

Science Paper

Plio-Pleistocene Western Retroarc Magmatic Evolution and Its Relation With Variable Subduction Settings in the Southern Central Andes (34–38 °S)

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Plio-Pleistocene magmatism in the Southern Central Andes (34–38 °S) developed contemporaneously with inferred steepening and destabilization of the subducted Nazca plate associated with a slab tearing at 38°S. Within this setting, arc-related magmatic activity developed in N-S striking belts. Particularly, the studied Varvarco Volcanic Field (VVF) formed in an unusual western retroarc position (70 °W), between the eastern retroarc (69°30' W) and the present-day arc (68°30' W). Here we present new field data along with major, minor, and trace elements analyses, Sr-Nd-Pb isotope systematics, and a zircon U/Pb age of ~2.36 Ma to better constrain the linkage between emplacement of the VVF during the Nazca plate steepening and the westward migration of the asthenospheric wedge. The VVF is characterized by basic to intermediate lavas interbedded with pyroclastic deposits, and rhyolitic intrusives. The Basal Lava Flows are calc-alkaline basaltic andesites to andesites, whereas the Upper Lava Flows are less evolved tholeiitic basalts to basaltic andesites. Steepening of the Nazca plate and the onset of the upper plate extension during the VVF emplacement favored the rapid ascent of the latest VVF magma pulses, which underwent low degrees of fractional crystallization. A regional comparison is made to evaluate the impact of the variable tectonic setting on Plio-Pleistocene Andean magmatism. The VVF magmatism shows an arc-like signature, although less pronounced than the present-day volcanic arc. This behavior is also seen when considering all Plio-Pleistocene western retroarc volcanism, whose moderate slab fluids input is associated with their higher distance to the trench relative to the main volcanic arc. Meanwhile, the upwelling of a plume-like structure associated with the Nazca plate tearing has only affected the southern Payenia eastern retroarc volcanoes and the southeastern magmatic units of the western retroarc located just above the tearing.

1. INTRODUCTION

The Southern Central Andes record Jurassic to recent arc-related magmatism emplaced during dynamic tectonic settings (Dungan et al., 2001; Stern, 2004). Changes in tectonic parameters, such as slab subduction geometry, convergence rate, age of the subducting plate, and thickness of the upper plate, influence the dynamics of the subduction regime and therefore, the development of the volcanic arc (England & Katz, 2010; Grove et al., 2009; Peacock, 1996; Syracuse et al., 2010). As a result, the location, structural features, and geochemistry of arc-related magmatism in the upper plate are indirect proxies of these tectonic controls (Hickey-Vargas et al., 2016; Turner &

Langmuir, 2015; Wieser et al., 2019). Particularly, variations in the geometry of the subducting slab and the associated development of shallow to flat-slab subduction regimes, have long been considered the main controls of arc evolution in the Southern Central Andes (Folguera et al., 2006; Kay et al., 1991; Kay, Burns, et al., 2006; Kay & Mancilla, 2001; Stern, 1989).

Tectonic settings characterized by shallow and flat-slab subduction have been identified worldwide, especially along the western margin of America. Representative cases of ancient flat-slab settings are the Cretaceous Laramide orogeny in North America (Saleeby, 2003) and the Early Permian San Rafael flat slab in South America (Martínez et al., 2006). Each of these examples is interpreted to show

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an initial compressive tectonic regime and foreland migration of arc-related magmatism during the shallow subduction period. This is followed by extensional collapse of the upper plate during the steepening of the subducting slab. Flat slab regimes, characterized by magmatic gaps in arc activity, are recognized worldwide as the Peruvian flat-slab (Bishop et al., 2017; Hu et al., 2016), the Chilean-Pampean flat-slab (Kay et al., 1991; Litvak et al., 2007), and the Mexican flat-slab (Manea et al., 2017). These segments differ from shallow subduction settings with active arc magmatism as the Ecuadorian subduction zone (Yepes et al., 2016) and the Cascades (McCrory et al., 2012).

In the Southern Central Andes (34–38°S), Cenozoic Andean magmatic activity has been directly linked to changes in the subduction geometry, which controls not only the time and style of deformation in the upper plate, but also the eastern expansion of arc-related magmas and the development of eastern retroarc within-plate magmatism (Folguera et al., 2008, 2009; Germa et al., 2010; Kay, Burns, et al., 2006; Litvak et al., 2015; Petrinovic et al., 2021; Ramos et al., 2014; Søger et al., 2013). By the Late Miocene, a shallow subduction regime was established at these latitudes, known as the Payenia shallow subduction segment (Kay, Mancilla, et al., 2006; Litvak et al., 2015; Ramos et al., 2014). The shallowing of the subducting slab controlled the expansion of calc-alkaline magmas to the east during the Late Miocene. Then, by the Early Pliocene, the steepening and destabilization of the Nazca plate influenced the development of Pliocene to recent alkaline magmatism in the eastern retroarc (Gudnason et al., 2012; Llambías et al., 2010; Søger et al., 2015), and the westward establishment of the main magmatic arc in the Andean axis (Hickey-Vargas et al., 2016; Sellés et al., 2004; Singer et al., 2014) (fig. 1). Pliocene slab steepening is believed to be associated with tearing of the slab at ~38°S (Pesicek et al., 2012) allowing the upwelling of an asthenospheric anomaly (Burd et al., 2014; Gianni et al., 2017; Rojas Vera et al., 2014). This asthenospheric ascent is responsible for the widespread alkaline magmatism at the present-day eastern retroarc (Bermúdez et al., 1993; Germa et al., 2010; Gudnason et al., 2012; Holm et al., 2016; Søger et al., 2013) (fig. 1).

In this context, between the easternmost retroarc (ER) and the present-day arc front, a Plio-Pleistocene N-S magmatic belt was emplaced, associated with the extensional regime caused by the steepening of the Nazca plate (Pesicek et al., 2012) (fig. 1). This magmatism is defined in this work as the western retroarc magmatic belt (WR) and is characterized by collapsed calderas, stratovolcanoes, and monogenetic cones along extensive volcanic fields located east of the present-day arc (fig. 1) (Hickey-Vargas et al., 2016; Hildreth et al., 1999, 2010; Hildreth & Moorbath, 1988). Between 34 and 38°S, the majority of these calderas and volcanic fields developed within the Las Loicas Trough, a NW-SE oriented Plio-Pleistocene extensional collapsed structure (Folguera et al., 2006; Hildreth et al., 1999). Although some authors have studied this western retroarc magmatism (Holm et al., 2014; Jacques et al., 2013; Sruoga et al., 2016; Traun et al., 2024), detailed volcano-strati-

graphic and geochemical studies and also regional works gathering all of these western retroarc volcanic centers are still missing. Here, we focus our study on the Varvarco Volcanic Field (VVF), one of the largest magmatic districts developed within the Las Loicas Trough in Plio-Pleistocene times. The VVF is located immediately to the north of the surface projection of the Nazca plate tearing (fig. 1). New field data and geochemical analyses of major, minor, and trace elements together with Sr-Nd-Pb isotope systematics, and a zircon U/Pb age are presented here as the first detailed work made in the area. Moreover, this new geochemical data from the VVF unit is regionally compared with coeval western and eastern retroarc magmatism and with the present-day volcanic arc units, to gain fruitful insights into the understanding of the tectonomagmatic evolution of arc-related magmatism in the Southern Central Andes.

There are two important questions related to the emplacement of VVF magmas. First, their western retroarc position raises the question of whether their genesis was directly associated with the steepening of the subducting slab and the westward migration of the asthenospheric wedge. In this case, VVF magmas should record geochemical signatures of slab-fluids, despite their position away from the trench. Second, what was the impact of slab tearing associated with Nazca plate steepening on regional magmatism? How did the upwelling of the asthenospheric anomaly impact VVF magmas and more regionally magmatism across the western retroarc belt, as intraplate-like geochemical features are described eastwards in the Payún Matrú volcanic field? (Germa et al., 2010; Søger et al., 2013). If western retroarc magmatism was directly associated with the steepening of the subducting slab and the westward migration of the asthenospheric wedge, it should record variations in geochemical compositions from calc-alkaline to alkaline-transitional and intraplate-like features. Comparison of the VVF rocks with a complete dataset of the main arc, the western and the eastern retroarc magmatism in the Southern Central Andes (34–38°S), helps to elucidate the main geochemical features of the western retroarc magmas, the cause for their position relative to the trench, and to track the regional extent of the asthenospheric anomaly.

The new geochemical data from VVF magmas show an intermediate geochemical signature between the eastern retroarc and the arc magmas composition. They record a slight slab-fluids influence due to its position away from the trench, with no influence from the upwelling mantle anomaly. In a regional comparison, we can see that western retroarc magmatism along the Southern Central Andes (34–38°S) shows common geochemical features, that overall, are mainly defined between arc and eastern retroarc magma compositions.

