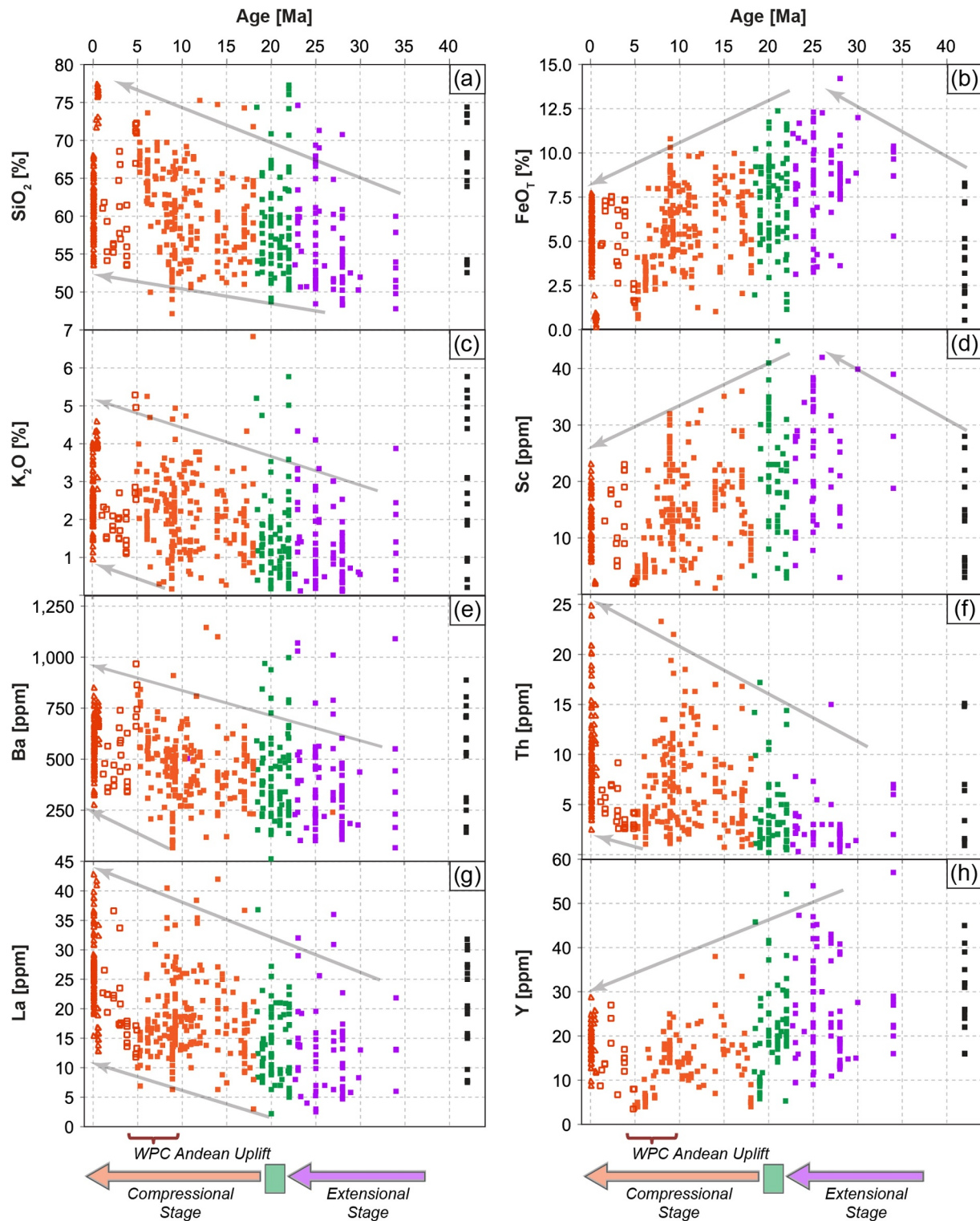


Figure 5. Variation against time of selected major and trace element concentrations of the studied rocks. (a) SiO_2 , (b) FeO_T , (c) K_2O , (d) Sc, (e) Ba, (f) Th, (g) La, (h) Y. Schemes at the bottom of the figure illustrate the corresponding main tectonic stages and events recorded in the margin at the study area. Gray arrows illustrate the overall increasing/decreasing trends discussed in the main text. WPC: Western Principal Cordillera. Symbols according to age as in Figure 4.

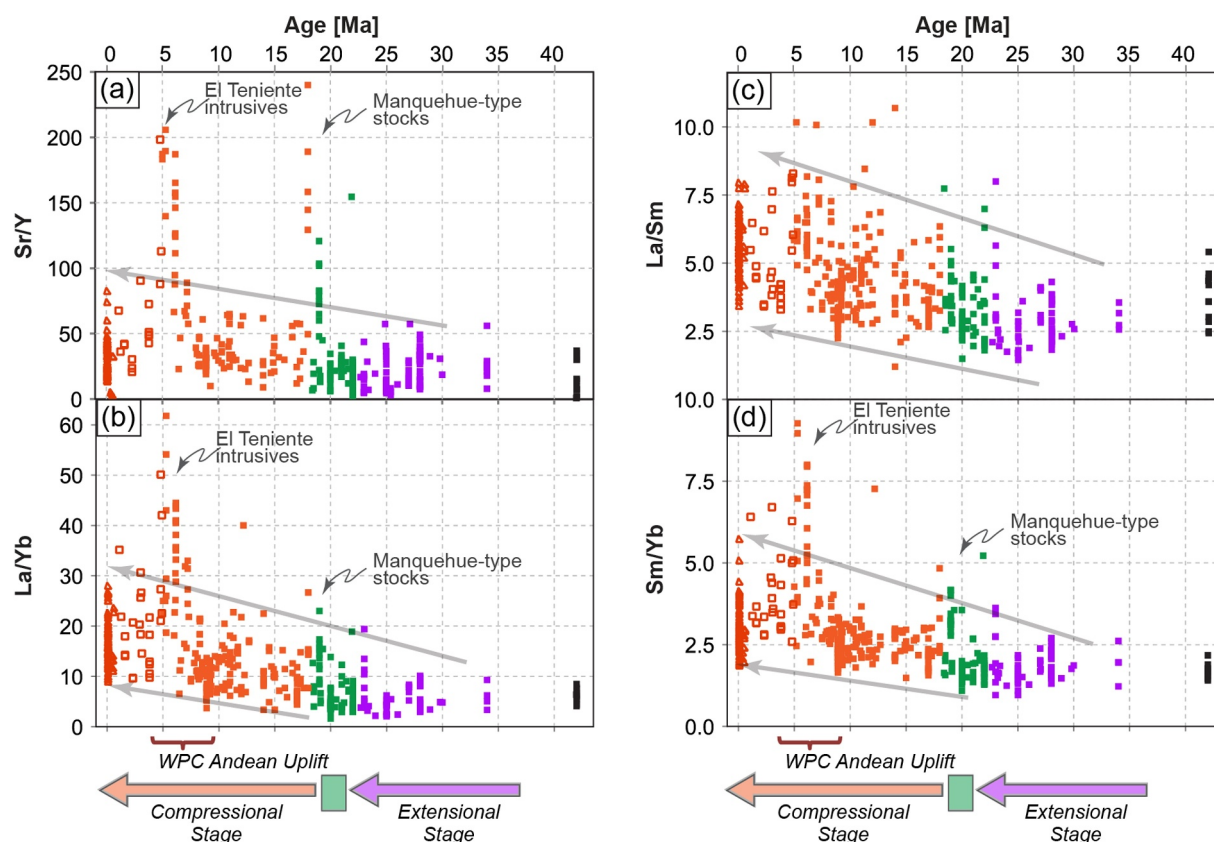


Figure 6. Variation of selected trace element ratios versus time for the studied rocks. (a) Sr/Y, (b) La/Yb, (c) La/Sm, (d) Sm/Yb. Schemes at the bottom of the figure illustrate the corresponding main tectonic stages and events recorded in the margin at the study area. Gray arrows illustrate the overall increasing/decreasing trends discussed in the main text. WPC: Western Principal Cordillera. Symbols according to age as in Figure 4.

signature resulted from extensive differentiation in deep large batholithic magma chambers. Later, Muñoz et al. (2012) invoked the additional participation of magmas derived from dehydration melting at the base of the thickening crust, a process where the residual mineral assemblages pass from amphibole dominated to garnet dominated. On the other hand, for the Manquehue intrusives, the involvement of garnet at the base of the crust is difficult to invoke as presumably such crust would not be thick enough at such an early stage of the compressive regime. Interestingly, one of the Manquehue intrusives, the sub-volcanic dacitic El Buitre Stock, actually has magmatic garnet and the preferred genetic explanation of Ojeda (2018) was the differentiation of magmas with anomalously high water contents (e.g., Rodríguez et al., 2007; Sellés et al., 2004).

Overall, the whole-rock Sr and Nd isotopic compositions recorded by the Cenozoic arc rocks agree with the compositional variations in time discussed this far. The isotopic signatures evolve from moderately depleted ones in the middle Eocene, to comparatively more depleted ones in the Oligocene-earliest Miocene, to a progressive enrichment developed from the Early Miocene onwards (Figure 7a). This evolving path was recognized in earlier studies of the region (Fuentes, 2004; Kay et al., 2005; Muñoz-Gómez, Fuentes, et al., 2020; Nyström et al., 1993, 2003) and it was also highlighted that the Sr and Nd isotopic variations are apparently independent of differentiation indexes (Kay et al., 2005). Reinforcing the latter, Kay et al. (2005) showed from simple mixing scenarios that it was impossible to generate the observed enrichment from the Early Miocene onwards by standard crustal contamination processes. In those models, the authors showed that to produce an enriched Quaternary arc magma from an unenriched Oligocene-earliest Miocene one requires an unreasonable amount of contamination from late Paleozoic-Early Triassic crust (up to 40%–50%). Such contaminant was selected considering the basement that crops out further east in the region, in the Frontal Cordillera, which in later works has been shown to underlie at least the Mesozoic swath of outcrops of the Eastern Principal Cordillera (Figures 1 and 2; Muñoz et al., 2013). Disregarding middle to upper crustal contamination processes as the main cause for the enrichment led to the consideration that this was controlled by deep processes (Kay et al., 2005). In turn, this opened the debate as to

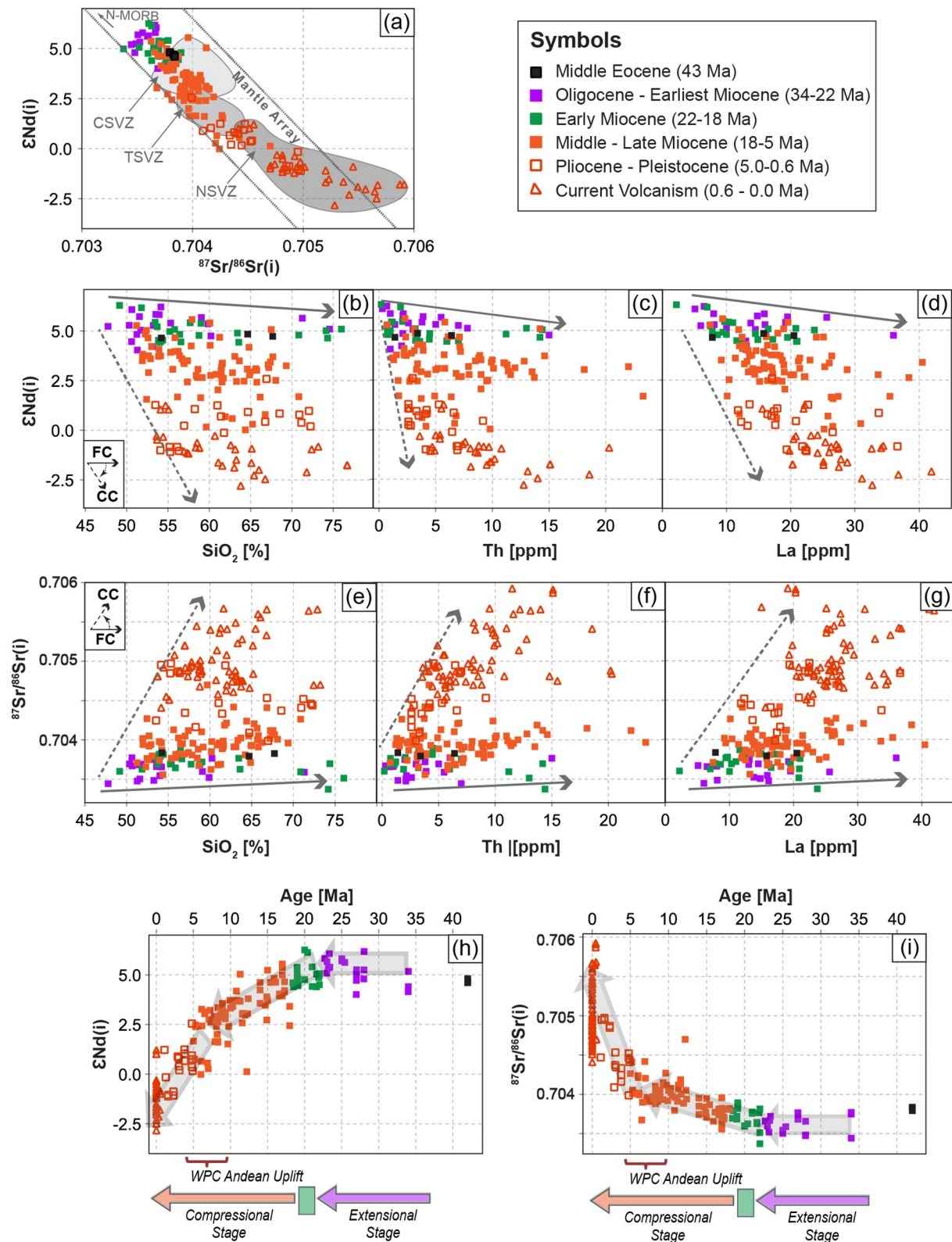


Figure 7.

whether such control resided deep in the crust, through MASH type processes (Muñoz et al., 2012, 2013), or in the sub-arc asthenospheric mantle, through source enrichment by subduction erosion of the forearc Paleozoic crust (Stern, 2020; Stern & Skewes, 1995; Stern et al., 2019).

The apparent lack of correlation noted by previous authors between the Sr-Nd isotopic signature and differentiation indexes is more elusive when considering the composite arc data presented in this work (Figure 7). The Sr and Nd isotopic compositions plotted against the silica contents show no correlation in both isotopic systems for rocks of different age groups, but with increasing scatter from the older to the younger rocks (Figures 7b and 7e). Notably, a clear correlation is observed between the progressively enriched isotopic values for each group and the minimum silica contents (segmented arrow in Figures 7b and 7e), which confirms that such enrichment is imprinted since early stages of differentiation. However, still discernible covariations within groups become pronounced when considering the trace elements shown previously to record more readily a progressive enrichment. This is the case, for example, for Th and La which should be more sensitive for tracking the involvement of crustal material (Figures 7c, 7d, 7f, and 7g). Against these parameters, rocks from all age groups display correlations with the isotopic signature, in particular in $\epsilon\text{Nd}(i)$, being progressively more pronounced for the Middle-Late Miocene rocks to the Pliocene-Quaternary ones (Figures 7c, 7d, 7f, and 7g).

All these observations show that a simple scenario of generating the progressively enriched signatures from the less evolved and less enriched ones is not the case. The characteristics described suggest a complex mixing scenario, where deep “source” processes as well as middle to upper crustal level contamination processes (as assimilation-fractional crystallization (AFC); DePaolo, 1981) are both variably involved in order to derive the signatures displayed by the Cenozoic arc rocks. The data also indicate that contamination processes at middle to upper crustal levels were less intense for magmas of the late Eocene and Oligocene-earliest Miocene, which formed during the extensional period, and were most intense for those of the Pliocene-Quaternary, which formed during the compressive regime and coevally or after the main uplifting event in the region. In this regard, it is remarkable that the Cenozoic arc rocks show variations in time in Sr-Nd isotopic signatures that tightly correlate with such major tectonic processes: the enrichment processes start after the initiation of the compressive regime (~22–18 Ma) and an increase in the rate of enrichment is observed after the main Andean uplifting event (~8 Ma; Figures 7h and 7i). This path strongly argues in favor of the continental crust as the main domain where the composition of the Cenozoic arc magmas is being conditioned, at least during the compressional stage, as a consequence of both its constitution and its reshaping throughout the construction of the modern Andean orogen.