2. GEOLOGICAL BACKGROUND

2.1. Latest Miocene to Pleistocene Magmatic Evolution in the Southern Central Andes (34–37°S)

From Mid to Late Miocene times (~16 to 4 Ma), magmatism in the Southern Central Andes developed during the shal-

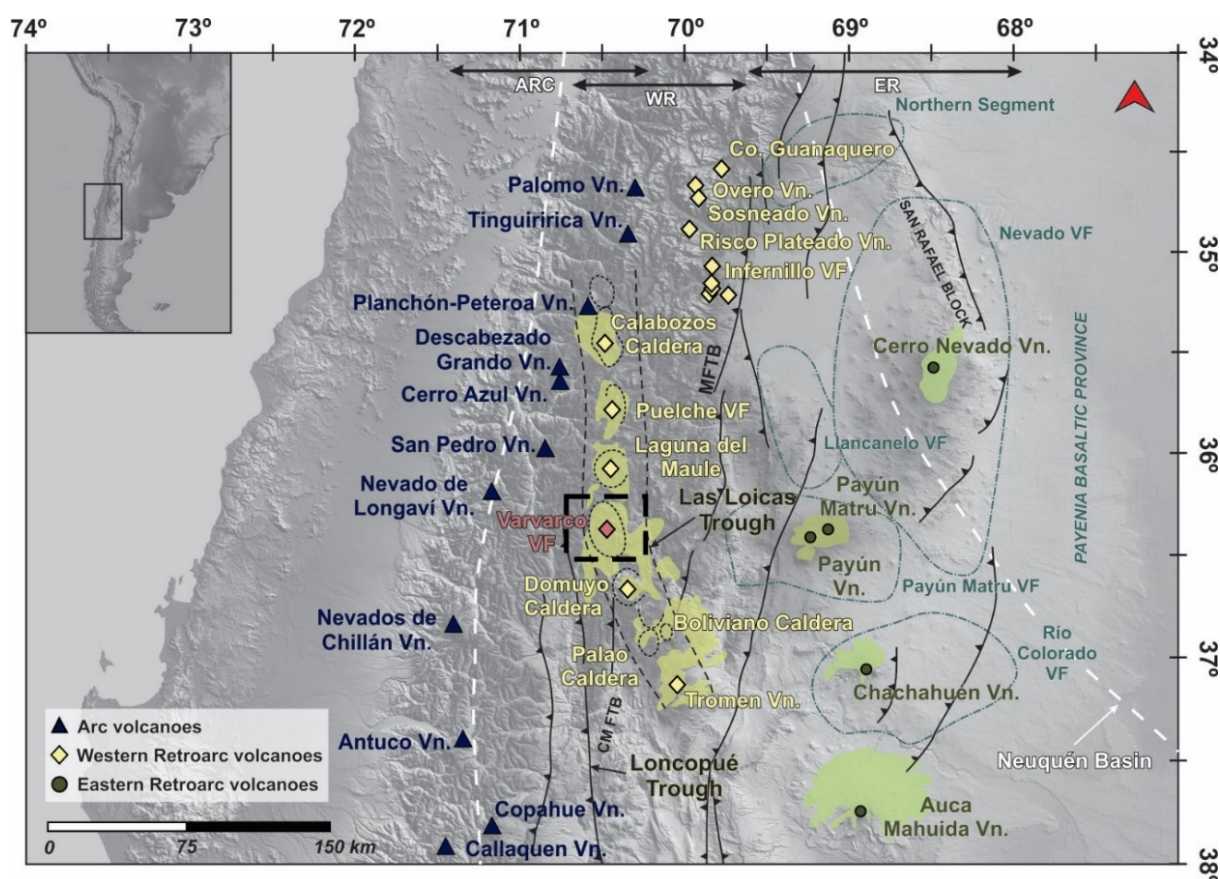


Figure 1. Schematic map showing the distribution of the magmatic-districts emplaced between Pliocene to Holocene times in the Southern Central Andes (34–38°S). Three main N-S-striking magmatic belts can be distinguished: the eastern retroarc (ER) (green circles), the western retroarc (WR) (yellow diamonds), and the main magmatic arc front (dark blue triangles). Vn = volcano; VF = volcanic field; CMFTB: Chos Malal Fold and Trust Belt; MFTB: Malargüe Fold and Trust Belt. Dashed white lines indicate the extension of the Neuquén Basin while dashed black lines show the extension of each volcanic field. Modified after Folguera et al. (2009), Jacques et al. (2013), Søager et al. (2013), Hickey-Vargas et al. (2016), and Pallares et al. (2016, 2019).

low subduction regime of the Nazca plate beneath the South American plate (Dyhr et al., 2013; Kay, Burns, et al., 2006; Kay, Mancilla, et al., 2006; Litvak et al., 2015; Ramos et al., 2014). The main cause for this shallowing subduction period is still debated, alternatively ascribed to 1) the subduction of an aseismic ridge (Ramos et al., 2014); 2) the influence of the northern subduction of the Juan Fernández Ridge (28–33°S) over the slab buoyancy to the south (Litvak et al., 2019); 3) the westward absolute shift of the South American plate after a stage of quasistatic motion (Spagnuolo et al., 2012) or 4) the existence of a subducted mantle plume beneath the Nazca plate (Gianni et al., 2017). This shallow subduction configuration led to a compressive regime and the consequently uplifting of the San Rafael block, a basement block whose exhumation is associated with the foreland propagation of the Malargüe Fold and Thrust Belt by Late Miocene times (fig. 1) (Folguera & Ramos, 2011). During this period, magmatism along the arc axis was volumetrically restricted, while arc-related magmas expanded towards the retroarc area (Dyhr et al., 2013; Kay, Burns, et al., 2006; Kay, Mancilla, et al., 2006; Litvak et al., 2015; Ramos et al., 2014). Thus, the Early Miocene eastern retroarc magmatism shows a slight geochemical im-

print of slab-related fluids influence, which increased from Middle to Late Miocene times during the development of the Payenia shallow subduction regime, reaching its maximum at ~4 Ma (Dyhr et al., 2013; Kay, Mancilla, et al., 2006; Kay & Copeland, 2006; Litvak et al., 2015). This eastern retroarc magmatism is characterized by andesitic to dacitic compositions with arc-related tholeiitic to calc-alkaline signatures (Dyhr et al., 2013; Kay, Mancilla, et al., 2006).

By the Early Pliocene, an increase in the subduction angle of the Nazca plate resulted in the onset of a widespread extensional regime and consequently the inversion of contractional structures and the extensional collapse of the San Rafael block (Folguera et al., 2006; Pesicek et al., 2012; Ramos et al., 2014; Ramos & Folguera, 2005). Even though an open discussion exists about the dominant deformation style (Branellec et al., 2016; Guzmán et al., 2007), most authors agree in an extensional relaxation period at least for the Early Pliocene caused by the increase in the slab dip (Burd et al., 2014; Folguera et al., 2006, 2008, 2009; Lara & Folguera, 2006; Melnick et al., 2006; Muñoz & Stern, 1988; Ramos & Kay, 2006). Evidence for this extensional regime during the steepening of the Nazca plate is the develop-

ment of N-S troughs along the Andean margin, such as the studied Las Loicas Trough between 35° and 37°S (Folguera et al., 2006) and the Loncopué Trough between 36.5° and 38.5°S (Ramos, 1978; Rojas Vera et al., 2014).

The steepening of the Nazca plate triggered the development of a vertical slab tear in the southern part (~ 38°S) of the Payenia segment (Pesicek et al., 2012). This slab tearing could be a consequence of the interaction between the subducting plate and an asthenospheric mantle anomaly (Burd et al., 2014) or a mantle plume (Gianni et al., 2017) located beneath the slab in the retroarc area. Moreover, previous weak structures in the Nazca plate and/or large-scale differences in the overriding lithosphere may have induced stress heterogeneities in the subducting plate and thereby favored the development of the slab tearing (Pesicek et al., 2012). North of 38°S, slab bending accommodates the transition between the slab tearing zone and the Chilean-Pampean flat slab (28°–33°S) (Gudnason et al., 2012; Pesicek et al., 2012). The slab tear at ~38°S, allowed the upwelling of asthenospheric material beneath the South American plate as visualized by seismic tomography (Burd et al., 2014).

This new tectonic regime was also responsible for the Early Pliocene westward migration of arc-related magmatism. Volcanism in the Andean axis developed as a series of stratovolcanoes and monogenetic cones with mainly basaltic to andesitic compositions (Dungan et al., 2001; Hildreth & Moorbath, 1988; López-Escobar, Cembrano, et al., 1995; Sellés et al., 2004; Sruoga et al., 2012; Tormey et al., 1991, 1995). At present, they are part of the active volcanic arc of the Transitional Southern Volcanic Zone (TSVZ; 34.5–37°S), which shows a variable geochemical signature along strike due to differences in the crustal thickness of the upper plate, variations in the subducted slab geometry, variable inputs of slab-derived fluids, and degrees of partial melting (Hickey-Vargas et al., 2016; Turner et al., 2017). At the studied latitudes (34–38°S), magmatism in the TSVZ was generated by the melting of a mantle wedge modified by fluids and/or melts from the subducted MORB-type altered oceanic crust and the overlying marine sediments (Hildreth & Moorbath, 1988; Jacques et al., 2013; Sellés et al., 2004). Several fracture zones characterize the subducted Nazca plate, like the Mocha Fracture Zone (MFZ) at 36°S, acting as preferential pathways for the upwelling of fluid fluxes (Dzierma et al., 2012). The current Nazca-South America convergence rate is ~7 cm/yr (Somaza & Ghidella, 2012), while Nazca plate dip is 30°E and converges with an obliqueness of 70° relative to the trench.

As a consequence of slab steepening, the Pliocene to Holocene Payenia Basaltic Province developed in the eastern retroarc area (Gudnason et al., 2012; Kay, Burns, et al., 2006; Llambías et al., 2010), characterized by voluminous alkaline magmatism with an intraplate signature and a low to moderate input from the subducting slab (Espanon et al., 2016; Gudnason et al., 2012; Hernando et al., 2012; Søgager et al., 2013). A signal of increasing slab-related fluids is recognized within Payenia magmatism: from the southern intraplate-like Auca Mahuida and Río Colorado to the Payún Matrú volcanic fields, up to the northern Nevado and the Northern Segment volcanic fields, which show the

strongest subduction-related signature (fig. 1) (Folguera et al., 2009; Gudnason et al., 2012; Holm et al., 2016; Pallares et al., 2023; Søgager et al., 2013). Along strike, geochemical variations would indicate the presence of different mantle sources: an EM1 OIB-type mantle in the south (Río Colorado, Auca Mahuida, and Payún Matrú volcanic fields) versus a South Atlantic MORB-type mantle in the north (Llancanelo and Nevado volcanic fields) (Espanon et al., 2016; Holm et al., 2014; May et al., 2018; Søgager et al., 2013). This is explained by the progressive steepening of the Nazca plate that allowed the ingression of an EM1 plume-type mantle flow at ~ 36–38°S (Burd et al., 2014; Gudnason et al., 2012).

During the Pliocene trenchward arc-related magma migration, a N-S oriented magmatic belt developed in the western retroarc area, east of the main Andean axis (Hildreth et al., 1999; Jacques et al., 2013; Muñoz Bravo et al., 1989). Between 36 and 38°S, this magmatic belt is characterized by collapse calderas, andesitic volcanism, rhyolitic domes, and basaltic flows with the most prominent volcanoes being the Tromen and Domuyo (Astort et al., 2019; Hildreth et al., 1999; Hildreth & Moorbath, 1988). These Plio-Pleistocene western retroarc centers developed along the Las Loicas Trough, like the Puelche (Hildreth et al., 1999), Calabozos (Hildreth et al., 1984), and Laguna del Maule volcanic fields (Frey et al., 1984; Hildreth et al., 2010) as well as the studied Varvarco Volcanic Field, focus of this work (Folguera et al., 2006; Miranda et al., 2006) (fig. 1). Farther north (34–36°S), Pliocene to Pleistocene western retroarc magmatic activity comprises stratovolcanoes and monogenetic cones like the Overo, Sosneado, and Risco Plateado volcanoes, mostly characterized by basaltic-andesitic to dacitic lava flows and interbedded pyroclastic deposits (fig. 1) (Folguera et al., 2009; Fuentes & Ramos, 2008; Sruoga et al., 2016). Contemporaneous and adjacent to the Las Loicas Trough, the Loncopué Trough was developed (fig. 1). This elongated topographic depression is 300 km long, located between 36 and 39° S, and is filled with synextensional volcano-sedimentary successions (Rojas Vera et al., 2014; Varekamp et al., 2010). Its magmatic products consist of Pliocene volcanic rocks that form a continuous lava plateau, minor caldera-collapsed silicic pyroclastic flows (2–2.6 Ma), and syn-glacial and post-glacial lava flows (800–300 ka) (Rojas Vera et al., 2014). Most Loncopué volcanism is basaltic, trachy-basaltic, and trachy-andesitic in composition (Varekamp et al., 2010). Geochemically, lava flows show transitional features between arc-like products in the northern and western areas to intraplate-like signals in the southern part (Rojas Vera et al., 2014; Varekamp et al., 2010).

2.2. Geological Setting of the Varvarco Volcanic Field

The Varvarco Volcanic Field (VVF) in the Southern Central Andes is located in the central part of the Las Loicas Trough (~ 36°30' S), to the west of the Payún Matrú volcanic field and to the north of the asthenospheric mantle anomaly beneath the Tromen volcanic area (fig. 1) (Astort et al., 2019; Burd et al., 2014).

The study area is structurally controlled by the Chos Malal Fold and Thrust Belt which records two main contractional phases: one in the Late Cretaceous-Eocene and the other in the Late Miocene (Folguera et al., 2006; Zamora Valcarce et al., 2009) (figs. 1 and 2). The oldest rocks cropping out in the VVF area are those of the Upper Permian-Lower Triassic Choiyoi Group, emplaced during an extensional regime (Sato et al., 2015). The Choiyoi magmatism comprises large rhyolitic plateaus and dacitic to rhyodacitic ignimbritic flows interbedded with breccias and volcanic sandstones (Strazzere et al., 2016). Afterward, the continuing extensional regime led to the Late Triassic opening of the Neuquén Basin (Legarreta & Uliana, 1991), which experienced both marine transgression and regression episodes between Early Jurassic and Early Cretaceous times (Aguirre-Urreta et al., 2011). Paleocene to early Pliocene times are mainly represented in the area by basaltic to andesitic lavas, and pyroclastic deposits of the Cayanta and Cajón Negro Formations (fig. 2) (Pesce, 1981).

The Plio-Pleistocene volcanic units in the study area were gathered in the Coyocho and Tilhué Formations, emplaced along normal faults during the Pliocene extensional phase (fig. 2) (González Díaz, 1979; Holmberg, 1976; Kay, Burns, et al., 2006). Both volcanic units are coetaneous with the development of the studied VVF sequence, thus the VVF products are formally included within these units (Zanettini, 2001). The Coyocho Formation is composed of basaltic flows, dacitic and basaltic tuffs, and basaltic volcanic agglomerates, while the Tilhué Formation consists of rhyolitic lavas, ignimbrites, and pyroclastic flow deposits (Kay, Burns, et al., 2006). In the studied area, the Tilhué Formation also includes porphyritic basaltic-andesitic to andesitic lavas, tuffs, and volcanic agglomerates (Zanettini, 2001). South of the VVF area, a 4.0 ± 0.4 Ma Ar/Ar age was obtained for the Tilhué Formation (Kay, Burns, et al., 2006). Nevertheless, in the VVF region, the stratigraphic relationships with neighboring units suggest a Late Pliocene-Early Pleistocene age (Zanettini, 2001).

3. SAMPLING AND ANALYTICAL TECHNIQUES

3.1. Petrography

We conducted detailed sampling of the Quaternary magmatic rocks of the VVF (fig. 2) and produce stratigraphic profiles to constrain the evolution of the VVF magmatism, (sample locations indicated on the geological map of figure 2).

A total of 53 samples were collected for detailed petrographic descriptions. Lava flows have been assigned to different facies based on their petrographic features, primarily based on mafic mineral abundances. Samples were initially classified through a qualitative modal phase estimation and according to the classification proposed by the IUGS (Supplementary Table S1).

3.2. Geochemistry

Ten representative samples were selected for geochemical analysis based on their stratigraphic position and degree of alteration (fig. 2, Supplementary Table S2). The magmatic products of the VVF have been divided into three main units: the Basal Lava Flows (BLF: samples TDM13, TDM16, TDM17, TDM18), the Upper Lava Flows (ULF: samples TDM07, TDM08, TDM11, TDM12, TDM15), and the Rhyolitic Intrusive (RI: sample TDM09), according to their stratigraphic position and their main geochemical features, which are described in the following sections. Whole rock samples were processed for major, minor, and trace elements in the geochemical laboratory of the University of Copenhagen (Denmark). The samples were cut using a diamond blade saw to remove alteration surfaces, and then crushed using a steel piston. Then, they were milled to a fine powder using an agate disc mill for 10–25 min. at 750 rpm depending on their hardness. The powders were analyzed for major and trace elements at AcmeLabs (Bureau Veritas Commodities Canada Ltd.) by lithium borate fusion dissolution followed by ICP-ES analyses of major elements (Code: LF300) and ICP-MS analyses of trace elements (Code: LF202). Results are reported in Supplementary Table S2.

Sr-Nd-Pb isotope analyses were performed over one basalt (TDM16) and one andesite (TDM17) from the Basal Lava Flows, two basalts (TDM08, TDM12) from the Upper Lava Flows, and one sample (TDM09) of the Rhyolitic Intrusive. Samples were analyzed at the Isotope Geochemistry Laboratory at the MARUM Institute at the University of Bremen (Germany) (Supplementary Table S3). Sr, Nd, and Pb isotope ratios were obtained through thermal ionization mass spectrometry (TIMS) on a Triton plus instrument (Thermo Scientific). Sample preparation, mass spectrometric analyses, and external reproducibility of the methods are documented in Höppner et al. (2018).

3.3. Geochronology

A zircon U/Pb age determination was made on a vitreous tuff (CV34) corresponding to the vitreous tuff level at the base of the VVF sequence (fig. 2). The analysis was made at LA.TE ANDES S.A. laboratory in Salta (Argentina) and the results are reported in Supplementary Table S4. The zircon concentrates were obtained from 2 kg of sample using traditional gravimetric, magnetic, and optic techniques. Zircons were then selected by hand picking based on their morphological features (without inclusions or fractures) and mounted in epoxy in a test tube of 25 mm in diameter. The test tube was polished, and zircons were analyzed by Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). The employed facility includes an Applied Spectra ablation laser with 193 nm wavelength and a triple quadrupole Agilent ICP-MS instrument (8900 model). Measurements include one spot per zircon with a spot diameter of 30 μm , a fluence of 2 J/cm^2 , and a frequency of 10 Hz. The element concentrations were obtained using NIST 610 as primary reference material (RM) and NIST 612 as secondary RM (Jochum et al., 2011). The U/

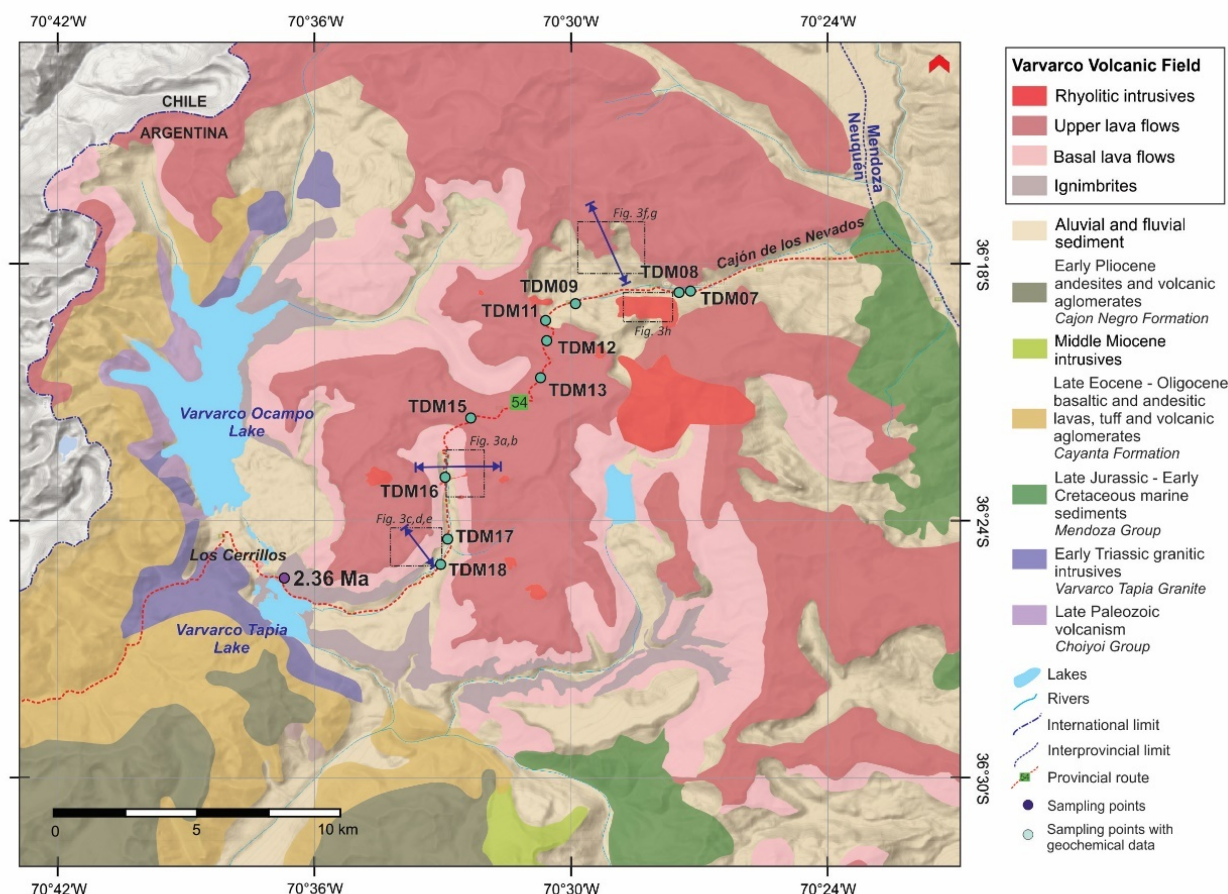


Figure 2. Geological map of the Varvarco Volcanic Field (VVF), with geochemical sample locations indicated with light blue circles and the dated sample location with a violet circle. Dashed squares show the location of the pictures included in figure 3, while blue lines indicate the location of the stratigraphic profiles.