Crustal thickness estimates are presented for the Cenozoic Andean arc and these strongly support the interpretations discussed in the previous sections in addition to providing improved constraints on the evolution of the region. Estimations have been obtained for several consecutive age ranges using the whole rock data in the multiproxy chemical mohometer of Luffi & Ducea (2022). Results are presented in Figure 9 and further details of the calculations and the full results given by the software are presented in the Supporting Information S1. Regarding the results themselves, it is first highlighted that for rocks younger than 3 Ma, the average current crustal thickness estimated for the arc region (Tassara & Echaurren, 2012) is tightly reproduced, thus validating the method. In a wider time frame, the results neatly track the variations in crustal thickness, which, as expected, correlate well with the major tectonic regimes interpreted in the region (Figure 8a). Progressively diminishing values, from ~35 km up to ~30 km, are recorded during the extensional stage between the middle Eocene and late Oligocene, thus corresponding the Oligocene to the time of maximum crustal attenuation. From then on progressively increasing values are observed up to the current ~55 km underneath the modern volcanic axis. It is also interesting to note that there are no relevant changes in crustal thickness from 7 Ma onwards (Figure 8a); this is after the main Andean uplifting event, an observation that reinforces the interpretation that by then the main configuration of the current orogen would have been reached (Fariás et al., 2010). Apart from grouping only by age ranges, additional calculations were performed for the Oligocene-earliest Miocene rocks incorporating a

Figure 7. Whole rock Sr and Nd isotope systematics of the studied rocks. Diagram (a) displays the covariation of $\epsilon\text{Nd}(i)$ versus $^{87}\text{Sr}/^{86}\text{Sr}(i)$ ratios including the fields defined by the Andean Southern Volcanic Zone (SVZ) in the Northern (NSVZ), Transitional (TSVZ) and Southern (TSVZ) segments. Diagrams (b, c, d) and (e, f, g) illustrate the covariation of respectively $\epsilon\text{Nd}(i)$ and $^{87}\text{Sr}/^{86}\text{Sr}(i)$ ratios respect to the SiO_2 , Th and La contents. For Sr and Nd isotopic composition against the latter incompatible elements, vectors illustrating the trends of Fractional Crystallization (FC) and Crustal Contamination (CC) processes are indicated in the left diagram. Gray arrows illustrate the overall increasing/decreasing trends discussed in the main text. Sr-Nd isotopic data for the SVZ taken from Stern et al. (1984), Futa and Stern (1988), Hickey et al. (1986), Hildreth and Moorbath (1988), Holm et al. (2014), Hickey-Vargas, Holbik, et al. (2016), Hickey-Vargas, Sun, and Holbik (2016), Muñoz-Gómez, Payacán, et al. (2020), and this work. WPC: Western Principal Cordillera.

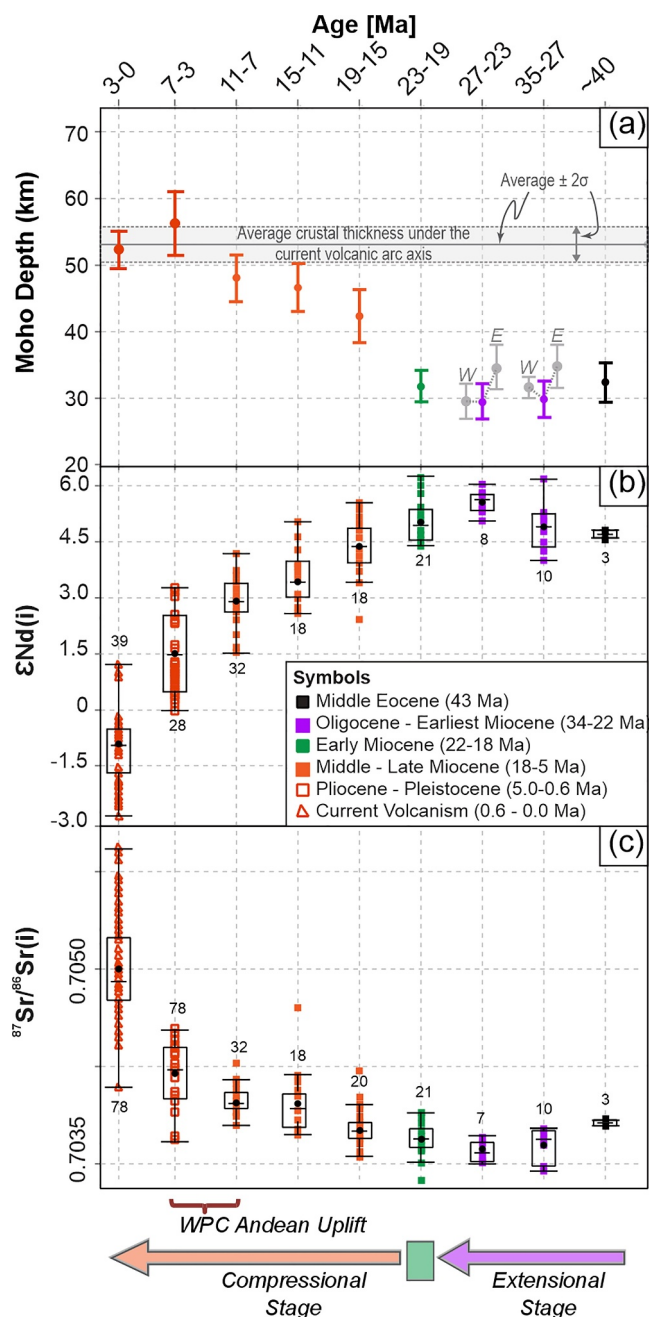


Figure 8. Crustal thickness calculation for different age ranges of the Cenozoic Andean arc data (a) and comparison against the Sr and Nd isotopic composition (b and c, respectively). (a) For crustal thickness, the mohometer of Luffi & Ducea (2022) has been used and results are displayed at 2σ error level. The average current crustal thickness under the active volcanic arc area is indicated by a gray band (taken from Tassara & Echaurren, 2012). The symbols in gray, labeled as E or W, correspond to additional calculations for the age range to which they are linked, but considering a spatial subdivision. These cases correspond mostly to the Abanico Formation outcrops, which currently shows an E-W width of up to ~55 km (see Figure 2) and was longitudinally divided in half for the displayed calculations. See the main text for further discussions. (b, c) Correspond to box and whisker plots and the full data for each age range has been included. Numbers inside these plots indicate data included. WPC: Western Principal Cordillera.

spatial discrimination (in gray in Figure 8a). These, which were formed during the extensional stage, mostly correspond to the Abanico Formation outcrops, in addition to coeval intrusives, which currently shows an E-W width of up to ~55 km (see Figure 2) and were longitudinally divided in half for the additional calculations.

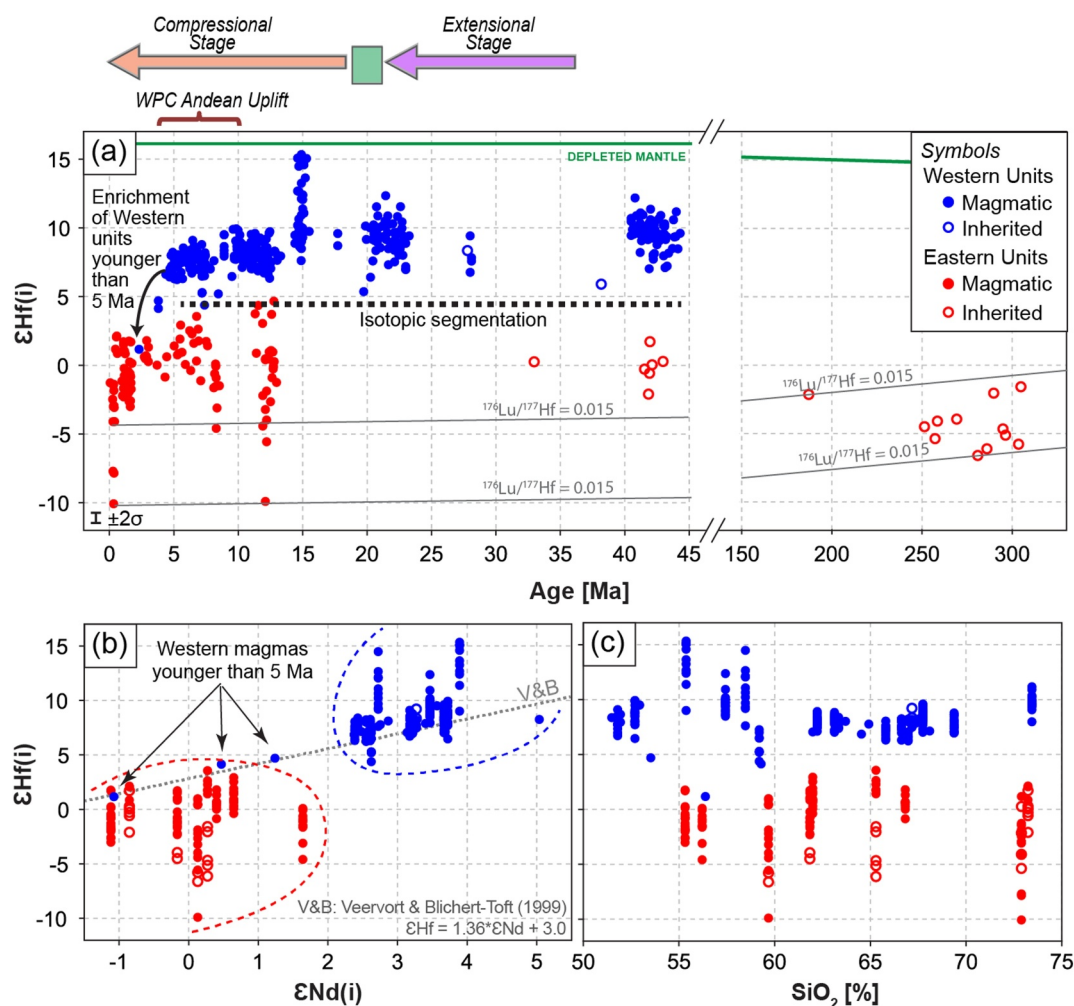


Figure 9. Initial $\epsilon_{\text{Hf}}(i)$ isotopic composition of the studied rocks and covariation of this parameter against the age (a), initial ϵ_{Nd} (b) and SiO_2 contents (c). In (a) $\epsilon_{\text{Hf}}(i)$ values have been plotted against the corresponding zircon U-Pb age, in the case of single mineral analyses, or against the reported rock age, in the cases of bulk zircon samples and whole rock analyses. The diagram also illustrates: (i) the evolution of the Depleted Mantle reservoir (green line; Bouvier et al., 2008; Veervoort & Blichert-Toft, 1999) and (ii) in gray lines a forward projection model up to present of initial ϵ_{Hf} values for the inherited Mesozoic and Paleozoic material using a bulk earth $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.015 (Goode & Veervoort, 2006). The present value of such projection has been termed as the ϵ_{Hf}^c parameter in the main text and facilitates evaluating the potential of the mentioned components as crustal contaminants for the Cenozoic arc magmas. In (b, c) only samples with $\epsilon_{\text{Hf}}(i)$ data along with corresponding whole rock SiO_2 contents and Nd isotope composition have been plotted. The only exceptions to this are some samples of the El Teniente deposit (TT150, TT101, TT90, TT102, TT94), which have been matched to the whole rock data in the corresponding units reported by Stern, Skewes, and Arévalo (2011). In all diagrams, samples have been grouped according to their occurrence in the WPC (blue; Western Principal Cordillera) and EPC (red; Eastern Principal Cordillera). In (a) schemes at the top of the figure illustrate the corresponding main tectonic stages and events recorded in the margin at the studied area.

Results reveal relevant E-W variations in crustal thickness, from ~ 30 km in the western rocks, which correspond to the frontal arc, to ~ 37 km in the eastern rocks. Finally, regarding the crustal control, there is a clear relationship between the geochemical enrichment and the increasing crustal thickness, which is also supported by the variations in the Sr and Nd isotopic compositions (Figure 8).

5.1.2. Hf and O Isotopic Composition

The first characteristic that stands out from Hf data is that the Cenozoic arc rocks display a marked spatial isotopic segmentation between the western and eastern magmatic units until the Early Pliocene (~ 5 Ma; Figure 9a), as it was first noted by Muñoz et al. (2013). Such segmentation is defined by igneous rocks currently exposed in

different portions of the orogen: the Western Principal Cordillera and the Eastern Principal Cordillera (Figure 2). For the western units, there is a record of Hf data discontinuously from the middle Eocene to Pleistocene (Figure 9a). This represents the arc activity that took place in the Abanico basin domain, throughout the extensional and the following contractional periods, waning until it was extinguished during the Neogene-Quaternary (Figure 2). For the eastern units, there is a fairly continuous record from the Middle Miocene onwards (Figure 9a), this is exclusively throughout the contractional period up to present. These igneous units were emplaced into the series of sedimentary and minor volcanic Mesozoic deposits currently comprising the Eastern Principal Cordillera, outside and immediately to the east of the Abanico basin domain (Figure 2). They also become progressively younger to the east, thus pinpointing the eastern migration of the arc activity, while this was waning in the western areas, until its establishment in the currently active arc area (Figure 2).

The eastern units are characterized by $\epsilon\text{Hf}(i)$ values mostly between +4 and −6, although a few scatter to as low as −10. These values show an evolutionary trend toward increasingly less depleted compositions in progressively younger units (Figure 9a), a feature recorded by the whole group trending to lower maximum values with decreasing age (Figure 9a). Single zircon crystal analyses reveal the presence of older inherited components with two general age groups, a more prominent one with late Paleozoic-Early Triassic ages and a subordinate one with Eocene-early Oligocene ages. Both record $\epsilon\text{Hf}(i)$ values within the range defined for the Cenozoic igneous zircons analyzed in this eastern area (Figure 9a). In terms of the ϵHf^C parameter (for its description see Section 3. Methods) the following ranges are defined by the inherited material: (a) between −5 and −10 for the late Paleozoic-Early Triassic component, a range coincident with the lowermost $\epsilon\text{Hf}(i)$ values of Cenozoic magmas, and (b) between +2 and −4 for the Eocene-early Oligocene component, values within the main range of $\epsilon\text{Hf}(i)$ values of Cenozoic magmas (Figure 9a). Notably, the more abundant late Paleozoic-Early Triassic component is present in zircon samples both as individual crystals and as inherited cores, thus evidencing the incorporation and partial digestion of this material by the hosting Cenozoic magmas of the Eastern Principal Cordillera. Such crustal contamination processes are likely also responsible for the large intra-sample isotopic variability observed in igneous units from this eastern region, which can reach up to 9 ϵHf units (Figure 9a). The latter also suggests a derivation of the eastern units from igneous reservoirs related to intense assembling processes from multiple magmatic feeders (e.g., Kemp et al., 2007).

The western units have distinct Hf isotopic compositions with respect to the eastern units prior to the earliest Pliocene (~5 Ma; Figure 9a). Before this time, they were characterized by relatively juvenile compositions with more radiogenic $\epsilon\text{Hf}(i)$ values mostly between +6 and +12 (Figure 9a). Importantly, the single zircon isotopic analyses reveal a limited intra-sample variability of less than 4 ϵHf units, with limited amounts of inherited material (Figure 9a). Where present, such material shows ages younger than middle Eocene and Hf isotopic signatures within the range of the hosting igneous units (Figure 9a). Altogether, the western units describe an evolutionary trend toward less depleted compositions with progressively younger ages. Units older than ~14 Ma reach comparatively more radiogenic values, with $\epsilon\text{Hf}(i)$ ranging to +12 and occasionally to +15 (coeval Depleted Mantle values), while younger units show less radiogenic values lower than +10 (Figure 9a). From around ~8 Ma onwards the $\epsilon\text{Hf}(i)$ signatures quickly decrease, reaching a minimum value of +1 in the youngest unit (Figure 9a). This latter value is within the range defined by the coeval eastern units, indicating that the spatial segmentation of the Hf isotopic signatures has disappeared by then and all the arc igneous rocks share the more crustal Hf signature of the eastern areas (Figure 9a).