Pb ages were calculated through the isotopic ratios using 91500 zircon as RM (Wiedenbeck et al., 2004) and repeated measurements of the Plesovice zircon (Sláma et al., 2008) were performed to monitor the accuracy and precision. The analytic procedure involved 25 seconds of background measurement (without ablation), followed by 25 seconds of ablation and 5 seconds of washing (turn off laser). The Software LADR 1.1.05 was used for the data reduction. The data processing was made using Isoplot 4.15 according to Ludwig (2003) and IsoplotR according to Vermeesch (2018). The recommended age (Ma) is based on the $^{206}\text{Pb}/^{238}\text{U}$ isotopic ratio (Gehrels et al., 2008). The discordance age calculation was made using the $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages. The mean age was obtained by selecting data according to their distance to the Concordia line. All of the age errors are calculated as standard errors (SE). Information about concordance and age calculations are included in Supplementary Table S4.

4. RESULTS

4.1. Field Work and Petrography

The VVF is mainly characterized by a succession of sub-horizontal basaltic to minor andesitic lava flows, locally interbedded with sedimentary deposits and pyroclastic levels. According to their stratigraphic position, lava flows are divided into the Basal Lava Flows (BLF) and the Upper Lava Flows (ULF), both of which are intruded by Rhyolitic Intrusives (RI) and minor sub-vertical mafic dykes (fig. 3). In several areas, a subhorizontal pyroclastic level has been recognized below the Basal Lava Flows, marking the beginning of the VVF volcanism (fig. 2). This level consists of vitreous tuffs (sample CV34) mainly composed of shards and pumice fragments, minor crystals fragments of quartz, plagioclase and biotite, and a few basaltic to andesitic lithic fragments (Supplementary Table S1).

In general, the BLF and ULF are mainly basaltic to basaltic-andesitic porphyritic lavas with variable contents of phenocrysts of plagioclase, olivine, clinopyroxene, orthopyroxene, and opaque minerals. The groundmass is mainly fresh and presents an intergranular to intersertal texture, while some lavas show vesicles filled with zeolites

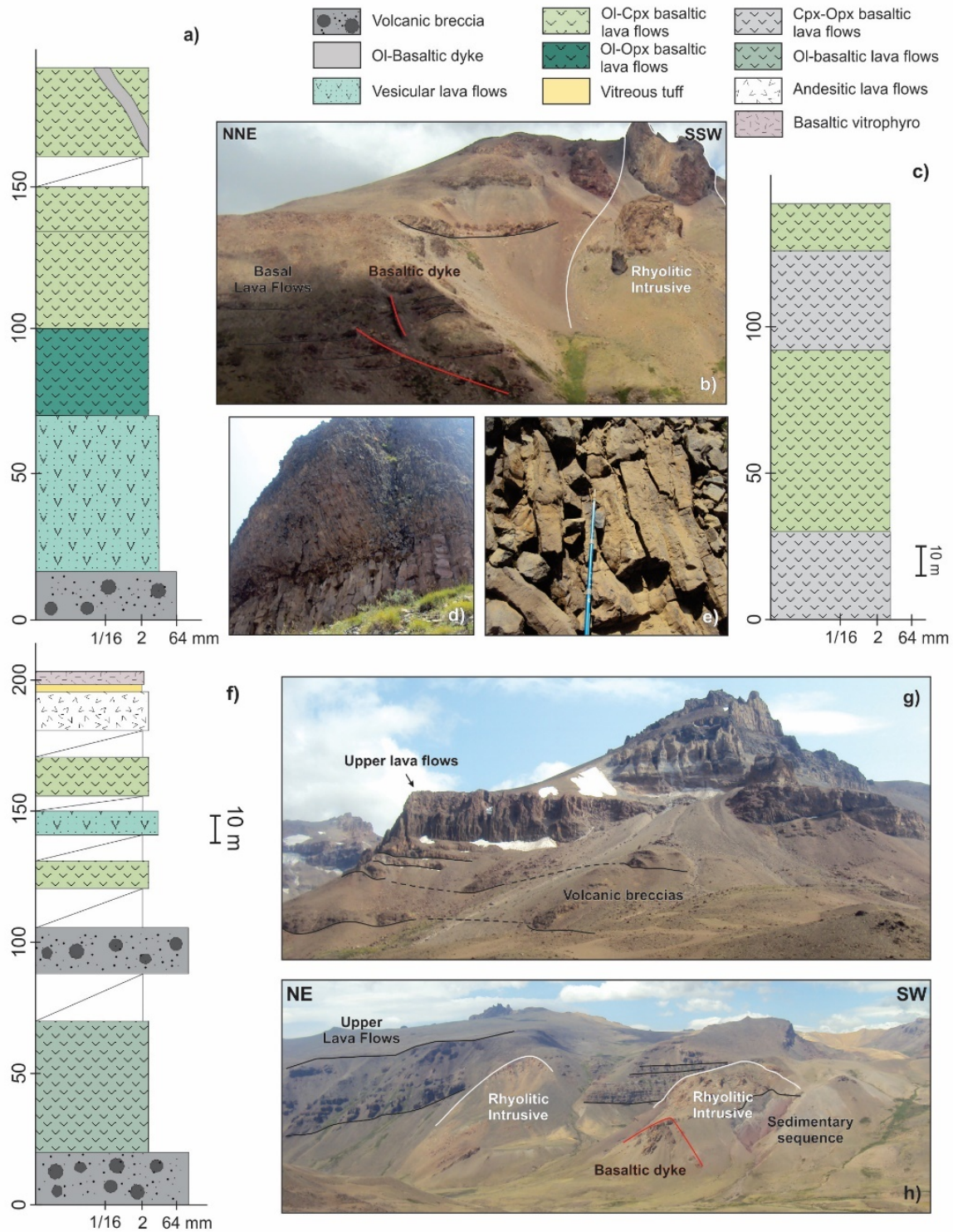


Figure 3. A) Stratigraphic column for the BLF deposits at the southern N-S valley in the VVF area (see location in [figure 2](#)). B) Rhyolitic intrusives and minor mafic dykes intruding the BLF lavas of profile a). C) Stratigraphic column for the BLF deposits near Varvarco Tapia Lake. D) BLF levels show well-developed columnar jointing. E) Detailed field photograph of BLF outcrops with columnar jointing. F) Stratigraphic column for the ULF deposits on the eastern side of the VVF (see location in [figure 2](#)). G) Volcanic breccias and porphyritic ULF lavas in the basal levels of the ULF stratigraphic profile. H) Rhyolitic intrusions in the eastern side of the VVF intruding the ULF subhorizontal lava flows and a fine-grained sedimentary sequence.

(Supplementary Table S1). Interbedded between the BLF and ULF rocks are recognized vitreous tuffs, vitrophyres, and fine-grained sediments (yellow-white fine-grained sandstones and grey-reddish limestones), which are also intruded by rhyolitic intrusions (RI) and sub-vertical mafic dykes (fig. 3B and H).

In the SW part of the VVF, the BLF outcrops dominate and are represented in two stratigraphic profiles (figs. 2 and 3), which consist of a succession of grey-reddish porphyritic to aphanitic lavas (fig. 3A and C) with columnar jointing (fig. 3D and E). In the first profile (fig. 3A), the sequence starts with a volcanic breccia level with palagonite alteration. Upwards, the BLF sequence comprises vesicular lavas, followed by porphyritic lava levels with plagioclase, olivine, and variable amounts of orthopyroxene and clinopyroxene phenocrysts, with an intersertal to intergranular and locally hyalopilitic groundmass (figs. 3A and 4A). The groundmass is composed of plagioclase, clinopyroxene, and opaque minerals; interstitial glass is usually fresh, though it may be locally devitrified. All these lava levels are divided into several petrographic facies according to their variable amounts of mafic mineral phases (orthopyroxene, clinopyroxene, and olivine) (Supplementary Table S1). Olivine phenocrysts are subhedral and are slightly altered to bowlingite and iddingsite, especially at the rims (fig. 4A). Orthopyroxene shows brownish to light green pleochroism and clinopyroxenes are typically twinned (fig. 4A). Usually, orthopyroxene shows a reaction rim of clinopyroxene, while clinopyroxene crystals intergrown with opaque minerals. Finally in this profile, the mafic dykes that intrude lava levels at the top of the BLF sequence, are dark grey aphanitic rocks with well-developed columnar jointing (fig. 3A and B). They are weakly porphyritic, with plagioclase and olivine phenocrysts, set in an intersertal groundmass, which is composed of fine-grained plagioclase microlites, clinopyroxene, opaque minerals, and fresh brownish glass. The mafic dykes also contain quartz xenocrysts with reaction rims of clinopyroxene and interstitial brownish glass (fig. 4B).