The marked spatial segmentation displayed by the Cenozoic arc rocks on an Hf isotopic basis was not observed previously in the whole-rock data of the region. Amongst the different chemical and isotopic parameters explored in this work, the only one that clearly records the segmentation is the Nd isotopic composition (Figure 9b). This is expected considering the similar geochemical behavior of both isotopic systems, and in their relation of $\epsilon\text{Hf} \approx 1.36 \cdot \epsilon\text{Nd} + 3.0$ (Vervoort & Blichert-Toft, 1999) besides the comparatively higher resolution of the Hf isotopic data that has enhanced the compositional contrast between different igneous rocks and regions.

Another aspect to highlight in comparing with the whole rock data is that the Hf isotopic signature is independent of the composition of the host rocks. These include intrusive and extrusive units, which vary from basalt to rhyolite in composition, and no covariation is observed between Hf isotopic values and other chemical parameters. In particular, the difference between the more crustal Hf signatures of the eastern units with respect to the western units is observed throughout the chemical compositional spectra (Figure 9c). This feature precludes a simple scenario of crustal contamination processes, at middle to upper crustal levels as AFC type, as the sole cause for the

difference in the isotopic compositions between both areas. Although such processes are evidently involved in the genesis of the eastern units, as recorded in zircon samples, they cannot solely explain the crustal Hf signatures of these units with respect to the western units. The latter is supported by simple mixing models analogous to those presented by Kay et al. (2005), as these were constructed using a primitive and unenriched Abanico basalt with an enriched younger unit, compositions which in fact correspond respectively to the western and eastern units discussed here. In order to reproduce the main range of Hf isotopic signatures of the eastern domain rocks, an average primitive basalt from the western Abanico domain needs to be mixed with 15%–65% of a late Paleozoic–Early Triassic contaminant of felsic composition. Moreover, this model overlooks the extreme crustal Hf signatures of some Cenozoic zircons, which are fully within the range of the late Paleozoic–Early Triassic inherited components (Figure 9a). It is also most relevant to consider the thermal state of the continental crust in the eastern domain throughout the studied time span. Unlike the western domain, which records intense and almost continuous Cenozoic arc magmatic activity for tens of millions of years, magmatic units emplaced in the eastern domain are scarce and document the eastern arc migration from the Middle Miocene to the present (Figure 2). Therefore, throughout this migration, such units were emplaced in a thermally immature and cold eastern domain, which would not have favored the occurrence of important middle to upper crustal level contamination processes.

The arguments presented above point to the existence of an enriched component involved early in the genesis of the Cenozoic magmas with less radiogenic and more crustal Hf isotopic signatures. Such early involvement can occur at lower crustal levels and/or at subcrustal levels after MASH domain and/or source enrichment processes at the subarc mantle. However, for the studied rocks, the spatial distribution and temporal variations of the Hf isotopic signature are strong arguments for deep crustal processes. Prior to the Middle Miocene, the western and eastern units defined a sharp spatial segmentation which can be ascribed to compositional differences in the deep basement underlying both areas, a more likely scenario than invoking a control from a compositionally segmented sub arc mantle source (Muñoz et al., 2013). It is also remarkable that variations in the isotopic composition closely correlate with major tectonic processes occurring in the upper lithosphere. First, the temporal evolution toward more enriched signatures occurs exclusively in the western domain during the compressional stage (Figure 9a). The same is observed for the eastern domain although there are no older igneous rocks to compare against for the extensional phase. Second, a more dramatic decrease in $\epsilon\text{Hf}(t)$ signatures of the western domain is observed since the occurrence of the main Andean uplifting processes (<8 Ma), and this decrease continues until the arc igneous rocks record crustal Hf isotopic signatures similar to those of the eastern domain (Figure 9a). The described compositional evolution can be considered as an expansion of the eastern signatures toward the west and fits neatly with the simple shear models of Andean thickening processes in the region (Muñoz et al., 2013). In these, the crustal thickening and uplifting developed since <8 Ma onwards is interpreted to result from deep underthrusting of the basement advancing beneath the eastern areas toward the western ones (see Figure 11).

The O isotope ratios in this and previous works (Muñoz et al., 2012) were measured on the same in single zircon crystals and areas used for the analyses of Hf isotopes and U–Pb ages. Cenozoic arc rocks older than ~5 Ma show a similar segmentation in terms of $\delta^{18}\text{O}_{\text{Zrc}}$ values, though less pronounced than the corresponding Hf data (Figures 10a and 10b). All units record $\delta^{18}\text{O}_{\text{Zrc}}$ values that significantly overlap with the range defined by zircons in equilibrium with mantle-derived melts ($+5.3\text{‰} \pm 0.6$; Valley et al., 1998). The eastern units range to higher $\delta^{18}\text{O}_{\text{Zrc}}$ values, up to $+6.7\text{‰}$, whereas the western units tend to record lower values, as low as $+3.3\text{‰}$ (Figures 10a and 10b). For all units, the isotopic systematics of O are similar to those of Hf in that: (a) intra-sample variability is higher in the eastern units compared to the western ones, reaching up to 3.2 and 1.8‰, respectively, and (b) the $\delta^{18}\text{O}_{\text{Zrc}}$ signature is independent of the chemical composition of the host igneous rocks (Figure 10c). Regarding the inherited late Paleozoic–Early Triassic component of eastern units, the $\delta^{18}\text{O}_{\text{Zrc}}$ values range between $+4.7\text{‰}$ and $+8.2$ (Figure 10a).

The range in $\delta^{18}\text{O}_{\text{Zrc}}$ values significantly higher and lower than those for zircons in equilibrium with mantle-derived melts requires involvement of respectively higher and lower $\delta^{18}\text{O}$ components. The first case, restricted to the Eastern Principal Cordillera, can be in part explained by a variable incorporation of the late Paleozoic–Early Triassic component identified in the inherited zircon record. A 30% contamination of this component, having the average $\delta^{18}\text{O}_{\text{Zrc}}$ signature from the full range observed ($+6.3\text{‰}$), would be necessary to reproduce the average signature of eastern magmas ($\delta^{18}\text{O}_{\text{Zrc}} = +5.7\text{‰}$) from a mantle derived melt ($\delta^{18}\text{O}_{\text{Zrc}} = +5.3\text{‰}$). This rough estimate could be significantly lowered if the enriched deep component of the eastern areas, inferred from the Hf isotopic basis, would also have elevated $\delta^{18}\text{O}$ values (see discussions in the following sections). The second case, posing the presence of a low $\delta^{18}\text{O}$ component, is mainly observed in the Western Principal Cordillera, although

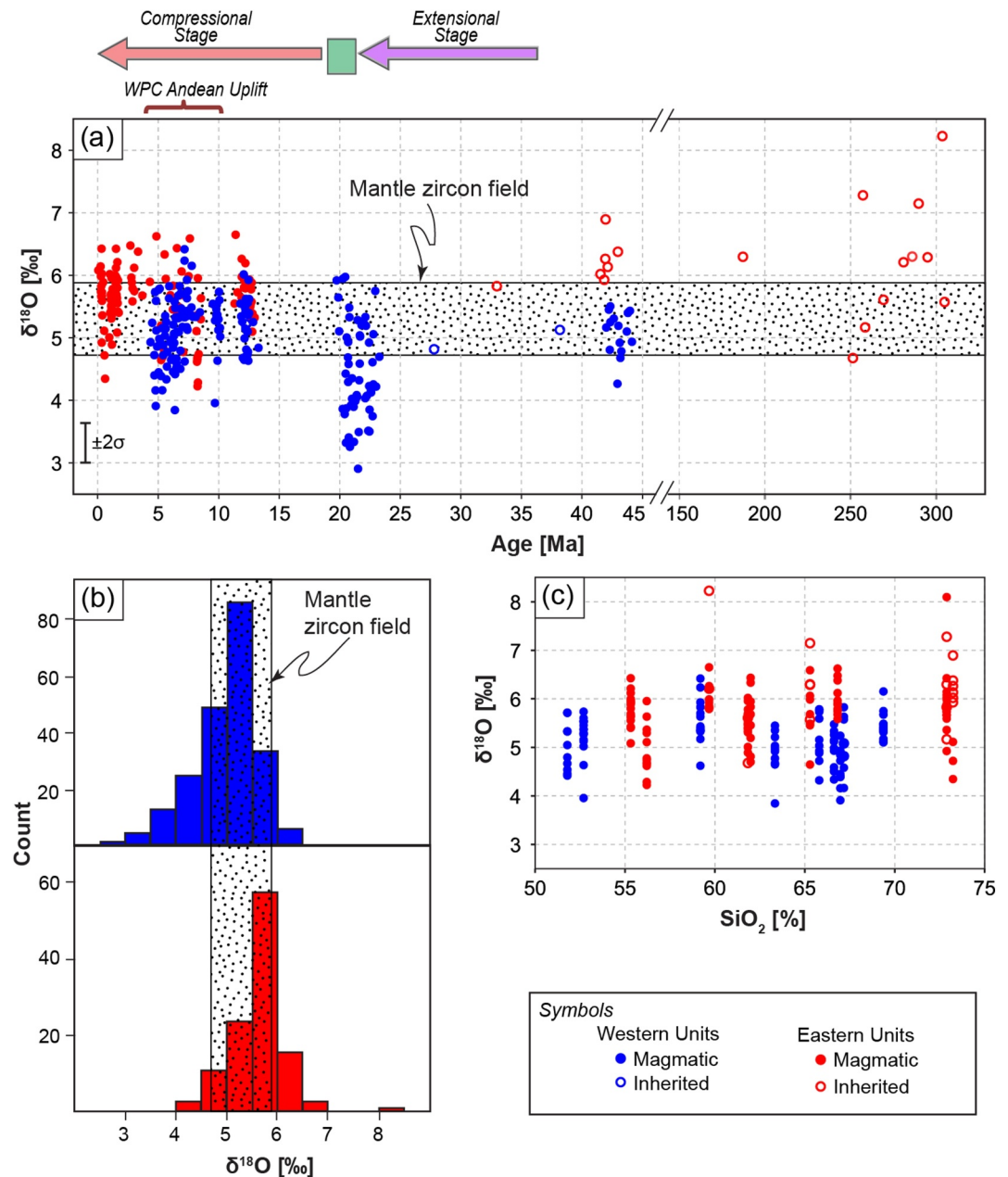


Figure 10. Zircon $\delta^{18}\text{O}$ composition of the studied rocks. (a, c) Diagrams illustrate $\delta^{18}\text{O}_{\text{Zrc}}$ values against the corresponding ages and whole rock SiO_2 contents (same plotting details as in Figure 9). (b) Histograms that illustrate the frequency of $\delta^{18}\text{O}_{\text{Zrc}}$ values for units from the WPC (blue; Western Principal Cordillera) and EPC (red; Eastern Principal Cordillera). Field of mantle zircon values taken from Valley et al. (1998; $5.3 \pm 0.6\text{‰}$). In (a) schemes at the top of the figure illustrate the corresponding main tectonic stages and events recorded in the margin at the studied area.

there is a slight signal also in the Eastern Principal Cordillera (Figures 10a and 10b). Low $\delta^{18}\text{O}$ components in the earth crust correspond to hydrothermally altered rocks, that is, rocks that have interacted with low $\delta^{18}\text{O}$ meteoric or sea waters at high temperatures (e.g., Bindeman, 2008; Bindeman & Valley, 2001, 2003; Bindeman et al., 2004, 2005, 2010; Eiler, 2001; Taylor, 1968), in addition to igneous rocks derived from their melting (e.g., Bindeman & Valley, 2001, 2003; Bindeman et al., 2005; Eiler, 2001; Wei et al., 2002, 2008; Yang et al., 2017; Zheng, Wu, et al., 2007). For the Western Principal Cordillera, the coupled Hf isotopic composition records elevated $\text{EHf}(i)$ values for the low $\delta^{18}\text{O}$ component (see Figure 12), indicating a juvenile reservoir. Incorporation of such a component early in magma genesis is supported by the fact that the isotopic signatures are independent of

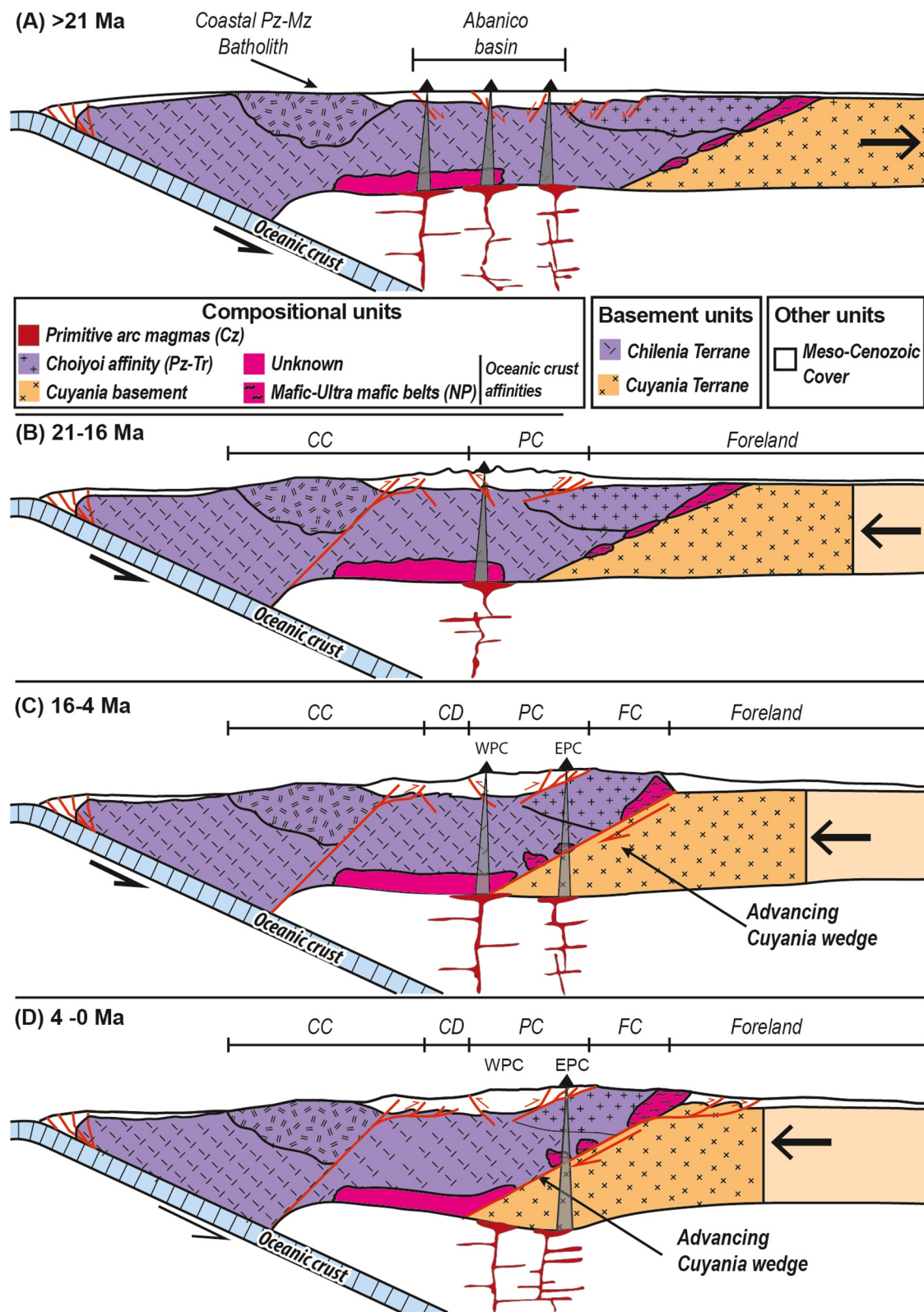


Figure 11.

differentiation parameters (see above) and that the inherited zircons do not have low $\delta^{18}\text{O}$ values. These characteristics argue against an AFC-type process as the means by which the discussed component is incorporated in magmas. It should be noted that the juvenile low $\delta^{18}\text{O}$ signature is recorded in two groups of igneous units, which likely represent the upper parts of extensive magmatic plumbing systems with deep roots in the crust. The first includes the La Obra Batholith ($\sim 33.5^\circ\text{S}$), in addition to two tuffs which are probably genetically related given their spatial proximity and similar age. The second group includes the intrusions related to the El Teniente porphyry Cu-Mo mega deposit ($\sim 34^\circ\text{S}$; see locations in Figure 2). The La Obra batholith corresponds to an Early Miocene unit (Kurtz et al., 1997; Piquer et al., 2021; Sellés & Gana, 2001; this work), of granitic to monzogranitic compositions, which covers an area of $\sim 224\text{ km}^2$ and shows at least 1 km of vertical exposure (Payacán et al., 2024; Rodríguez, 2022). The second group includes a series of mostly plutonic units, from gabbroic to granitic compositions, which constitute an almost continuous record of magmatic and vigorous hydrothermal activity from the Middle Miocene to the earliest Pleistocene in the area (e.g., Cuadra, 1986; Maksaeu et al., 2004; Muñoz et al., 2012; Stern, Skewes, & Arévalo, 2011). For the latter units, Muñoz et al. (2012) concluded that the juvenile low $\delta^{18}\text{O}$ values should be inherited from the deep crust based on a detailed characterization of their zircon O and Hf isotopic composition.