The second stratigraphic profile of the BLF sequence (fig. 3C) is located in the southernmost part of the studied region (fig. 2). It begins with vesicular porphyritic lavas followed by 50 meters of porphyritic lavas with well-developed columnar jointing (fig. 3C, D, and E). Upwards, lavas become increasingly more porphyritic and are mainly composed of plagioclase phenocrysts with variable amounts of clinopyroxene, orthopyroxene, and olivine. Plagioclase exhibits sieve texture, while olivine is mostly altered to bowlingite. Clinopyroxene with reaction rims and with opaque intergrowth textures are also common. The groundmass in the basal levels of the sequences is intersertal to hyalopilitic, while towards the top, intergranular groundmass predominates. It is composed of plagioclase, opaque minerals, and pyroxene; when glass is present, it is fresh and light brown.

ULF lavas mainly outcrop in the northeastern sector of the VVF with an average thickness of 200 meters (figs. 2, 3E, and 3G). This sequence begins with volcanic breccias, followed by porphyritic lava flows composed of subhedral to

euhedral, sieve-textured plagioclase and subhedral olivine partially replaced by bowlingite (fig. 4C). Clinopyroxene and orthopyroxene phenocrysts are also present in variable amounts (Supplementary Table S1). The groundmass shows a fine-grained intersertal texture with plagioclase microlites, clinopyroxene, and opaque minerals. Towards the top, the groundmass transitions to an intergranular texture, less interstitial glass, lower grain sizes, and locally interstitial secondary light-green clays. Near the top, a moderately porphyritic andesitic lava flow is interbedded with the basaltic lavas (fig. 4D). The andesites are composed of plagioclase, orthopyroxene, and amphibole phenocrysts in a fine-grained intergranular groundmass. Orthopyroxene phenocrysts show brownish-pink to light-green pleochroism, while amphibole phenocrysts display a slightly brownish pleochroism and resorption rims (fig. 4D). The profile concludes with a basaltic vitrophyre composed of plagioclase, orthopyroxene, and minor clinopyroxene phenocrysts, immersed in a vitreous groundmass with a fresh brownish color and fluidal texture (figs. 3F and 4E).

Finally, the rhyolitic intrusives (RI) locally intrude the BLF and ULF rocks, as well as the interbedded fine-grained sedimentary levels (fig. 2). Both the lava and sedimentary layers are partially folded in contact with the intrusive bodies (fig. 3H). The RI are white to reddish fine- to medium-grained porphyritic rocks, with abundant plagioclase, amphibole, biotite, alkali feldspar, and minor anhedral quartz phenocrysts. The groundmass is composed of fine-grained quartz and feldspar, which locally displays spherulitic textures (fig. 4F). A thin level of pyroclastic deposits, which comprises vitreous to crystalline tuffs and crops out almost ubiquitously in the VVF district, has been identified between the sedimentary deposits and the lava flow levels.

4.2. Major and Trace Element Geochemistry

The VVF samples selected for geochemical characterization are remarkably fresh, showing no evidence of alteration or secondary minerals filling vesicles, with a loss on ignition (LOI) below 1.6 wt.% (Supplementary Table S2).

Silica content ranges from 53.9 and 61.6 wt.% for BLF, 50.7 and 54.7 wt.% for ULF, and is 77.9 wt.% for RI rocks (Supplementary Table S2). The BLF lavas exhibit a subalkaline affinity, classifying as basaltic trachy-andesites and trachy-andesites based on their alkali vs. silica content ($\text{Na}_2\text{O}+\text{K}_2\text{O}$: 5.75–7.38 wt.%). The ULF rocks present a subalkaline to transitional geochemical behavior classifying as trachy-basalts, basaltic andesites, and basaltic trachy-andesites ($\text{Na}_2\text{O}+\text{K}_2\text{O}$: 5.03–6.01 wt.%) (fig. 5A). The RI sample plots in the rhyolitic field with a $\text{Na}_2\text{O}+\text{K}_2\text{O}$ of 8.68 wt.% (fig. 5A). A slight decrease in alkali and silica contents is observed from the older BLF to the younger ULF samples. The K_2O content ranges from 2.07 to 2.95 wt.% for the BLF rocks and from 1.33 to 1.75 wt.% for the ULF samples, while the RI sample has a K_2O value of 4.41 wt.%. All of them exhibit high-K calc-alkaline compositions, based on their K_2O and SiO_2 contents. Decreasing K_2O values are observed from BLF to ULF lavas (fig. 5B). This is also consistent with the slightly Fe-rich tholeiitic affinity of the ULF rocks

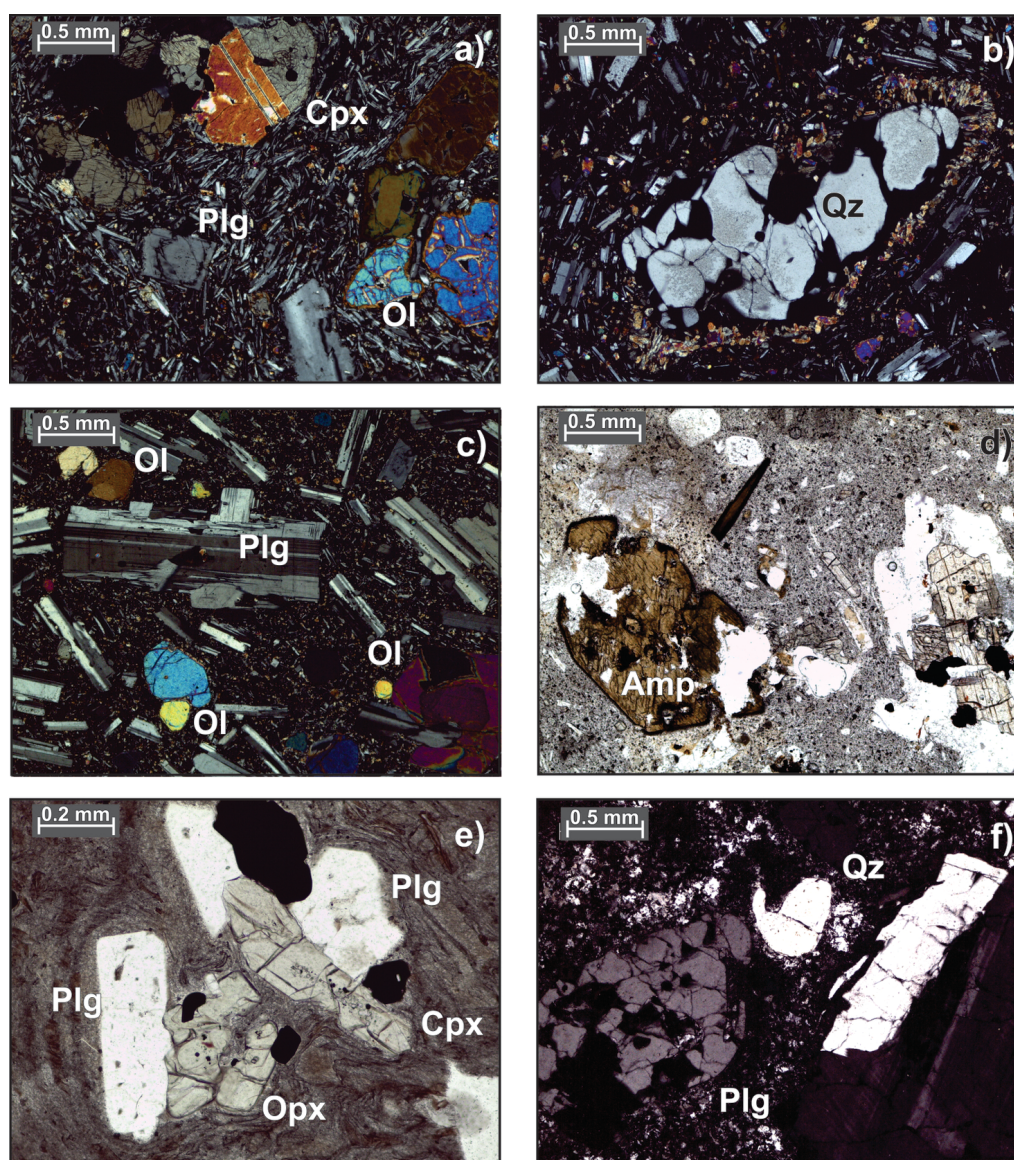


Figure 4. Representative photomicrographs of the analyzed volcanic rocks from the VVF (A, B, C, and F in crossed polarized light view, D and E in plane-polarized light view). A) Olivine, clinopyroxene-basaltic lava flow from the BLF showing twinned clinopyroxene (Cpx) and olivine (Ol) phenocrysts. B) Quartz (Qz) xenocryst with clinopyroxene (Cpx) rim from a mafic dyke sample. C) ULF lava showing plagioclase (Plg) and fresh olivine (Ol) phenocrysts. D) Amphibole (Amp) phenocrysts with green-brownish pleochroism and opaque mineral resorption rims from an andesitic lava of the ULF sequence. E) Vitrophyre sample showing plagioclase (Plg), clinopyroxene (Cpx), and orthopyroxene (Opx) phenocrysts within a fresh vitreous groundmass with fluidal texture. F) Rhyolitic intrusive showing fresh plagioclase (Plg) and quartz (Qz) phenocrysts within a fine-grained quartz and feldspar-rich groundmass.

compared to the calc-alkaline signature of the BLF rocks (FeO_t/MgO : 1.57–2.7 for the BLF, 1.51–2.5 for the ULF, and 22.9 for the RI) (fig. 5C).

As SiO_2 increase, Al_2O_3 , FeO_t , TiO_2 , MgO , and MnO contents decrease in the VVF sequence (Supplementary fig. S1A, B, C, D, and E). Na_2O positively correlates with silica content, showing a decrease from BLF to ULF rocks. The RI sample has a slightly lower Na_2O content compared to the more evolved BLF samples (Supplementary fig. S1G). A slight deflection in P_2O_5 is observed at ~55 wt. % SiO_2 along BLF and ULF trends (Supplementary fig. S1H). Both BLF and ULF rocks show decreasing Sc and increasing Zr values with

decreasing MgO. However, the ULF samples are enriched in Sc and depleted in Zr relative to the BLF rocks (Supplementary fig. S2A and B). The BLF and ULF rocks partially exhibit decreasing Nb and increasing Ti values with increasing MgO contents (Supplementary fig. S2C and D).

Primitive mantle-normalized multielement plots for the BLF and ULF rocks are quite similar but display some relevant differences (fig. 6A and B). The BLF samples show a pronounced enrichment in LILE (large-ion lithophile elements) relative to the HFSE (high field-strength elements) (fig. 6A). They also present positive anomalies in Rb relative to Cs and Ba, in U relative to Nb, and in K relative to Ta and

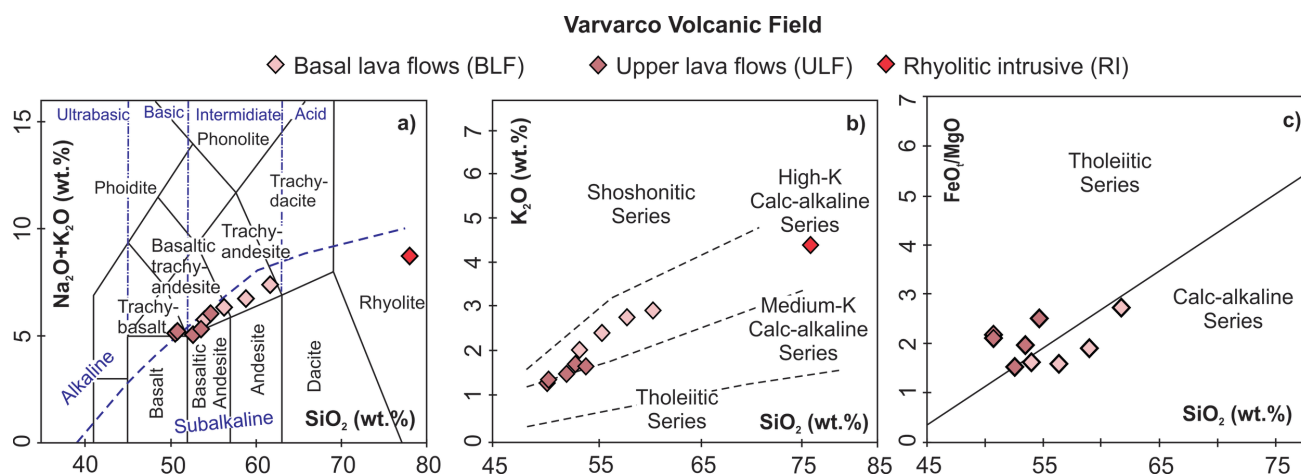


Figure 5. A) Total alkali vs. SiO_2 classification diagram from Le Maitre (2002) for the studied VVF rocks. The alkaline/subalkaline division is according to Irvine and Baragar (1971). B) K_2O vs. SiO_2 diagram (Le Maitre, 2002). C) FeO_t/MgO vs. SiO_2 according to Miyashiro (1974) for the ULF and BLF rocks. The RI sample falls outside the diagram due to its high FeO_t/MgO ratio over 22.

La, along with negative spikes for Nb, Ta, and Ti (fig. 6A). In contrast, the ULF samples show a less pronounced enrichment in LILE compared to HFSE than the BLF rocks (fig. 6B). Concentrations of Rb, Ba, Th, and U in the ULF rocks are lower than those in the BLF rocks. The Nb, Ta, and Ti troughs in the ULF lavas are also less notable than those in the BLF rocks (fig. 6B). On the other hand, the RI sample shows more pronounced troughs at Ba, Sr, and Ti elements than the rest of the VVF sequence, along with positive spikes at U and K elements (figs. 6C).

The BLF rocks show enrichment in LREE relative to HREE, displaying more fractionated REE patterns than the ULF rocks ($(\text{La}/\text{Yb})_N = 9.6\text{--}11.6$ (BLF) vs. $7.0\text{--}8.5$ (ULF), where the subscript N indicates normalization using chondrite abundances from Sun and McDonough (1989)). The RI sample shows a flat HREE pattern consistent with a lower $(\text{La}/\text{Yb})_N$ ratio of 6.5. It also displays a strong trough in Eu, with a $\text{Eu}/\text{Eu}^* = 0.21$ ($\text{Eu}/\text{Eu}^* = \text{Eu}_N/\sqrt{(\text{Sm}_N \cdot \text{Gd}_N)}$). In contrast, both BLF ($\text{Eu}/\text{Eu}^* = 0.73\text{--}0.85$) and ULF ($\text{Eu}/\text{Eu}^* = 0.84\text{--}0.92$) show slight to moderate troughs in this element.

The BLF rocks have La/Ta values ranging from 41.3 to 50.4, whereas the ULF rocks exhibit ratios between 44.2 and 68.7, which are consistent with an arc-like signature for both groups (fig. 6D). When considering their Ba/Ta (BLF: 737–893; ULF: 734–1175) vs. La/Ta ratios, the compositions of both BLF and ULF rocks are similar to the present-day volcanic arc at the studied latitudes (fig. 6E).

4.3. Whole rock Sr-Nd-Pb isotope data

Sr, Nd, and Pb isotopic data are presented for the BLF, ULF, and RI rocks of the Varvarco Volcanic Field (fig. 7) (Supplementary Table S3). Compiled samples from the Plio-Pleistocene volcanism located in the present-day volcanic arc, the western retroarc (WR), and the northern and southern eastern retroarc (ER) at the Southern Central Andes ($34\text{--}38^\circ\text{S}$) are also included for later discussion (figs. 1 and 7).

The VVF rocks show a relatively uniform Sr and Nd isotope composition, especially for the BLF ($0.70392\text{--}0.70415$; $0.51272\text{--}0.512805$) and the ULF ($0.70407\text{--}0.704129$; $0.512723\text{--}0.512731$) samples (fig. 7A). The RI sample has slightly higher $^{87}\text{Sr}/^{86}\text{Sr}$ (0.705543) and lower $^{143}\text{Nd}/^{144}\text{Nd}$ (0.512674) ratios, plotting near the pelagic sediment compositional field (SED) (fig. 7A). The general isotopic compositions of the VVF magmatic rocks differ significantly from those of the local basement rocks of the Choiyoi Group (CHOI).

Pb isotopic ratios also show a striking similarity between the BLF and ULF rocks, while the RI sample is characterized by slightly more radiogenic values, plotting near the western retroarc rocks and the trench sediments compositional field (SED) (BLF-ULF: $18.58\text{--}18.60$, $15.58\text{--}15.59$, and $38.40\text{--}38.45$ vs. RI: 18.65 , 15.60 and 38.52) (fig. 7B and C). The VVF rocks plot close to other districts of the western retroarc and roughly between the eastern retroarc rocks and those of the present-day arc of the Transitional Southern Volcanic Zone (TSVZ) (fig. 7B and C).

4.4. Geochronology

U/Pb zircon dating was carried out on a vitreous tuff (CV34) from the thick pyroclastic level beneath the BLF deposits of the VVF (figs. 2, 8A, 8B, and 8C). Analysis of 88 zircons yielded similar ages that overlap within error, suggesting a common source. The mean age obtained was $2.369 \pm 0.044/0.086$ Ma, based on selected data according to their proximity to the Concordia line (fig. 8D and E). A small number of zircons ($n = 4$) show ages ranging from 304 to 297 Ma (see figs. A and E in Supplementary Table S4), which are interpreted to be inherited from the Late Carboniferous–Early Permian pre-Choiyoi magmatic products that crop out south of the studied area (Sato et al., 2015). Thus, the result presented in this work indicates an Early Pleistocene age for the dated vitreous tuff sample found in the basal levels of the Varvarco Volcanic Field.