Overall, the Hf and O isotopic data and the conclusions drawn from them are in full agreement with the whole-rock geochemistry and Sr-Nd isotopic compositions for the Cenozoic arc igneous rocks. Both data sets show: (a) an increasing enrichment in progressively younger rocks whose timings closely correlate with major tectonic episodes developed in the upper continental lithosphere, (b) the role of the deep crust as a major control on the arc magmas composition, and (c) the occurrence of subordinate medium to upper level crustal contamination processes.

5.2. Components Involved in Arc Magma Genesis

5.2.1. The Late Paleozoic-Early Triassic Component: Frontal Cordillera

Undoubtedly, the first and most straightforward component to identify is the late Paleozoic-Early Triassic crystalline basement, which is directly recorded from the ages of inherited zircons in the arc igneous units emplaced in the Eastern Principal Cordillera. Such a basement constitutes most of the current Frontal Cordillera in Argentina and this morphostructural unit immediately limits the Eastern Principal Cordillera to the east (Figures 1 and 2). Thus, the inherited zircon evidence that the late Paleozoic-Early Triassic crystalline basement is continued to the west, at subsurface levels, underneath the Mesozoic sedimentary swath of outcrops that comprise the Eastern Principal Cordillera (Figures 1 and 2). Estimating the vertical location and extension of such component is elusive, yet thickness estimates for the current Mesozoic sedimentary swath are less than $\sim 15\text{ km}$ (Farías et al., 2010; Giambiagi & Ramos, 2002; Ramos, 2004), placing it at medium to upper crustal levels at least. It is also likely that the late Paleozoic-Early Triassic crystalline basement does not extend significantly into western areas, as the magmatic record in the Western Principal Cordillera shows no inherited components of such ages (Figures 9c and 9d).

5.2.2. The Deep Enriched Component: Cuyania Terrane

As previously discussed, the Hf isotopic systematics of the Cenozoic arc rocks signal both (a) the presence and influence of an enriched deep basement underneath the eastern areas and (b) the westward deep underthrusting of such basement underneath the western areas after the main Andean uplifting event ($< 8\text{ Ma}$). Muñoz et al. (2013) ascribed this to the Cuyania terrane (Figures 1a and 1c; Figure 9), one of the several terranes composing the deep basement of southwestern South America which derive from the Paleozoic accretionary history of the margin (e.g., Ramos, 1994, 2009; Ramos et al., 2004, 2010). The Cuyania terrane corresponds to a Grenville age

Figure 11. Schematic profiles of the Cenozoic evolution of central Chile that illustrate the main components involved in arc magma genesis. Extensional tectonics prompting the development of the Abanico intra-arc basin were active at least since the middle Eocene to early Miocene (a). Later, compressional tectonics set in the margin and were responsible for basin inversion and construction of the modern orogen (b–d). In this region, shortening processes account for the thickening and uplifting of the current modern Andes and these have been ascribed to the western underthrusting of the South American craton (e.g., Farías et al., 2010). The four main magmatic components identified here correspond to: (i) primitive arc basalts, (ii) a late Paleozoic—Early Triassic component, similar to units currently outcropping at the Frontal Cordillera (Choiyoi affinity), (iii) a deep evolved component, ascribed to the Cuyania basement, and (iv) a deep juvenile low- $\delta^{18}\text{O}$ component, of oceanic crust affinity. Acronyms Cz: Cenozoic, Pz-Tr: late Paleozoic—Early Triassic, NP: Neoproterozoic, WPC: Western Principal Cordillera, EPC: Eastern Principal Cordillera.

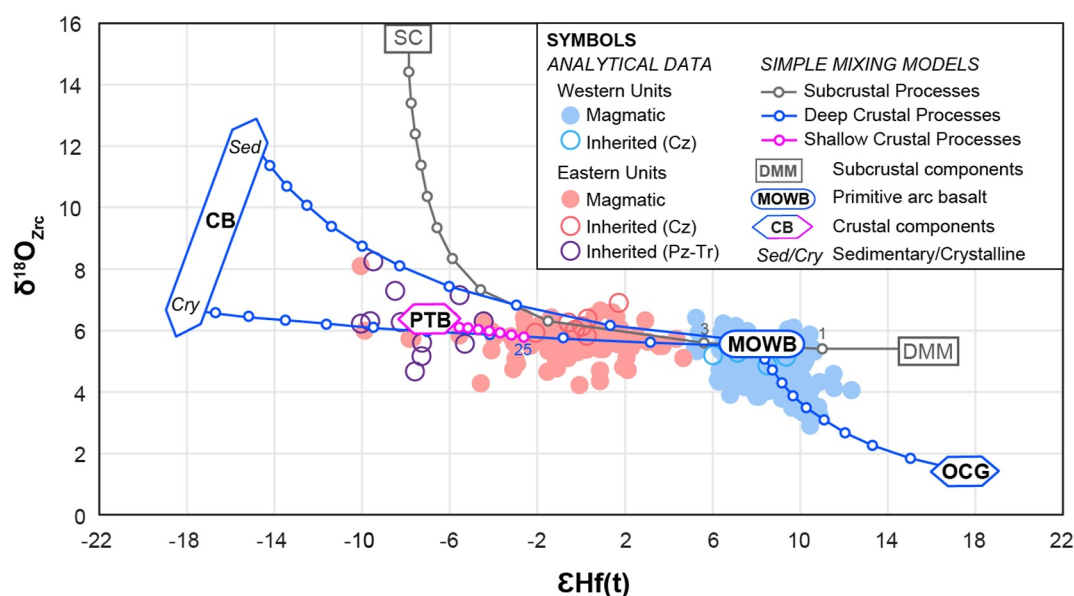


Figure 12. Zircon Hf-O isotopic composition for the studied rocks and simple mixing models. The displayed models follow sequential events described in the main text in Section 5.3. Simple mixing curves show ticks every 10% increments, except where signaled with numbers in the graph. Plotted data exclusively correspond to coupled Hf and O isotopic analyses in individual zircon crystals (Muñoz et al., 2012, 2013; This work). In the case of inherited material of late Paleozoic—Early Triassic ages the ϵHf^C values have been plotted. Components correspond to SC: Subduction Component; DMM: Depleted Morb Mantle; OCG: Oceanic Crust Gabbro; MOWB: Mantle Oxygen Western Basalt; CB: Cuyania Basement (Cry: Crystalline; Sed: Sedimentary); PTB: late Paleozoic—Early Triassic Basement. Other acronyms are Cz: Cenozoic, Pz-Tr: late Paleozoic—Early Triassic. The detailed composition of end member components is indicated in Table 2.

composite exotic block amalgamated to the western margin of Gondwana in the Middle to Late Ordovician (e.g., Ramos, 1994; Ramos, 2004, 2009; Ramos et al., 2004). It is partially exposed in Argentina between $\sim 29^\circ$ and 39° S, in the Precordillera fold and thrust belts and in scattered ranges further south (Figure 1a; e.g., Ramos et al., 2004; Martin et al., 2019), but it would constitute an important section of the deep basement underneath the western areas of the Andes, extending at least under the Eastern Principal Cordillera (Figure 1c; Ramos, 2004). Its distribution in deep crustal sections toward such areas in Chile would be the result of the westward basement underthrusting responsible in the region for the shortening, thickening and uplifting processes leading to the construction of the modern Andean orogen (Figure 1c; e.g., Farías et al., 2010; Ramos, 2004).

The Cuyania terrane has been inferred to correspond to Laurentian Mesoproterozoic crust formed in an island arc setting overlain by Paleozoic mostly sedimentary strata (e.g., Kay et al., 1996; Martin et al., 2019; Ramos, 2004). In a region encompassing the area studied in this work ($\sim 28^\circ$ – 35° S), recent studies on detrital zircon crystals have shown an enriched current Hf signature for the Grenville age components. For these, the ϵHf^C values vary between -22 and -8 (Martin et al., 2019), which make it a most suitable component for imprinting the base level unradiogenic Hf isotopic signatures recorded in the studied rocks. Interestingly, in the region further north, between 28° and 32° S (see locations in Figure 1a), equivalent Cenozoic igneous rocks exposed in the Argentina Precordillera show the presence of a Grenville age component controlling their geochemical and isotopic enrichment. For these, Jones et al. (2015) showed two distinguishing characteristics with respect to coeval rocks outcropping further west: (a) they are particularly enriched and show crustal $\epsilon Hf(i)$ signatures varying mostly between -4 and 0 , and (b) they contain Grenville age inherited zircon crystals which, in addition, show ϵHf^C between -8 and -5 . The reason why Cenozoic arc rocks exposed in the Argentina Precordillera actually show the inherited Grenvillian components, while those studied here do not, most likely relates to the depth of such basement underneath the two areas. Throughout magmatic evolution, incorporation of this component in late stages would favor the preservation of its record after partial digestion of the inherited zircons. Such is the case for the Cenozoic arc magmas emplaced in the Argentina Precordillera, where the presence of this component at upper crustal levels is recorded in the dispersed outcrops of the Grenvillian basement themselves. An early incorporation, at lower crustal levels and higher magmatic temperatures, would in turn favor the total digestion of the

inherited material, leaving only a record of the compositional enrichment and the evolved isotopic compositions as seen in the rocks studied here (Figure 9). In this case, the late stage component corresponds to the late Paleozoic—Early Triassic basement, recorded in the inherited zircon of magmas from the Eastern Principal Cordillera.

As well as the Hf isotopic signatures, the studied Cenozoic arc magmas also show a spatial segmentation in $\delta^{18}\text{O}$ isotope signatures, with values higher in the Eastern Principal Cordillera than those in the western units (Figure 10). The higher $\delta^{18}\text{O}$ values in the eastern units can be explained by the incorporation of early- and late-stage magmatic components discussed up to here, as deduced from the signatures recorded in the inherited zircon record. The Grenvillian component shows $\delta^{18}\text{O}_{\text{Zrc}}$ values ranging between +6.1 and +7.2‰ (Jones et al., 2015) while the late Paleozoic—Early Triassic component shows $\delta^{18}\text{O}_{\text{Zrc}}$ values between +4.7 and +8.2‰ (this work).

5.2.3. The Deep Juvenile Low- $\delta^{18}\text{O}$ Component: Oceanic Crust (?)

As recorded mostly by igneous units from the Western Principal Cordillera, a low $\delta^{18}\text{O}$ component is involved in the magma generation processes of the studied Cenozoic arc segment. Several hypotheses can be discussed in terms of the nature and possible origin of such a component, yet these must fit three main observations: (a) the juvenile isotopic composition recorded from Hf signatures, (b) location at deep crustal levels, as inferred from its early involvement throughout magmatic evolution, and (c) presence on a regional scale in the area.

Low $\delta^{18}\text{O}$ domains in large spatial extensions of the earth crust have been documented both for the continental crust and the oceanic crust. The first case has been invoked as the source of low $\delta^{18}\text{O}$ granites formed in rift and/or anorogenic settings (Zhao et al., 2007; Zheng, Wu, et al., 2007; Zheng, Zhang, et al., 2007; Wei et al., 2008). The origin of such domains has been ascribed to events of widespread meteoric-hydrothermal processes, prompted by magmatism, causing massive ^{18}O -depletion in large areas of the crust (e.g., Bindeman et al., 2010; Troch et al., 2020; Zheng, Wu, et al., 2007). In the second case, a relatively standard variation of $\delta^{18}\text{O}$ values is recorded through the oceanic crust profile, which was first described by Gregory and Taylor (1981) and confirmed later in numerous studies. Such compositional configuration responds to the common environment and processes to which the oceanic crust is subjected. From top to bottom, O isotopic values vary from high $\delta^{18}\text{O}$ in the uppermost deep-sea sediments ($\sim +15$ to $+42$ ‰) and hydrothermally altered upper crust (pillow basalts and dikes; $\sim +7$ to $+15$ ‰), low $\delta^{18}\text{O}$ in the hydrothermally altered gabbros and ultramafic rocks (0 to $+6$ ‰), and normal mantle $\delta^{18}\text{O}$ in the underlying unaltered mantle peridotites ($+5.5$ to $+5.9$ ‰; Bindeman et al., 2005; Eiler, 2001).

Two main observations favor the hypothesis of an oceanic crust type domain, located in the continental crust, for the identified low $\delta^{18}\text{O}$ component in the studied Cenozoic arc magmas: (a) the already documented involvement of such a component in current magma genetic processes of the southern SVZ (37° – 46°S) and (b) the outcrops of oceanic crust lithologies in the central Chile–Argentina Andean region. Regarding the first, Hickey-Vargas et al. (1995) reported the presence of oceanic metabasaltic xenoliths in andesitic lavas from the Calbuco volcano, a currently active Andean volcano located at $41^{\circ}20'\text{S}$ (see location in Figure 1a). These correspond to granuloblastic pyroxene granulites, derived from an incompatible trace element depleted basaltic protolith with isotopically juvenile compositions ($\text{ENd}(t)$: $+4.0$ to $+8.6$), which also show evidence of melting and melt extraction. Regarding the outcrops of such a component in central Chile–Argentina, these have been recognized in two main swaths (Figures 1a and 1b): (a) along the coast, as interbedded oceanic basalts in the metamorphic complexes derived from the Paleozoic Gondwana margin accretionary prism (see reviews in Díaz-Alvarado et al., 2019), (b) along the western margin of Precordillera in Argentina, as dispersed ophiolitic complexes mostly marking the suture between the Cuyania terrane and the westerly amalgamated Chilenia terrane (Figures 1a and 1b; see reviews in Boedo et al., 2021). The first case is unlikely to provide a juvenile low $\delta^{18}\text{O}$ component, as such units are characterized by the association of metasedimentary rocks ($\sim$ high $\delta^{18}\text{O}$ and enriched compositions) and subordinated oceanic basalts ($\sim$ high $\delta^{18}\text{O}$ and depleted compositions). In contrast, the Precordillera ophiolitic complexes constitute a suitable alternative given the common and abundant presence of lithologies from the deeper sections of an oceanic crust profile, that is, hydrothermally altered gabbros and ultramafic rocks (see reviews in Boedo et al., 2021).

Even though the ophiolitic complexes are an attractive alternative, they can be readily invoked for the scarce low $\delta^{18}\text{O}$ signatures recorded in magmas from the Eastern Principal Cordillera, but not so for those from the Western Principal Cordillera. Under the scenario that these units mark the suture between Chilenia and Cuyania terranes, a key issue is the location in time of such a suture underneath the western and eastern areas (Figure 11). As previously discussed, the arrival of the Cuyania basement beneath the Western Principal Cordillera is recorded at ~ 5 Ma from

the Hf isotopic compositions. This precludes the involvement of the ophiolitic complexes in the genesis of magmas formed earlier in the western domain, as is the case for those with marked low $\delta^{18}\text{O}$ signatures such as the La Obra Batholith (~20 Ma; Piquer et al., 2021; this work) and the intrusions from the El Teniente Cu-Mo deposit (age range ~4.5–7 Ma for those with coupled O isotopic data; Makshev et al., 2004; Muñoz et al., 2012). In turn, these considerations leave the deep Chilena terrane basement beneath the Western Principal Cordillera as the likely location of the component (Figure 11). Further inferences are elusive because of the current limited knowledge of the Chilena terrane. This is considered to represent a presumed Grenville age exotic block of Laurentian origin that collided with the Cuyania terrane in the Late Devonian (Jacques et al., 2020; Ramos, 1994, 2004). Along the continental margin, there are scarce rock exposures attributed to the Chilena terrane, so this basement remains poorly characterized. Nevertheless, some inferences about its composition have been made based on the chemical and isotopic composition of Paleozoic, Mesozoic and Cenozoic igneous rocks exposed over the domain of this basement terrane. Recently, Jacques et al. (2020) indicated that the Chilena terrane hosts at least two geochemical components: (a) one with unradiogenic Pb isotopes, representing the lower crust and/or lithospheric mantle, and (b) one with more radiogenic Pb isotopes, similar to Chilean Phanerozoic metasedimentary and igneous rocks (Coastal Batholith and Choiyoi province). The first is plausible as the juvenile low $\delta^{18}\text{O}$ component.

5.2.4. The Subarc Mantle Sourcing Primary Magmas

Under the paradigm of a destructive continental margin setting, the subduction modified depleted mantle component corresponds to the ultimate source of the studied Cenozoic arc magmas (Figure 11). Their chemical and isotopic composition indicates that overall these correspond to mainly juvenile additions from the subarc mantle, which are later overprinted variably by the crustally allocated components discussed so far. Such juvenile nature is particularly well exemplified in the radiogenic Hf isotopic compositions for units of the Western Principal Cordillera from the Eocene to the Middle Miocene. Their $\epsilon\text{Hf}(t)$ values vary mostly between +6 and +12, close to the value of +13 reported as the average of current island arc magmas (Dhuime et al., 2011). Considered in a wider time frame, Andean arc magmatism in the region from Jurassic, Cretaceous and Cenozoic times constitute important additions of juvenile material to the crust, in contrast to that from the Paleozoic and Triassic, which represent intense recycling of Proterozoic continental crust (e.g., Lucassen et al., 2004). Among the Cenozoic arc igneous rocks, however, so far, not a single primary arc basalt has been identified to directly address the subarc mantle component. Nevertheless, units such as the Yerba Loca stock, which has highly radiogenic $\epsilon\text{Hf}(t)$ values up +16 (current Depleted Mantle value; Figure 9), should be investigated in detail as possible magmas with a strong imprint of such a source.

5.3. Simple Mixing Models

Simple mixing models for the range in zircon Hf-O isotopic compositions have been performed to evaluate the involvement of the four main components discussed in the genesis of Cenozoic Andean arc magmas (Figure 12). These models are bulk mixtures between two end members and do not relate to particular processes. Thus, they are rough estimations as they do not accommodate the complexities of magmatic processes along the full trans-lithospheric magmatic arc column related to each sample, from the asthenospheric source to the final emplacement level. However, as displayed in Figure 12, it is remarkable that variable mixing of the discussed components can reproduce the compositional diversity displayed by the Cenozoic Andean arc magmas. We review the following one of several likely compositional paths and indicate details of the geochemical poles in Table 2 and Table S10 in Supporting Information S1.

In early subcrustal processes, source mixing of ~1%–3% of a Subduction Component (SC; acronyms as indicated in Figure 12) with the Depleted Morb Mantle (DMM) generates the full compositional range of units from the Western Principal Cordillera with mantle-like $\delta^{18}\text{O}_{\text{Zr}}$ signatures ($+5.3\text{‰} \pm 0.6$; Valley et al., 1998; Figure 12). The SC in this case has the composition of the Paleozoic metasedimentary basement distributed along the coast in the region (Jacques et al., 2020; Table 2) and thus the described mixing conceptually represents subduction erosion processes. Alternatively, if the SC has the composition of the current trench sediments (Jacques et al., 2020), then the amount needed to obtain the same results is 3%–25%. The latter range exceeds the ~2.5% average that has been estimated for the SC in arcs (e.g., Eiler et al., 2000) and also the higher values are inconsistent with the Sr depleted isotopic signatures of these magmas (Figure 7). Therefore, these estimations enhance the role of subduction erosion in the margin to control the primary subcrustal isotopic signature of the Cenozoic Andean arc magmas. We note that changing the DMM compositional pole to an E-MORB mantle

Table 2
Compositional Poles Used in the Simple Mixing Models of $\delta^{18}\text{O}_{\text{Zrc}}-\text{EHf}(t)$ Displayed in Figure 12

Component	Acronym	$\delta^{18}\text{O}_{\text{Zrc}}$ [‰]	EHf ^a	Hf [ppm]
Depleted Morb Mantle	DMM	5.3 ^b	15.6 ^c	0.16 ^d
Subduction Component	SC	15.4 ^e	−8.0 ^e	3.8 ^e
Mantle Oxygen Western Basalt	MOWB	5.5 ^f	7.9 ^f	2.5 ^g
Oceanic Crust Gabbro	OCG	1.3 ^h	17.3 ⁱ	0.8 ^j
Cuyania Basement Crystalline	CB Cry	6.7 ^k	−18.0 ^l	5.1 ^m
Cuyania Basement Sedimentary	CB Sed	12.0 ⁿ	−15.0 ^o	9.1 ^p
Late Paleozoic—Early Triassic Basement	PTB	6.3 ^q	−7.0 ^r	4.0 ^s

^aCalculated using the CHUR values of Bouvier et al. (2008). ^bMantle oxygen value ($5.3 \pm 0.6\text{‰}$; Valley et al., 1998). ^cCalculated using the $^{176}\text{Hf}/^{177}\text{Hf}$ of the current depleted mantle of Vervoort and Blichert-Toft (1999). ^dAverage depleted mantle value (Workman & Hart, 2005). ^eAverage values for the metasedimentary basement along the coast of central Chile (Jacques et al., 2020). ^fValues after mixing 3% of the Subduction Component with the Depleted Morb Mantle component. ^gCommon values of modern primitive basalts from the Andean arc (Hickey-Vargas, Sun, & Holbik, 2016) and oceanic ridges (Gale et al., 2013). ^hValue after the following considerations. A whole rock $\delta^{18}\text{O}_{\text{WR}} = 2.0\text{‰}$, which is within the range for gabbros from the oceanic crust and ophiolite complexes (Alt & Teagle, 2000), is converted to $\delta^{18}\text{O}_{\text{Zrc}}$ using the relation $\delta^{18}\text{O}_{\text{WR}} = 0.06 \cdot (\text{SiO}_2 \text{ wt\%}) - 2.25 + \delta^{18}\text{O}_{\text{Zrc}}$ (Valley et al., 1994; WR: Whole Rock). For the SiO_2 wt%, a value of 49% has been used, which is among the most frequent ones for gabbros from ophiolitic complexes (Kelemen et al., 2020; <https://www.earthchem.org/>). ⁱTaken from current EHf values of granulite xenoliths with MORB affinities from Calbuco volcano (Hickey-Vargas et al., 1995) and using the conversion $\text{EHf} \approx 1.36 \cdot \text{EHf} + 3.0$ (Vervoort & Blichert-Toft, 1999). ^jCommon value of gabbros from modern oceanic crust (e.g., Barling et al., 1997; Hart et al., 1999) and ophiolite units (e.g., Tribuzio et al., 2014). ^kAverage value of Grenvillian inherited zircons in Andean Cenozoic igneous rocks (Jones et al., 2015). See location in Figure 1. ^lValue within the range of EHf^{C} reported for Grenvillian zircons from the Cuyania basement (Martin et al., 2019). For details on EHf^{C} calculation see Section 3 of the main text. ^mCommon value for felsic igneous rocks, also consistent with that reported for Proterozoic igneous units from the Cuyania basement (Jacques et al., 2020). ⁿAverage value for sedimentary rocks (Bindeman, 2008), also consistent with that reported for Proterozoic igneous units from the Cuyania basement (Jacques et al., 2020). ^oValue within the range of current EHf values determined in whole rock for Proterozoic metasedimentary units from the Cuyania basement (Jacques et al., 2020). ^pValue within the range of that reported for Proterozoic metasedimentary units from the Cuyania basement (Jacques et al., 2020). ^qValue within the range of those reported for late Paleozoic—Early Triassic zircons inherited in Cenozoic arc igneous units of the Eastern Principal Cordillera in central Chile (Muñoz et al., 2013; this work). ^rValue within the range of EHf^{C} reported for late Paleozoic—Early Triassic zircons inherited in Cenozoic arc igneous units of the Eastern Principal Cordillera in central Chile (Muñoz et al., 2013; this work). For details on EHf^{C} calculation see Section 3 Methods of the main text. ^sCommon value for felsic intrusives, also consistent with values reported for Paleozoic igneous rocks in Chile (Mpodozis & Kay, 1992; Parada et al., 1999; Willner et al., 2008).

source and/or considering the secular enrichment of the subarc mantle under island arcs (Dhuime et al., 2011) would have negligible effects in the models presented, modifying the mixing proportions by less than 1%.

Following crustal processes involve the contamination of a primitive arc basalt with the deep components discussed in the previous section. Such basalt, labeled here as Mantle Oxygen Western Basalt (MOWB), has the average composition of magmas from the Western Principal Cordillera with mantle oxygen $\delta^{18}\text{O}_{\text{Zrc}}$ signatures, and can be generated by the previous subcrustal mixing model by the addition of 2% SC into the DMM (Figure 12). Regarding the western igneous units, the spreading of their compositions toward high $\text{EHf}(t)$ —low $\delta^{18}\text{O}_{\text{Zrc}}$ signatures can be reproduced by mixing an Oceanic Crust Gabbro component (OCG) with the MOWB. The proportion of the former component is variable; a 35% addition results in $\delta^{18}\text{O}_{\text{Zrc}}$ values up to $\sim +4.0\text{‰}$ (Figure 12), which is the lower limit for most of the low-O signatures observed (Figure 10). To reproduce even lower signatures, between +3 and +4‰, as those displayed by the La Obra Batholith and related units, up to 60% of the OCG component is needed (Figure 12). These are unrealistically high values, which suggest an overestimation of this component in the simple mixing model presented. Regarding the eastern igneous units, most of their spreading toward low $\text{EHf}(t)$ values can be reproduced by mixing the MOWB with up to 20%–25% of a Cuyania Basement component (CB) with a crystalline or sedimentary nature (Figure 12). Subsequently, the composition resulting from this latter mixing can be variably mixed with the late Paleozoic—Early Triassic component for a further restricted enrichment toward lower $\text{EHf}(t)$ signatures (Figure 12).

Although the models discussed describe the compositional range observed, the proportion of crustally allocated components seems too high, particularly when considering the lowest values of $\text{EHf}(t)$ and $\delta^{18}\text{O}_{\text{Zrc}}$ (Figure 12). Regarding the low $\text{EHf}(t)$ data, magmatic zircons with this composition from units of the Eastern Principal Cordillera show a key feature: they have $\text{EHf}(t)$ and $\delta^{18}\text{O}_{\text{Zrc}}$ values indistinguishable from those of the inherited late Paleozoic—Early Triassic zircons (EHf^{C} displayed for these in Figure 12). In addition, the $\text{EHf}(t)$ composition of such zircons is also anomalously low with respect to the rest of the magmatic zircons analyzed in the corresponding samples (Figure 9a). These characteristics indicate that they were not in isotopic equilibrium with the final hosting magmas. Therefore, the extreme values for the compositional range observed could be disregarded and thus lower the high proportions of some crustally allocated components in the mixing models. The same could be the case for the involvement of the OCG component in the genesis of magmas from the Western Principal Cordillera (Figure 11). These considerations require focusing on the mixing models in average values which, in turn, represent the common compositions of the Cenozoic arc upper crustal reservoirs. In the case of extreme $\text{EHf}(t)$ and $\delta^{18}\text{O}_{\text{Zrc}}$ signatures, these are probably traces of deeper magmas of a compositional spectra toward the end-member components which were blended when reaching upper crustal magmatic reservoirs.

5.4. An Integrated Picture of the Cenozoic Andean Arc and Final Remarks

The main result of this study is to document the major role of the continental crust over the composition of continental arc magmas. As important, but more elusive to track geochemically, the primitive magmas derived from the subarc mantle constitute the motor driving the magmatic arc factory itself. Within this frame, the compositional control of the continental crust can be accommodated by the integrated dynamics of deep arc magmatic processes, as those in MASH and/or Hot Zone domains (e.g., Annen et al., 2006; Hildreth, 2007; Hildreth & Moorbath, 1988; Otamendi et al., 2012; Walker et al., 2015), and transcrustal magmatic systems (e.g., Dufek et al., 2022; Giordano & Caricchi, 2022; Sparks et al., 2019). Thus, upper crustal arc magmas such as those here studied correspond to the differentiated products of an extensive evolution, taking place along tens of kilometers below their emplacement level, and which includes repeated processes such as crystallization, devolatilization, melt segregation, mixing, melting and assimilation, amongst others (Figure 13). Through such a column, magmatic systems at the lower and middle crust are responsible for most of the differentiation and their activity and longevity, along with that for shallower systems, is modulated by the key upper transfer of both mass and heat from the underlying mantle (e.g., Annen et al., 2006; Hildreth & Moorbath, 1988; Otamendi et al., 2012; Solano et al., 2012; Sparks et al., 2019; Walker et al., 2015). In an arc system like this, primitive arc magmas ascending from the mantle are very unlikely to reach upper crustal levels, which conceals the subcrustal processes that conditioned their early composition (Figure 13). Either a favorable extensional regime and/or structural arrangement should prompt less arc magma processing, as seen here for magmas from the Western Principal Cordillera; however, the extent of this is uncertain.

For the Cenozoic Andean arc of Central Chile, the crustal control is first tracked by the variations displayed in the whole rock chemical compositions and Sr-Nd isotopic compositions. These systems signal in general the increasing digestion of continental crust material, from the early magmatic stages, which is likely prompted by increasing crustal residence times. The latter is expected after the recorded increase in crustal thickness and closure of volcanic systems (waning of volcanic activity) that develop through the compressional stage set in the region since the Early Miocene. The Hf and O isotopic compositions also track the crustal involvement and, most importantly, provide additional geochemical dimensions to identify the major components involved in magma genesis. For the latter, the analyses of areas within single zircon crystals have been fundamental to resolve information unattainable from whole rock data.