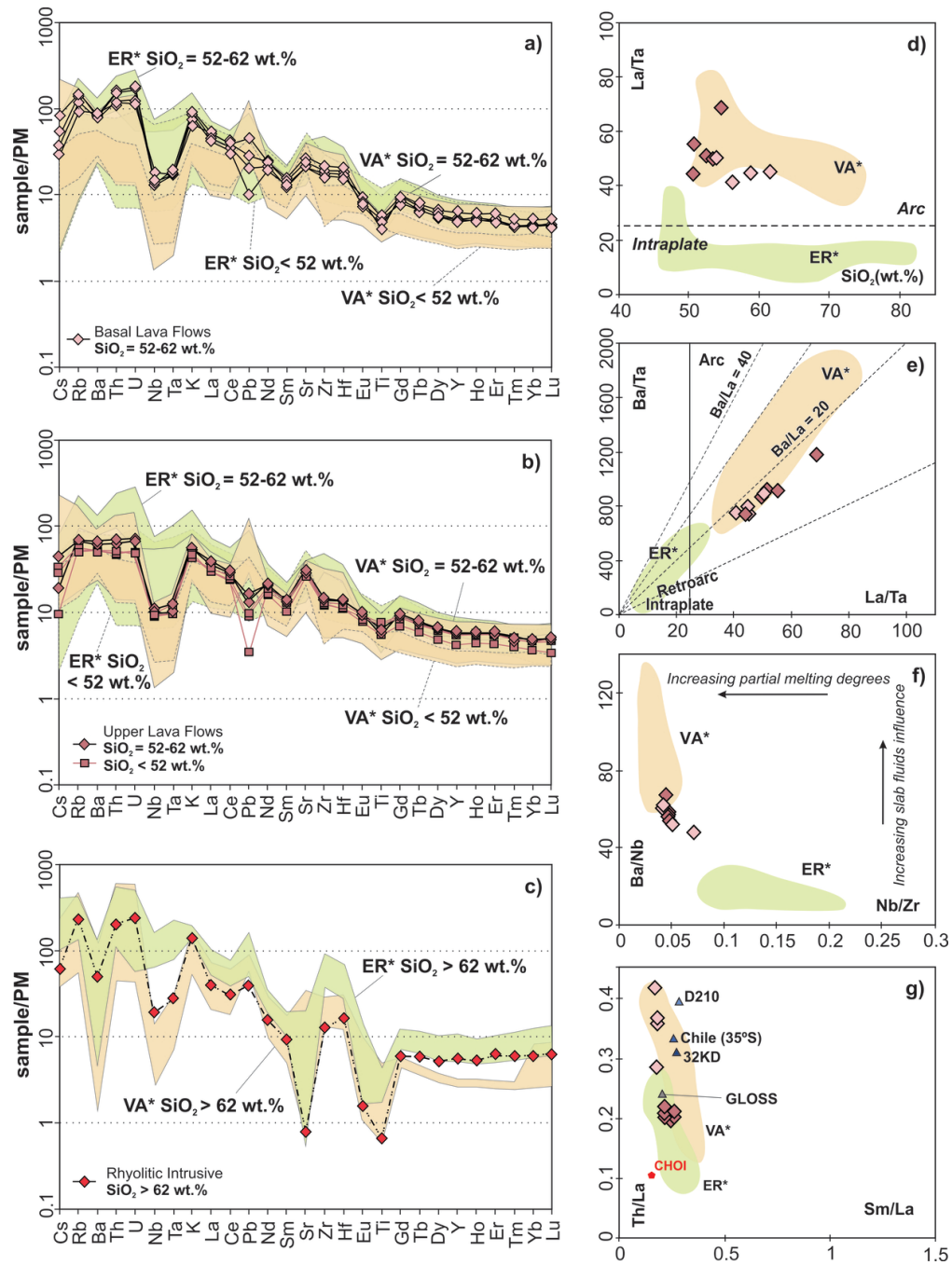


Figure 6. A), B), and C) Primitive mantle-normalized diagrams for the BLF, ULF, and the RI rocks, respectively. Primitive mantle normalized values are from Sun and McDonough (1989). D) La/Ta vs. SiO_2 (wt.%) for the studied VVF rocks; arc and intraplate compositional fields are from Kay et al. (1991) and Kay, Mancilla et al. (2006). E) Ba/Ta vs. La/Ta diagram for the VVF rocks; division lines and compositional fields are from Kay et al. (1991) and Kay, Burns et al. (2006). F) Ba/Nb vs. Nb/Zr for the VVF rocks, with arrows indicating trends for increasing partial melting degrees and increasing slab fluids input (Hickey et al., 1986; Kay et al., 2013). G) Th/La vs. Sm/La diagram (Plank, 2005; Wieser et al., 2019) shows the BLF and ULF rocks and trench sediments data (32KD, Chile 35°S and D210) from Lucassen et al. (2010), Plank (2014), and Jacques et al. (2013). Data for GLOSS (Global Subducting Sediments; Plank, 2014) and for Choiyoi magmatism (CHOI; Gómez et al., 2015; Iannelli et al., 2020) are also included. The green field is for the Southern Central Andes eastern retroarc rocks (ER) magmatism at 35–36°S (Germa et al., 2010; Søager et al., 2013) while the orange field is for the Southern Central Andes rocks of the present-day active volcanic arc (VA) at 35–36°S (Costa & Singer, 2002; Ferguson et al., 1992; Hickey et al., 1986; Jacques et al., 2013; Tormey et al., 1991; Wehrmann et al., 2014). Diagrams E, F, G, and H only include basic to intermediate samples.

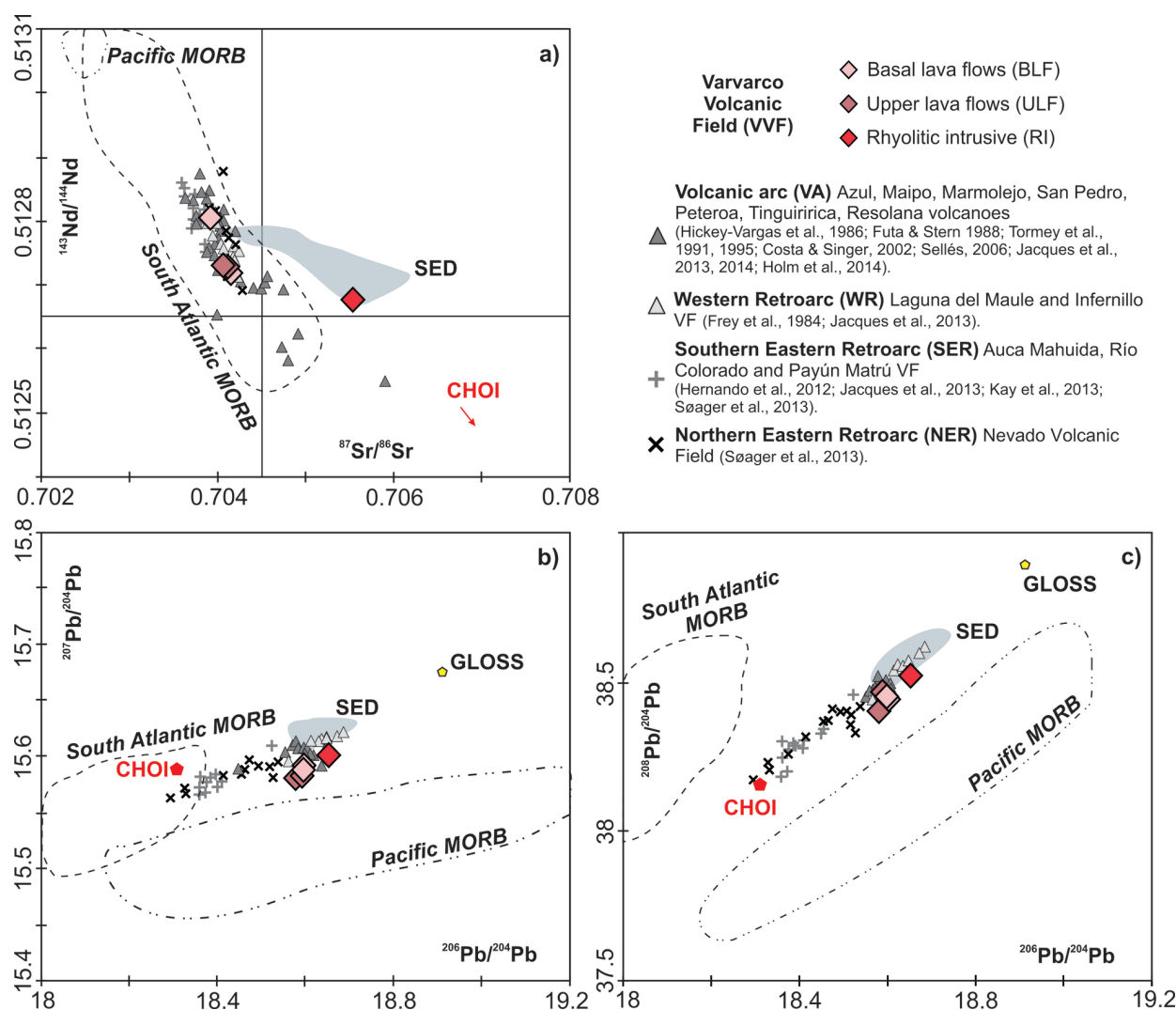


Figure 7. A) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the studied VVF rocks. B) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and C) $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ ratios for the studied VVF rocks. Data for the fields of South Atlantic MORB and Pacific MORB at latitudes between 36° and 50°S are from PetDB (<http://www.earthchem.org/petdb>). SED corresponds to the Pacific pelagic sediments at 36°S (Lucassen et al., 2010) and GLOSS (Plank, 2014) is the average composition for the Global Subducting Sediments. CHOI represents the local basement rocks of the Choiyoi Group (Gómez et al., 2015; Iannelli et al., 2020).

5. DISCUSSION

5.1. Geochemical Evolution of Varvarco Volcanic Field

VVF magmatism is primarily characterized by basaltic to andesitic lava flows, which are divided into the BLF and ULF groups, each with distinctive geochemical patterns. Both groups are intruded by rhyolitic intrusives (RI) (figs. 2 and 5). The U/Pb age of 2.36 Ma obtained from a basal vitreous tuff level of the VVF sequence indicates that this magmatism began during Early Pleistocene times (fig. 8).

The Harker diagrams suggest that the geochemical behavior of both BLF and ULF rocks is explained by variable degrees of fractional crystallization, with both BLF and ULF magmas being part of a cogenetic magmatic suite (Supplementary fig. S1). The negative correlation observed between Al_2O_3 , MgO , $\text{FeO}_{(\text{t})}$, and TiO_2 with silica content in-

dicates fractionation of olivine, clinopyroxene, plagioclase, and titanomagnetite/ilmenite. In contrast, the inflections in Na_2O and P_2O_5 suggest fractionation of alkali feldspar and apatite, respectively, for both groups (Supplementary fig. S1). ULF lavas have higher Sc and lower Zr values compared to BLF rocks, indicating less evolved magmatic composition for ULF rocks, which is consistent with their higher MgO and lower SiO_2 contents (Supplementary figs. S2A and S2B). The olivine, clinopyroxene, and titanomagnetite fractional assemblage explains the increasing Nb and decreasing Ti values observed from ULF to BLF rocks (Supplementary figs. S2C and S2D).