From the three crustally allocated magmatic components resolved, the late Paleozoic—Early Triassic basement is the only one with direct evidence of its involvement, this from the presence of inherited zircon crystals. Inferences about the remaining two deep basement components rely on the distinct isotopic signature they have imprinted on the traversing magmas. Such basement compositional control seems to be a common feature for continental arc magmas, as it has been shown for other systems extensively studied as; for example, Mesozoic and Cenozoic igneous rocks from northern Chile and southern Perú (Mamani et al., 2010) and the Sierra Nevada Batholith (see Lackey et al., 2008, 2012 and references therein). Remarkably, in the latter system, the regional boundaries of the $^{87}\text{Sr}/^{86}\text{Sr} = 706$ line and the PA/NA break (e.g., Kistler, 1990; Lackey et al., 2008, 2012), which have been ascribed to differences in the basement, are analogous to the spatial Hf isotopic segmentation recorded here for the Cenozoic Andean arc. Overall, our abilities to identify these features are conditioned by the compositional

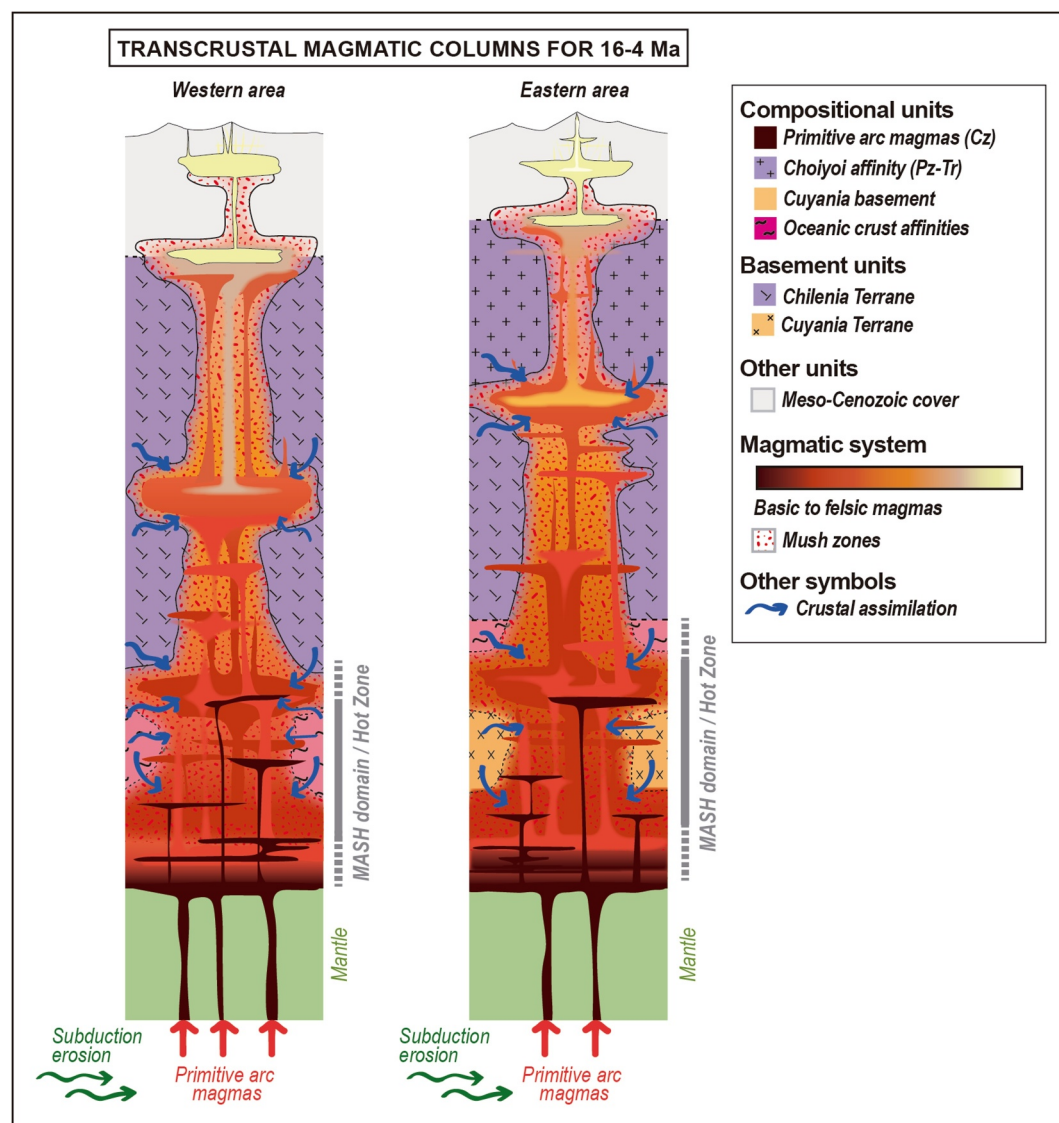


Figure 13. Transcrustal magmatic columns for the Cenozoic Andean arc between 16 and 4 Ma in the western and eastern regions depicted in Figure 11. Based on the data and discussions laid out in the main text and the conceptualization of arc magmatic systems presented in Hildreth & Moorbath (1988), Annen et al. (2006), Otamendi et al. (2012), Sparks et al. (2019), and Giordano and Caricchi (2022).

contrast between the basement itself and the ascending primitive arc magmas and the appropriate isotopic tools. In this regard, in the study of MASH-type processes occurring in a deep crustal arc section, Walker et al. (2015) have shown that the crustal digestion by primitive arc magmas occurs along with an elemental and isotopic decoupling, leaving as the only trace of such process the isotopic signature. Another most relevant result from similar studies is the recognition of the significant isotopic exchange that can develop among reservoirs with contrasting compositions in MASH domains (Otamendi et al., 2012). These complexities are not accommodated by simple mixing models such as those presented here, and thus their results overestimate the proportion of crustal contaminants over the primitive arc magmas.

The juvenile low- $\delta^{18}\text{O}$ component, which has been interpreted as of oceanic crust affinity, merits further discussion. Such interpretation relies on the occurrence of its particular isotopic signature at the regional scale, plus the recognition of akin lithologies both in the geological background, in the ophiolitic complexes in westernmost Argentina, and as xenoliths in current arc lavas from southern Chile. The juvenile Hf isotopic composition of this component is indistinguishable from that of primitive arc magmas; therefore, it is not possible to track its

involvement solely on the basis of Hf isotopic ratios. Thus, the O isotopic ratio is its only tracer and the signal is characterized by $\delta^{18}\text{O}_{\text{Zrc}}$ values lower than those expected for mantle-derived magmas. No units from the Western Principal Cordillera, where this component is mainly recorded, show $\delta^{18}\text{O}_{\text{Zrc}}$ values significantly higher than the mantle range. Altogether, these observations indicate that the high- $\delta^{18}\text{O}$ portions of the oceanic crust component (pillow basalts and sheeted dikes) must be involved in arc magmatic processes proportionally against the much thicker layers of low- $\delta^{18}\text{O}$ portions (altered gabbros), or not be significantly involved. Finally, the recognition of this component mainly in the Western Principal Cordillera leaves questions to be addressed in the future, in particular regarding: (a) its origin, whether a part of the Chilena terrane basement or the result of later processes, and (b) its possible relation with distinctive Cenozoic Andean arc magmas whose genetic processes are still debated, as those with adakite-like signatures and/or related to Cu-Mo mineralization.

6. Conclusions

The Cenozoic Andean arc of Central Chile ($\sim 32^{\circ}40' - 34^{\circ}30'\text{S}$) represents a remarkable example of the control exerted by the continental crust over the composition of arc magmas. The architecture and constitution of this domain have conditioned in particular the isotopic composition of ascending magmas in a dynamic scenario throughout its reshaping in an evolving continental margin. The whole-rock chemical and Sr-Nd isotope data clearly record the increasing crustal digestion of these magmas, while the Hf and O isotopic compositions allows to identify the major components involved in their genesis. In terms of the latter, the compositional range defined by the Cenozoic Andean arc can be explained by four major components: (a) the primitive magmas derived from the subarc mantle, (b) a late Paleozoic—Early Triassic crystalline component, as that currently outcropping in the Frontal Cordillera, which is underlying the Mesozoic swath of outcrops that comprise the Eastern Principal Cordillera, (c) a deep enriched component, which likely corresponds to the Cuyania terrane basement, and (d) a deep juvenile low- $\delta^{18}\text{O}$ component, interpreted as a basement with oceanic crust affinities. These results highlight the predominant crustal imprint of arc magmas from continental margin settings and the limits of our ability to confidently infer subcrustal processes from the study of their composition.

Data Availability Statement

Supporting Information S1 for this study is available at the Research Data Repository of Universidad Andrés Bello via Muñoz Gómez et al. (2025). This includes the description of the analytical methods, the data tables of analytical determinations (whole rock geochemical and Sr-Nd isotopic composition, ^{39}Ar - ^{40}Ar and U-Pb ages, zircon Hf and O isotopic composition), the composite data set of compiled whole rock geochemistry and Sr-Nd isotopic composition for the study region, and the end member components used in the simple mixing models.

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References

- Aguirre, L., Robinson, D., Bevins, R. E., Morata, D., Vergara, M., Fonseca, E., & Carrasco, J. (2000). A low-grade metamorphic model for the Miocene volcanic sequences in the Andes of central Chile. *New Zealand Journal of Geology and Geophysics*, 43(1), 83–93. <https://doi.org/10.1080/00288306.2000.9514871>
- Alt, J. C., & Teagle, D. A. H. (2000). Hydrothermal alteration and fluid fluxes in ophiolites and oceanic crust. In Y. Dilek, E. M. Moores, D. Elthon, & A. Nicolas (Eds.), *Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program* (pp. 273–282). Geological Society of America Special Paper.
- Annen, C., Blundy, J. D., & Sparks, S. J. (2006). The genesis of intermediate and silicic magmas in deep crustal hot zones. *Journal of Petrology*, 47(3), 505–539. <https://doi.org/10.1093/petrology/egi084>
- Balgord, E. (2016). Triassic to Neogene evolution of the Andean retroarc: Neuquén Basin, Argentina Ph.D. Thesis. (p. 177). Department of Geosciences, The University of Arizona.
- Barling, J., Hertogen, J., & Weis, D. (1997). 18. Whole-rock geochemistry and Sr-, Nd-, and Pb-isotopic characteristics of undeformed, deformed, and recrystallized gabbros from sites 921, 922, and 923 in the Mark area. In J. A. Karson, M. Cannat, D. J. Miller, & D. Elthon (Eds.), *Proceedings of the Ocean Drilling Program* (pp. 351–362). Scientific Results.
- Bindeman, I., Schmitt, A. K., & Evans, D. A. D. (2010). Limits of hydrosphere-lithosphere interaction: Origin of the lowest known $\delta^{18}\text{O}$ silicate rock on Earth in the Paleoproterozoic Karelian rift. *Geology*, 38(7), 631–634. <https://doi.org/10.1130/g30968.1>
- Bindeman, I. N. (2008). Oxygen Isotopes in mantle and crustal magmas as revealed by single crystal analysis. *Reviews in Mineralogy and Geochemistry*, 69(1), 445–478. <https://doi.org/10.2138/rmg.2008.69.12>
- Bindeman, I. N., Eiler, J. M., Yogodzinski, G. M., Tatsumi, Y., Stern, C. R., Grove, T. L., et al. (2005). Oxygen isotope evidence for slab melting in modern and ancient subduction zones. *Earth and Planetary Science Letters*, 235(3–4), 480–496. <https://doi.org/10.1016/j.epsl.2005.04.014>
- Bindeman, I. N., Ponomareva, V. V., Bailey, J. C., & Valley, J. W. (2004). Volcanic arc of Kamchatka: A province with high- $\delta^{18}\text{O}$ magma sources and large-scale $^{18}\text{O}/^{16}\text{O}$ depletion of the upper crust. *Geochimica et Cosmochimica Acta*, 68(4), 841–865. <https://doi.org/10.1016/j.gca.2003.07.009>
- Bindeman, I. N., & Valley, J. W. (2001). Low- $\delta^{18}\text{O}$ rhyolites from Yellowstone: Magmatic evolution based on analyses of zircons and individual phenocrysts. *Journal of Petrology*, 42(8), 1491–1517. <https://doi.org/10.1093/petrology/42.8.1491>

- Bindeman, I. N., & Valley, J. W. (2003). Rapid generation of both high- and low- $\delta^{18}\text{O}$, large-volume silicic magmas at the Timber Mountain/Oasis Valley caldera complex, Nevada. *Geological Society of America Bulletin*, 115, 581–595. [https://doi.org/10.1130/0016-7606\(2003\)115<0581:rgobha>2.0.co;2](https://doi.org/10.1130/0016-7606(2003)115<0581:rgobha>2.0.co;2)
- Boedo, F. L., Pérez Luján, S., Ariza, J. P., & Vujovich, G. I. (2021). The mafic-ultramafic belt of the Argentine Precordillera: A geological synthesis. *Journal of South American Earth Sciences*, 110, 103354. <https://doi.org/10.1016/j.jsames.2021.103354>
- Boedo, F. L., Willner, A. P., Vujovich, G. I., & Massone, H.-J. (2016). High-pressure/low-temperature metamorphism in the collision zone between the Chilenia and Cuyania microcontinents (western Precordillera, Argentina). *Journal of South American Earth Sciences*, 72, 227–240. <https://doi.org/10.1016/j.jsames.2016.09.009>
- Bouvier, A., Vervoort, J. D., & Patchett, P. J. (2008). The Lu–Hf and Sm–Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters*, 273(1–2), 48–57. <https://doi.org/10.1016/j.epsl.2008.06.010>
- Camus, F. (2003). *Geología de los Sistemas Porfíricos en los Andes de Chile* (p. 267). Servicio Nacional de Geología y Minería.
- Charrier, R., Baeza, O., Elgueta, S., Flynn, J. J., Gana, P., Kay, S. M., et al. (2002). Evidence for Cenozoic extensional basin development and tectonic inversion south of the flat-slab segment, southern Central Andes, Chile (33°–36°S.L.). *Journal of South American Earth Sciences*, 15(1), 117–139. [https://doi.org/10.1016/s0895-9811\(02\)00009-3](https://doi.org/10.1016/s0895-9811(02)00009-3)
- Charrier, R., Pinto, L., & Rodríguez, M. P. (2007). Tectonostratigraphic evolution of the Andean orogen in Chile. In T. Moreno & W. Gibbons (Eds.), *The Geology of Chile* (pp. 21–114). The Geological Society.
- Cuadra, P. (1986). Geocronología K–Ar del yacimiento El Teniente y áreas adyacentes. *Andean Geology*, 27, 3–26.
- Deckart, K., Godoy, E., Bertens, A., Saeed, A., & Jeréz, D. (2010). Barren Miocene granitoids in the central Andean metallogenic belt, Chile: Geochemistry and Nd–Hf and U–Pb isotope systematics. *Andean Geology*, 37, 1–31. <https://doi.org/10.4067/s0718-71062010000100001>
- DePaolo, D. J. (1981). A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. *Journal of Geophysical Research*, 86(B11), 10470–10488. <https://doi.org/10.1029/jb086b11p10470>
- Dhuime, B., Hawkesworth, C. J., & Cawood, P. (2011). When continents formed. *Science*, 331(6014), 154–155. <https://doi.org/10.1126/science.1201245>
- Díaz-Alvarado, J., Galaz, G., Oliveros, V., Creixell, C., & Calderón, M. (2019). Fragments of the late Paleozoic accretionary complex in central and northern Chile: Similarities and differences as a key to decipher the complexity of the late Paleozoic to Triassic early Andean events. In B. K. Horton & A. Folguera (Eds.), *Andean Tectonics* (pp. 509–530). Springer.
- Dufek, J., Cashman, K., Hooft, E., & Bedrosian, P. (2022). The nature of active magma reservoirs and storage underneath cascade volcanoes. *Elements*, 18(4), 239–245. <https://doi.org/10.2138/gselements.18.4.239>
- Eiler, J. M. (2001). Oxygen isotope variations in basaltic lavas and upper mantle rocks. *Reviews in Mineralogy and Geochemistry*, 43(1), 319–364. <https://doi.org/10.2138/gsrmg.43.1.319>
- Eiler, J. M., Crawford, A., Elliott, T., Farley, K. A., Valley, J. W., & Stopler, E. M. (2000). Oxygen isotope geochemistry of oceanic-arc lavas. *Journal of Petrology*, 41(2), 229–256. <https://doi.org/10.1093/petrology/41.2.229>
- Farías, M., Charrier, R., Carretier, S., Martinod, J., Fock, A., Campbell, D., et al. (2008). Late Miocene high and rapid surface uplift and its erosional response in the Andes of central Chile (33°–35°S). *Tectonics*, 27, TC1005. <https://doi.org/10.1029/2006TC002046>
- Farías, M., Comte, D., Charrier, R., Martinod, J., Tassara, A., & Fock, A. (2010). Crustal-scale structural architecture of the central Chile Andes based on 3D seismic tomography, seismicity, and surface geology: Implications for mountain building in subduction zones. *Tectonics*, 29, TC3006. <https://doi.org/10.1029/2009TC002480>
- Fock, A. (2005). *Cronología y tectónica de la exhumación en el Neógeno de los Andes de Chile central entre los 33° y los 34°S*. Departamento de Geología, Universidad de Chile (p. 179). M.Sc. Thesis.
- Fock, A., Charrier, R., Farías, M., & Muñoz, M. (2006). Fallas de vergencia oeste en la Cordillera Principal de Chile central: inversión de la cuenca de Abanico (33°–34°S). *Revista de la Asociación Geológica Argentina*, 48–55.
- Fuentes, F. (2004). Petrología y metamorfismo de muy bajo grado de unidades volcánicas oligo-miocenas en la ladera occidental de los Andes de Chile Central (33°S) Ph.D. Thesis. (p. 398). Departamento de Geología, Universidad de Chile.
- Futa, K., & Stern, C. R. (1988). Sr and Nd isotopic and trace element compositions of Quaternary volcanic centers of the southern Andes. *Earth and Planetary Science Letters*, 88(3–4), 253–262. [https://doi.org/10.1016/0012-821x\(88\)90082-9](https://doi.org/10.1016/0012-821x(88)90082-9)
- Gale, A., Dalton, C. A., Langmuir, C. H., Su, Y., & Schilling, J.-G. (2013). The mean composition of ocean ridge basalts. *Geochemistry, Geophysics, Geosystems*, 14(3), 489–518. <https://doi.org/10.1029/2012gc004334>
- Giambiagi, L. B., & Ramos, V. A. (2002). Structural evolution of the Andes in a transitional zone between flat and normal subduction (33°30'–33°45'S), Argentina and Chile. *Journal of South American Earth Sciences*, 15(1), 101–116. [https://doi.org/10.1016/s0895-9811\(02\)00008-1](https://doi.org/10.1016/s0895-9811(02)00008-1)
- Giordano, G., & Caricchi, L. (2022). Determining the state of activity of transcrustal magmatic systems and their volcanoes. *Annual Review of Earth and Planetary Sciences*, 50(1), 231–259. <https://doi.org/10.1146/annurev-earth-032320-084733>
- Godoy, E., & Hildreth, W. (2001). Cerro Amarillo rhyolites, advanced AFC in the Northern SVZ, Chile. III South American symposium on isotope geology Pucón. *Proceedings*, 21–24.
- Goodge, J. W., & Vervoort, J. D. (2006). Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence. *Earth and Planetary Science Letters*, 243(3–4), 711–731. <https://doi.org/10.1016/j.epsl.2006.01.040>
- Gregory, R. T., & Taylor, H. P. (1981). An oxygen isotope profile in a section of Cretaceous oceanic crust, Samail Ophiolite: Evidence for $\delta^{18}\text{O}$ buffering of oceans by deep (>5 km) seawater-hydrothermal circulation at mid-ocean ridges. *Journal of Geophysical Research*, 86(4), 2737–2755. <https://doi.org/10.1029/jb086ib04p02737>
- Hart, S. R., Blusztajn, J., Dick, H. J. B., Meyer, P. S., & Muehlenbachs, K. (1999). The fingerprint of seawater circulation in a 500-meter section of ocean crust gabbros. *Geochimica et Cosmochimica Acta*, 63(23–24), 4059–4080. [https://doi.org/10.1016/s0016-7037\(99\)00309-9](https://doi.org/10.1016/s0016-7037(99)00309-9)
- Hickey, R., Frey, F. A., Gerlach, D. C., & Lopez-Escobar, L. (1986). Multiple source for basaltic arc rocks from the Southern Volcanic Zone of the Andes (34°–41°S): Trace element and isotopic evidence for contributions from subducted crust, mantle, and continental crust. *Journal of Geophysical Research*, 91(B6), 5963–5983. <https://doi.org/10.1029/jb091ib06p05963>
- Hickey-Vargas, R., Abodlahi, M. J., Parada, M. A., 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. <https://doi.org/10.1007/bf00286933>
- Hickey-Vargas, R., Holbik, S., Tormey, D., Frey, F. A., & Moreno, 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*, 258–259, 115–132. <https://doi.org/10.1016/j.lithos.2016.04.014>

- Hickey-Vargas, R., Sun, M., & Holbik, S. (2016). Geochemistry of basalts from small eruptive centers near Villarrica stratovolcano, Chile: Evidence for lithospheric mantle components in continental arc magmas. *Geochimica et Cosmochimica Acta*, 185, 358–382. <https://doi.org/10.1016/j.gca.2016.03.033>
- Hildreth, W. (2007). Quaternary magmatism in the Cascades—Geologic perspectives. In *U. S. Geological Survey, Professional Paper 1744, Reston, Virginia* (p. 125).
- Hildreth, W., & Moorbath, S. (1988). Crustal contributions to arc magmatism in the Andes of central Chile. *Contributions to Mineralogy and Petrology*, 98(4), 455–489. <https://doi.org/10.1007/bf00372365>
- Hildreth, W., & Moorbath, S. (1991). Reply to comment on “Crustal contributions to arc magmatism in the Andes of Central Chile”. In W. Hildreth & S. Moorbath (Eds.), *Contributions to Mineralogy and Petrology* (Vol. 108, pp. 247–252). <https://doi.org/10.1007/bf00307342>
- Hollings, P., Cooke, D. R., & Clark, A. H. (2005). Regional geochemistry of Tertiary igneous rocks in Central Chile: Implications for the geodynamic environment of giant porphyry copper and epithermal gold mineralization. *Economic Geology*, 100(5), 887–904. <https://doi.org/10.2113/gsecongeo.100.5.887>
- Holm, P. M., Sogger, N., Dyhr, C. T., & Nielsen, M. R. (2014). Enrichments of the mantle sources beneath the Southern Volcanic Zone (Andes) by fluids and melts derived from abraded upper continental crust. *Contributions to Mineralogy and Petrology*, 167(5), 1004. <https://doi.org/10.1007/s00410-014-1004-8>
- Horton, B. K., & Fuentes, F. (2016). Sedimentary record of plate coupling and decoupling during growth of the Andes. *Geology*, 44(8), 647–650. <https://doi.org/10.1130/g37918.1>
- Irvine, T. N., & Baragar, W. R. A. (1971). A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences*, 8(5), 523–548. <https://doi.org/10.1139/e71-055>
- Jacques, G., Hauff, F., Hoernle, K., Jung, S., Kay, S. M., Garbe-Schönberg, D., & Bindeman, I. (2020). Sr-Nd-Pb-Hf-O isotopic constraints on the Neoproterozoic to Miocene upper and mid crust in central Chile and western Argentina and trench sediments (33°–35°S). *Journal of South American Earth Sciences*, 104, 102879. <https://doi.org/10.1016/j.jsames.2020.102879>
- Jara, P., & Charrier, R. (2014). Nuevos antecedentes estratigráficos y geocronológicos para el Meso-Cenozoico de la cordillera Principal de Chile entre 32° y 32°30'S: Implicancias estructurales y paleogeográficas. *Andean Geology*, 41(1), 174–209. <https://doi.org/10.5027/andgeov41n1-a07>
- Jones, R., Kirstein, L., Kasemann, S., Dhuime, B., Elliott, T., Litvak, V., et al. (2015). Geodynamic controls on the contamination of Cenozoic arc magmas in the southern Central Andes: Insights from the O and Hf isotopic composition of zircon. *Geochimica et Cosmochimica Acta*, 164, 386–402. <https://doi.org/10.1016/j.gca.2015.05.007>
- Kay, S. M., Godoy, E., & Kurtz, A. (2005). Episodic arc migration, crustal thickening, subduction erosion, and magmatism in the south-central Andes. *Geological Society of America Bulletin*, 117(1), 67–88. <https://doi.org/10.1130/b25431.1>
- Kay, S. M., Orrell, S., & Abbruzzi, J. M. (1996). Zircon and whole rock Nd-Pb isotopic evidence for a Grenville age and a Laurentian origin for the basement of Precordillera in Argentina. *The Journal of Geology*, 104, 647–648.
- Kelemen, P. B., Matter, J. M., Teagle, D. A. H., Coggon, J. A., & the Oman Drilling Project Science Team. (2020). Site GT1. In P. B. Kelemen, J. M. Matter, D. A. H. Teagle, J. A. Coggon, & the Oman Drilling Project Science Team (Eds.), *Proceedings of the Oman Drilling Project: College Station, TX (International Ocean Discovery Program)*. <https://doi.org/10.14379/OmanDP.proc.106.2020>
- Kemp, A. I. S., Hawkesworth, C. J., Foster, G. L., Paterson, B. A., Woodhead, J. D., Hergt, J. M., et al. (2007). Magmatic and crustal differentiation history of granitic rocks from Hf-O isotopes in zircon. *Science*, 315(5814), 980–983. <https://doi.org/10.1126/science.1136154>
- Kistler, R. W. (1990). Two different lithosphere types in the Sierra Nevada, California. In L. Anderson (Ed.), *The Nature and Origin of Cordilleran Magmatism* (Vol. 174, pp. 271–281). Geological Society of America, Memoirs.
- Kurtz, A., Kay, S. M., Charrier, R., & Farrar, E. (1997). Geochronology of Miocene plutons and exhumation history of the El Teniente region, Central Chile (34°–35°S). *Andean Geology*, 24, 75–90.
- Lackey, J. S., Cecil, M. R., Windham, M. R., Windham, C. J., Frazer, R. E., Bindeman, I., & Gehrels, G. E. (2012). The fine gold intrusive suite: The roles of basement terranes and magma source development in the Early Cretaceous Sierra Nevada batholith. *Geosphere*, 8, 292–313.
- Lackey, J. S., Valley, J. W., Chen, J. D. S., & Stockli, D. F. (2008). Dynamic magma systems, crustal recycling, and alteration in the central Sierra Nevada batholith: The oxygen isotope record. *Journal of Petrology*, 49(7), 1397–1426. <https://doi.org/10.1093/petrology/egn030>
- Lavandaio, E. O. L., Marengo, H. G., & Rosas, M. A. (2023). *Mapa geológico de la provincia de Mendoza* (p. 63). Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino (SEGEMAR), Serie Publicaciones N° 181.
- Le Maitre, R. W. (1989). A classification of igneous rocks and glossary of terms. In *Recommendations of the IUGS Commission on the Systematics of Igneous Rocks*. Blackwell.
- Lucassen, F., Trumbull, R., Franz, G., Creixell, C., Vázquez, P., Romer, R., & Figueroa, O. (2004). Distinguishing crustal recycling and juvenile additions at active continental margins: The Paleozoic to recent compositional evolution of the Chilean Pacific margin (36–41°S). *Journal of South American Earth Sciences*, 17(2), 103–119. <https://doi.org/10.1016/j.jsames.2004.04.002>
- Luffi, P., & Ducea, M. N. (2022). Chemical mohometry: Assessing crustal thickness of ancient orogens using geochemical and isotopic data. *Reviews of Geophysics*, 60(2), e2021RG000753. <https://doi.org/10.1029/2021rg000753>
- Maksaev, V., Munizaga, F., McWilliams, M., Fanning, C. M., Mathur, R., Ruiz, J., & Zentilli, M. (2004). New chronology for El Teniente, Chilean Andes, from U-Pb, ⁴⁰Ar/³⁹Ar, Re-Os, and fission-track dating: Implications for the evolution of a supergiant porphyry Cu-Mo deposit. In R. H. Sillitoe, J. Perelló, & A. Vidal (Eds.), *Andean Metallogeny: New Discoveries, Concepts and Updates* (Vol. 11, pp. 15–54). Society of Economic Geologists Special Publication. <https://doi.org/10.5382/sp.11.02>
- Mamani, M., Wörner, G., & Sempere, T. (2010). Geochemical variations in igneous rocks of the Central Andean orocline (13°S to 18°S): Tracing crustal thickening and magma generation through time and space. *Geological Society of America*, 122, 162–182.
- Martin, E. L., William, J. C., & Spencer, C. J. (2019). Laurentian origin of the Cuyania suspect terrane, western Argentina, confirmed by Hf isotopes in zircon. *GSA Bulletin*, 132(1–2), 273–290. <https://doi.org/10.1130/b35150.1>
- Montecinos, P., Schärer, U., Vergara, M., & Aguirre, L. (2008). Lithospheric origin of Oligocene-Miocene magmatism in central Chile: U-Pb ages and Sr-Pb-Hf isotope composition of minerals. *Journal of Petrology*, 49(3), 555–580. <https://doi.org/10.1093/petrology/egn004>
- Mpodozis, C., & Kay, S. M. (1992). Late Paleozoic to Triassic evolution of the Gondwana margin: Evidence from Chilean frontal cordilleran batholiths (28°S to 31°S). *Geological Society of America Bulletin*, 104(8), 999–1014. [https://doi.org/10.1130/0016-7606\(1992\)104<0999:lptee>2.3.co;2](https://doi.org/10.1130/0016-7606(1992)104<0999:lptee>2.3.co;2)
- Muñoz, M., Aguirre, L., Vergara, M., Demant, A., Fuentes, F., & Fock, A. (2010). Prehnite-pumpellyite facies metamorphism in the Cenozoic Abanico Formation, Andes of central Chile (33°50'S): Chemical and scale controls on mineral assemblages, reaction progress and the equilibrium state. *Andean Geology*, 37(1), 54–77. <https://doi.org/10.4067/s0718-71062010000100003>

- Muñoz, M., Charrier, R., Fanning, C. M., Maksiyev, V., & Deckart, K. (2012). Zircon trace element and O-Hf isotope analyses of mineralized intrusions from El Teniente ore deposit, Chilean Andes: Constraints on the source and magmatic evolution of porphyry Cu-Mo related magmas. *Journal of Petrology*, 53(6), 1091–1122. <https://doi.org/10.1093/petrology/egs010>
- Muñoz, M., Farías, M., Charrier, R., Fanning, C. M., Polvé, M., & Deckart, K. (2013). Isotopic shifts in the Cenozoic Andean arc of central Chile: Records of an evolving basement throughout cordilleran arc mountain building. *Geology*, 41(8), 931–934. <https://doi.org/10.1130/g34178.1>
- Muñoz, M., Fuentes, F., Vergara, M., Aguirre, L., Nyström, J. O., Feraud, G., & Demant, A. (2006). Abanico East formation: Petrology and geochemistry of volcanic rocks behind the Cenozoic arc front in the Andean Cordillera, central Chile (33°50'). *Andean Geology*, 33(1), 109–140. <https://doi.org/10.5027/andgeov33n1-a05>
- Muñoz Gómez, M., Fanning, C. M., Tapia, F., Payacán, I., Fuentes, F., Farías, M., et al. (2025). Replication data for: Resolving crustal and subcrustal dynamic sources in continental arc magmas: The Cenozoic Andean Arc of Central Chile [Dataset]. *Research Data repository - Universidad Andrés Bello (Chile)*, V1. <https://doi.org/10.60483/UNAB/PLCJLQ>
- Muñoz-Gómez, M., Fuentes, C., Fuentes, F., Tapia, F., Benoit, M., Farías, M., et al. (2020). Eocene arc petrogenesis in Central Chile (c. 33.6°S) and implications for the late Cretaceous–Miocene Andean setting: Tracking the evolving tectonic regime. *Journal of the Geological Society*, 177(2), 258–275. <https://doi.org/10.1144/jgs2019-042>
- Muñoz-Gómez, M., Payacán, I., Gutiérrez, F., Farías, M., Charrier, R., & Polvé, M. (2020). Silicic volcanism triggered by increased denudation rates in the Quaternary Andean arc of central Chile between 33°50'–34°30'S. *Lithos*, 354–355, 105242. <https://doi.org/10.1016/j.lithos.2019.105242>
- Nyström, J. O., Parada, M. A., & Vergara, M. (1993). Sr-Nd isotope compositions of Cretaceous to Miocene volcanic rocks in Central Chile: A trend towards a MORB signature and a reversal with time. In *International Symposium on Andean Geodynamics* (pp. 411–414). Extended Abstracts.
- Nyström, J. O., Vergara, M., Morata, D., & Levi, B. (2003). Tertiary volcanism in central Chile (33°15'–33°45'S): A case of Andean magmatism. *Geological Society of America Bulletin*, 115(12), 1523–1537. <https://doi.org/10.1130/b25099.1>
- Ojeda, F. (2018). *Cristales de granate en intrusivo subvolcánico mioceno de la zona de Santiago. Origen e implicancias para la génesis de magmas adakíticos* (p. 74). Carrera de Geología, Universidad Andrés Bello, Geologist Professional Degree Thesis.
- Oliva, C. (2002). *Petrología y geoquímica de cuerpos subvolcánicos oligo-miocenos al norte del valle central (32°–33°S–70°–71°W)*. Departamento de Geología (p. 67). Universidad de Chile, Geologist Professional Degree Thesis.
- Otamendi, J. E., Ducea, M. N., & Bergantz, G. W. (2012). Geological, petrological and geochemical evidence for progressive construction of an arc crustal section, Sierra de Valle Fértil, famatinian arc, Argentina. *Journal of Petrology*, 53(4), 761–800. <https://doi.org/10.1093/petrology/egr079>
- Parada, M. A., Nyström, J. O., & Levi, B. (1999). Multiple sources for the coastal Batholith of central Chile (31–34°S): Geochemical and Sr–Nd isotopic evidence and tectonic implications. *Lithos*, 46(3), 505–521. [https://doi.org/10.1016/s0024-4937\(98\)00080-2](https://doi.org/10.1016/s0024-4937(98)00080-2)
- Pardo, M., Comte, D., & Monfret, T. (2002). Seismotectonic and stress distribution in the central Chile subduction zone. *Journal of South American Earth Sciences*, 15(1), 11–12. [https://doi.org/10.1016/s0895-9811\(02\)00003-2](https://doi.org/10.1016/s0895-9811(02)00003-2)
- Payacán, I., Covarrubias, M. A., Rodríguez, N., Tavazzani, L., Gutiérrez, F., Roperch, P., et al. (2024). Diverse intrusion modes during the construction of a high-silica magma reservoir: Evidence from La Obra-Cerro Blanco intrusive suite (central Chile). *Geosphere*, 20(6), 1622–1654. <https://doi.org/10.1130/ges02746.1>
- Piquer, J., Rivera, O., Yáñez, G., & Oyarzún, N. (2021). The Piuquencillo fault system: A long-lived, Andean-transverse fault system and its relationship with magmatic and hydrothermal activity. *Solid Earth*, 12(1), 253–273. <https://doi.org/10.5194/se-12-253-2021>
- Ramos, V. A. (1994). Terranes of southern Gondwanaland and their control in the Andean structures (30–33°S lat.). In K. J. Reutter, E. Scheuber, & P. J. Wigger (Eds.), *Tectonics of the southern central Andes, structure and evolution of an active continental margin* (pp. 249–261). Springer Verlag.
- Ramos, V. A. (2004). Cuyania, an exotic block to Gondwana: Review of a historical success and present problems. *Gondwana Research*, 7(4), 1009–1026. [https://doi.org/10.1016/s1342-937x\(05\)71081-9](https://doi.org/10.1016/s1342-937x(05)71081-9)
- Ramos, V. A. (2009). Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle. In S. M. Kay, V. A. Ramos, & W. R. Dickinson (Eds.), *Backbone of the Americas: Shallow subduction, plateau uplift, and ridge collision* (Vol. 204, pp. 31–65). The Geological Society of America Memoir. [https://doi.org/10.1130/2009.1204\(02\)](https://doi.org/10.1130/2009.1204(02))
- Ramos, V. A., Aguirre-Urreta, M. B., Álvarez, P. P., Colluccia, A., Giambiagi, L. B., Pérez, D. J., et al. (2010). *Hoja Geológica 3369-III, Cerro Tupungato* (p. 133). Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino (SEGEMAR), Boletín No. 386.
- Ramos, V. A., Zapata, T., Cristallini, E., & Introcaso, A. (2004). The Andean thrust system—Latitudinal variations in structural styles and orogenic shortening. In K. R. McClay (Ed.), *Thrust Tectonics and Hydrocarbon Systems* (Vol. 82, pp. 30–50). AAPG Memoir.
- Reich, M. (2001). *Estudio petrográfico, mineraloquímico y geoquímico de los cuerpos intrusivos de Sewell y La Huífa, yacimiento El Teniente, VI Región, Chile* (p. 104). Departamento de Ciencias de la Tierra, Universidad de Concepción, Geologist Professional Degree Thesis.
- Rodríguez, C., Sellés, D., Dungan, M., Langmuir, C. H., & Leeman, W. P. (2007). Intracrustal origin of Holocene adakitic magmas at Nevado de Longaví volcano (Chile, Southern Volcanic Zone, 32.6°S). *Journal of Petrology*, 49, 2033–2061.
- Rodríguez, N. (2022). *Emplazamiento del batolito La Obra y su relación con la deformación externa, Chile Central (33°35'S–33°47'S): Inferencias desde el estudio de la fábrica magmática y microtexturas* (p. 70). Escuela de Geología, Universidad Mayor, Geologist Professional Degree Thesis.
- Sellés, D. (1999). La Formación Abanico en el Cuadrángulo Santiago (33°15'–33°30'S; 70°30'–70°45'O). Departamento de Geología M.Sc. Thesis. (p. 154.). Universidad de Chile.
- Sellés, D. (2000). *Geoquímica de las unidades intrusivas y volcánicas de la Hoja Santiago, Informe Preliminar* (p. 27). Sernageomin, Unpublished Report.
- Sellés, D., & Gana, P. (2001). *Geología del área Talagante-San Francisco de Mostazal: Regiones Metropolitana y del Libertador General Bernardo O'Higgins, Escala 1:100.000*. Carta Geológica de Chile, Serie Geología Básica, N° 74. Sernageomin.
- Sellés, D., Rodríguez, C., Dungan, M., 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, 293–315.
- Sernageomin. (2003). *Mapa Geológico de Chile, 1:1000000*. Servicio Nacional de Geología y Minería.
- Sillitoe, R. H. (2010). Porphyry copper systems. *Economic Geology*, 105(1), 3–41. <https://doi.org/10.2113/gsecongeo.105.1.3>
- Söderlund, U., Patchett, P. J., Vervoort, J. D., & Isachsen, C. E. (2004). The ¹⁷⁶Lu decay constant determined by Lu-Hf and U-Pb isotope systematics of Precambrian mafic intrusions. *Earth and Planetary Science Letters*, 219(3–4), 311–324. [https://doi.org/10.1016/s0012-821x\(04\)00012-3](https://doi.org/10.1016/s0012-821x(04)00012-3)
- Solano, J. M. S., Jackson, M. D., Sparks, R. S. J., Blundy, J. D., & Annen, C. (2012). Melt segregation in deep crustal hot zones: A mechanism for chemical differentiation, crustal assimilation and the formation of evolved magmas. *Journal of Petrology*, 53(10), 1999–2026. <https://doi.org/10.1093/petrology/egs041>

- Somoza, R., & Ghidella, M. (2005). Convergencia en el margen occidental de América del Sur durante el Cenozoico: subducción de las placas de Nazca, Farallón y Aluk. *Revista de la Asociación Geológica Argentina*, 60, 797–809.
- Sparks, R. S. J., Annen, C., Blundy, J. D., Cashman, K. V., Rust, A. C., & Jackson, M. D. (2019). Formation and dynamics of magma reservoirs. *Philosophical Transactions of the Royal Society A*, 377(2139), 20180019. <https://doi.org/10.1098/rsta.2018.0019>
- Sruoga, P., Etcheverría, M. P., Feineman, M., Rosas, M., Burkert, C., & Ibañez, O. (2012). Complejo Caldera Dimanate-Volcán Maipo (34°10'S, 69°50'O): evolución volcanológica y geoquímica e implicancias en su peligrosidad. *Revista de la Asociación Geológica Argentina*, 69, 508–530.
- Sruoga, P., Llambías, E. J., Fauqué, L., Schonwandt, D., & Repol, D. G. (2005). Volcanological and geochemical evolution of the Diamante caldera-Maipo volcano complex in the southern Andes of Argentina (34°10'S). *Journal of South American Earth Sciences*, 19(4), 399–414. <https://doi.org/10.1016/j.jsames.2005.06.003>
- Stern, C. R. (1988). Source region versus intra-crustal contamination in the petrogenesis of the Quaternary volcanic centers at the northern end (33–34°S) of the Southern Volcanic Zone of the Andes (Vol. 3, pp. 129–143). V Congreso Geológico Chileno.
- Stern, C. R. (1989). Pliocene to present migration of the volcanic front, Andean Southern volcanic zone. *Revista Geológica de Chile*, 16, 145–162.
- Stern, C. R. (1991a). Role of subduction erosion in the generation of Andean magmas. *Geology*, 19(1), 78–81. [https://doi.org/10.1130/0091-7613\(1991\)019<0078:roseit>2.3.co;2](https://doi.org/10.1130/0091-7613(1991)019<0078:roseit>2.3.co;2)
- Stern, C. R. (1991b). Comment on “Crustal contributions to arc magmatism in the Andes of Central Chile”. In W. Hildreth & S. Moorbath (Eds.), *Contributions to Mineralogy and Petrology* (Vol. 108, pp. 241–246). <https://doi.org/10.1007/bf00307341>
- Stern, C. R. (2020). The role of subduction erosion in the generation of Andean and other convergent plate boundary arc magmas, the continental crust and mantle. *Gondwana Research*, 88, 220–249. <https://doi.org/10.1016/j.gr.2020.08.006>
- Stern, C. R., Amini, H., Charrier, R., Godoy, E., Hervé, F., & Varela, J. (1984). Petrochemistry and age of rhyolitic pyroclastic flows which occur along the drainage valleys of the río Maipo and río Cachapoal (Chile) and the río Yaucha and río Papagayos. *Andean Geology*, 23, 39–52.
- Stern, C. R., Floody, R., & Espiñeira, D. (2011). Olivine-hornblende-lamprophyre dikes from Quebrada los Sapos, El Teniente, Central Chile (34°S): Implications for the temporal geochemical evolution of the Andean subarc mantle. *Andean Geology*, 38, 1–22. <https://doi.org/10.5027/andgeov38n1-a02>
- Stern, C. R., Moreno, H., López-Escobar, L., Clavero, J. E., Lara, L. E., Naranjo, J. A., et al. (2007). Chilean volcanoes. In T. Moreno & W. Gibbons (Eds.), *The Geology of Chile* (pp. 147–178). The Geological Society.
- Stern, C. R., & Skewes, A. (1995). Miocene to present magmatic evolution at the northern end of the Andean Southern Volcanic Zone. *Andean Geology*, 22, 261–272.
- Stern, C. R., Skewes, A., & Arévalo, A. (2011). Magmatic evolution of the giant El Teniente Cu-Mo deposit, Central Chile. *Journal of Petrology*, 52(7–8), 1591–1617. <https://doi.org/10.1093/petrology/egq029>
- Stern, C. R. P. K.-N., Hao-Yang, L., Skewes, A., Arévalo, A., & Arévalo, A. (2019). Implications of Hf isotopes for the evolution of the mantle source of magmas associated with the giant El Teniente Cu-Mo megabreccia deposit, Central Chile. *Minerals*, 9, 550. <https://doi.org/10.3390/min9090550>
- Tassara, A., & Echaurren, A. (2012). Anatomy of the Andean subduction zone; three-dimensional density model upgraded and compared against global-scale models. *Geophysical Journal International*, 189(1), 161–168. <https://doi.org/10.1111/j.1365-246x.2012.05397.x>
- Tassara, A., Götze, H.-J., Schmidt, S. T., & Hackney, R. (2006). Three-dimensional density model of the Nazca plate and the Andean continental margin. *Journal of Geophysical Research*, 111, B09404.
- Taylor, H. P. (1968). The oxygen isotope geochemistry of igneous rocks. *Contributions to Mineralogy and Petrology*, 19, 1–71. <https://doi.org/10.1007/bf00371729>
- Thiele, R. (1980). *Hoja Santiago* (Vol. 21). Instituto de Investigaciones Geológicas. 1 mapa.
- Tribuzio, R., Renna, M. R., Dallai, L., & Zanetti, A. (2014). The magmatic–hydrothermal transition in the lower oceanic crust: Clues from the Ligurian ophiolites, Italy. *Geochimica et Cosmochimica Acta*, 130, 188–211. <https://doi.org/10.1016/j.gca.2014.01.010>
- Troch, J., Ellis, B. S., Harris, C., Bachmann, O., & Bindeman, I. (2020). Low- $\delta^{18}\text{O}$ silicic magmas on Earth: A review. *Earth-Science Reviews*, 208, 103299. <https://doi.org/10.1016/j.earscirev.2020.103299>
- Valley, J. W., Chiarenzelli, J. R., & McLelland, J. M. (1994). Oxygen isotope geochemistry of zircon. *Earth and Planetary Science Letters*, 126(4), 187–206. [https://doi.org/10.1016/0012-821x\(94\)90106-6](https://doi.org/10.1016/0012-821x(94)90106-6)
- Valley, J. W., Kinny, P., Schulze, D. J., & Spicuzza, M. J. (1998). Zircon megacrysts from kimberlite: Oxygen isotope variability among mantle melts. *Contributions to Mineralogy and Petrology*, 133(1–2), 1–11. <https://doi.org/10.1007/s004100050432>
- Vervoort, J. D., & Blichert-Toft, J. (1999). Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. *Geochimica et Cosmochimica Acta*, 63(3–4), 533–556. [https://doi.org/10.1016/s0016-7037\(98\)00274-9](https://doi.org/10.1016/s0016-7037(98)00274-9)
- Vidal, A. (2007). Petrología y metamorfismo de muy bajo grado en rocas volcánicas cenozoicas del área de Laguna Negra-Río Yeso, Cajón del Maipo, Santiago M.Sc. Thesis. (p. 190). Departamento de Geología, Universidad de Chile.
- Walker, B. A., Bergantz, G. W., Otamendi, J. E., Ducea, M. N., & Cristofolini, E. A. (2015). A MASH zone revealed: The mafic complex of the Sierra Valle Fértil. *Journal of Petrology*, 56(9), 1863–1896. <https://doi.org/10.1093/petrology/egv057>
- Wei, C.-S., Zhao, Z.-F., & Spicuzza, M. J. (2008). Zircon oxygen isotopic constraint on the sources of late Mesozoic A-type granites in eastern China. *Chemical Geology*, 250(1–4), 1–15. <https://doi.org/10.1016/j.chemgeo.2008.01.004>
- Wei, C.-S., Zheng, Y.-F., Zhao, Z.-F., & Valley, J. W. (2002). Oxygen and neodymium isotope evidence for recycling of juvenile crust in northeast China. *Geology*, 30(4), 375–378. [https://doi.org/10.1130/0091-7613\(2002\)030<0375:oanief>2.0.co;2](https://doi.org/10.1130/0091-7613(2002)030<0375:oanief>2.0.co;2)
- Willner, A. P., Gerdes, A., & Massone, H.-J. (2008). History of crustal growth and recycling at the Pacific convergent margin of South America at latitudes 29°–36°S revealed by a U–Pb and Lu–Hf isotope study of detrital zircon from late Paleozoic accretionary systems. *Chemical Geology*, 253(3–4), 114–129. <https://doi.org/10.1016/j.chemgeo.2008.04.016>
- 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. <https://doi.org/10.1016/j.epsl.2004.12.005>
- Yang, W.-B., Niu, H.-C., Hollings, P., Zurevinski, S., & Li, N.-B. (2017). The role of recycled oceanic crust in the generation of alkaline A-type granites. *Journal of Geophysical Research: Solid Earth*, 122(12), 9775–9783. <https://doi.org/10.1002/2017jb014921>
- Zhao, Z.-F., Zheng, Y.-F., Wei, C.-S., & Wu, Y.-B. (2007). Post-collisional granitoids from the Dabie orogen in China: Zircon U–Pb age, element and O isotope evidence for recycling of subducted continental crust. *Lithos*, 93(3–4), 248–272. <https://doi.org/10.1016/j.lithos.2006.03.067>
- Zheng, Y.-F., Wu, Y.-B., Gong, B., Chen, R.-X., Tang, J., & Zhao, Z.-F. (2007). Tectonic driving of Neoproterozoic glaciations: Evidence from extreme oxygen isotope signature of meteoric water in granite. *Earth and Planetary Science Letters*, 256(1–2), 196–210. <https://doi.org/10.1016/j.epsl.2007.01.026>
- Zheng, Y.-F., Zhang, S.-B., Zhao, Z.-F., Wu, Y.-B., Li, X., Li, Z., & Wu, F.-Y. (2007). Contrasting zircon Hf and O isotopes in the two episodes of Neoproterozoic granitoids in South China: Implications for growth and reworking of continental crust. *Lithos*, 96(1–2), 127–150. <https://doi.org/10.1016/j.lithos.2006.10.003>