BLF and ULF rocks exhibit similar patterns of trace element distribution, which supports the proposal of a common magmatic source (fig. 6A and B). BLF rocks are slightly more enriched in incompatible elements than the ULF due to their more evolved nature (fig. 6A and B). Both BLF and ULF lavas display arc-like trace-element signatures, such

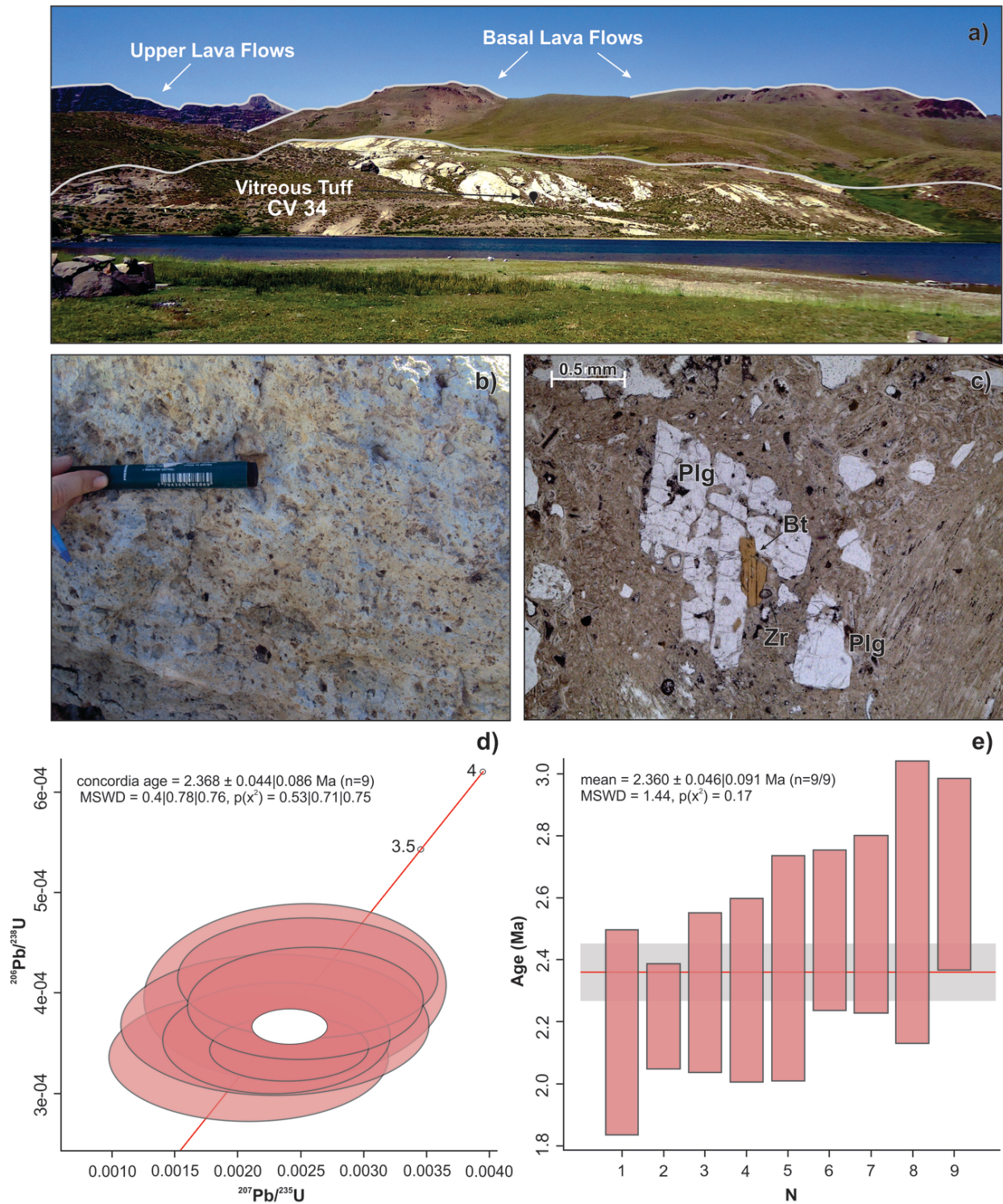


Figure 8. A) Outcrop of the vitreous tuff deposits near the Varvarco Tapia Lake, where the dated sample CV34 (black diamond) was collected. B) Close-up field photograph of the vitreous tuff deposit. C) Plane polarized light view photomicrograph of the dated sample CV34 showing plagioclase (Plg), biotite (Bt), and zircon (Zr) crystal fragments within a vitreous matrix. D) $^{206}\text{Pb}/^{238}\text{U}$ vs. $^{207}\text{Pb}/^{235}\text{U}$ diagram showing the concordia age. E) Weighted average diagram for the dated sample CV34 using data deviating less than 10% from the concordia line. The diagrams in figures 8D and 8E are made using only results with discordance of less than 10 % (n = number of data; MSWD = mean square weighted deviation).

as low Nb and Ta, and high relative U and Th concentrations (Kay et al., 1991). In contrast, the RI sample shows a different pattern with pronounced negative troughs at P, Ti, and Eu, indicating apatite, titanomagnetite, and plagioclase feldspar fractionation, respectively (fig. 6C).

Arc-like signatures in volcanic rocks are characterized by high LILE/HFSE and LREE/HFSE ratios, such as Ba/Ta, Ba/La, and La/Ta (Kay et al., 1991). Since these ratios are assumed to be unaffected by fractional crystallization in the primitive and intermediate magmas (Supplementary figs. S2E, S2F, S2G, S2H), they are commonly used as proxies for slab fluid influence and are indicative of a subduction zone signature (Gill, 1981; Kay et al., 1991, 2013). Measured Ba/Nb and Ba/La ratios in BLF rocks indicate an arc-like geochemical signature, although these ratios are slightly lower than those of the present-day volcanic front at the studied latitude in the TSVZ (fig. 6E). ULF lavas have a similar arc-like geochemical behavior but show slightly lower Ba/Ta and Ba/La ratios than BLF rocks (fig. 6E). Similarly, Ba/Nb ratios indicate that both BLF (Ba/Nb: 61.5–47.3) and ULF (Ba/Nb: 67.1–53.5) rocks have a slab fluid signal (fig. 6F). In particular, both BLF and ULF show a weaker but persistent influence of slab-fluids compared to the compositionally basic to intermediate contemporaneous rocks of the present-day volcanic arc, which display higher La/Ta and Ba/Ta ratios (fig. 6D, E, and F). This is consistent with the western retroarc position of the VVF sequence, which is located further away from the trench than the active volcanic arc (fig. 1).

Th/La ratio can serve as a potential indicator of crustal contamination and input of melted subducted sediments into the mantle source, as this ratio is not significantly affected by fractional crystallization or partial melting in basic to intermediate volcanic rocks (Kay et al., 2013; Plank, 2005). Increasing Th/La values, with nearly constant Sm/La ratios, might indicate a sediment-derived contribution to the mantle source during the evolution of the VVF magmatism (fig. 6G). In this context, the BLF rocks show a slightly similar composition (Th/La: 0.29–0.42) to the trench sediment samples at the studied latitudes (32KD, D210) (Jacques et al., 2013; Lucassen et al., 2010), and to the average trench sediment composition at 35°S (Th: 5.08; Th/La: 0.33) (Plank, 2014) (fig. 6G). However, ULF lavas have lower Th contents (Th_{BLF}: 10.1–13.3 vs. Th_{ULF}: 4.1–5.9) and lower Th/La ratios (0.19–0.21) compared to BLF rocks. The higher Th/La ratio in BLF rocks relative to ULF rocks might be attributed to a sediment-like contribution from pelagic sediment in the trench. Alternatively, assimilation of a metasedimentary crust during magma ascent could also explain the observed Th/La ratios (fig. 6G). In the case of the highly evolved RI sample, fractional crystallization may account for its high Th/La ratio (0.64).

BLF and ULF rocks display similar $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios, indicating a common magmatic source for both groups. Their $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (0.70392–0.70415 and 0.512723–0.512805, respectively) fall within the mantle array, and are similar to ratios observed in coterminous main arc, western retroarc, and eastern retroarc volcanic

rocks (fig. 7A). However, Pb isotopes indicate that BLF and ULF are isotopically more similar to western retroarc and main arc magmatic units, while differing from the eastern retroarc rocks (fig. 7B and C). In contrast, the rhyolitic sample (RI) exhibits higher Sr, lower Nd, and higher Pb isotopic ratios compared to BLF and ULF lavas, which might suggest crustal contamination. However, since its $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are similar to the SED field (Pacific pelagic sediments at 36°S, Lucassen et al., 2010), trench sediment assimilation cannot be excluded for this latest and more evolved magmatic stage of the VVF magmatism.

The geochemical evolution of BLF and ULF magmas is primarily controlled by fractional crystallization processes (FC). We use the FC-AFC-FCA (Fractional Crystallization - Assimilation and Fractional Crystallization - Fractional Crystallization and Assimilation) model of Ersoy and Helvacı (2010) to quantify the influence of FC on VVF magmatic evolution. Model results suggest that the composition of the BLF and ULF rocks is linked through the FC process, displaying a continuous trend when considering different incompatible elements (fig. 9). However, BLF samples show a slight deviation from the FC trend. This might suggest that secondary processes, such as trench sediment addition or crustal contamination with a metasedimentary crust during magma ascent, could be influencing the magmatic evolution of BLF lavas (fig. 9). The observed decrease in Th/La from BLF to ULF rocks at a similar $^{87}\text{Sr}/^{86}\text{Sr}$ range may result from either a reduction in sediment input into the mantle source over time or due to lesser degrees of contamination with a metasedimentary crust with similar isotopic ratios (fig. 7A) (Dungan & Davidson, 2004; Hickey-Vargas et al., 2016). Jacques et al. (2013) and Wehrmann et al. (2014) previously proposed that the TSVZ at the studied latitudes (figs. 6G and 7A) was influenced by sediment-derived fluids in the mantle wedge. However, the assimilation of a metasedimentary crust can also contribute to the sediment-like signal seen in the BLF samples, so this possibility cannot be completely discarded.

Geochemical signatures of older BLF compared to younger ULF lavas indicate a progressive decrease in the degree of fractional crystallization from a common magmatic source with a similar MORB-type composition as the coeval present-day arc. This geochemical trend is accompanied by a decrease in sediment-like input or decreasing degrees of metasedimentary crustal contamination. However, fractional crystallization (FC) is the primary mechanism for explaining the evolution from BLF to ULF rocks. The presence of a less evolved magma composition in the younger lava pulses aligns with the development of a widespread extensional regime during the progressive steepening of the Nazca plate since Pliocene times. This tectonic setting enabled faster ascent of magmas through the crust, resulting in a decreased fractional crystallization in the younger ULF lavas, as well as reduced crustal contamination and/or trench sediment assimilation. The latest rhyolitic pulses (RI) of the VVF are likely associated with the steepening of the Nazca plate, during which ascending of hotter asthenospheric mantle flow would have promoted underplat-

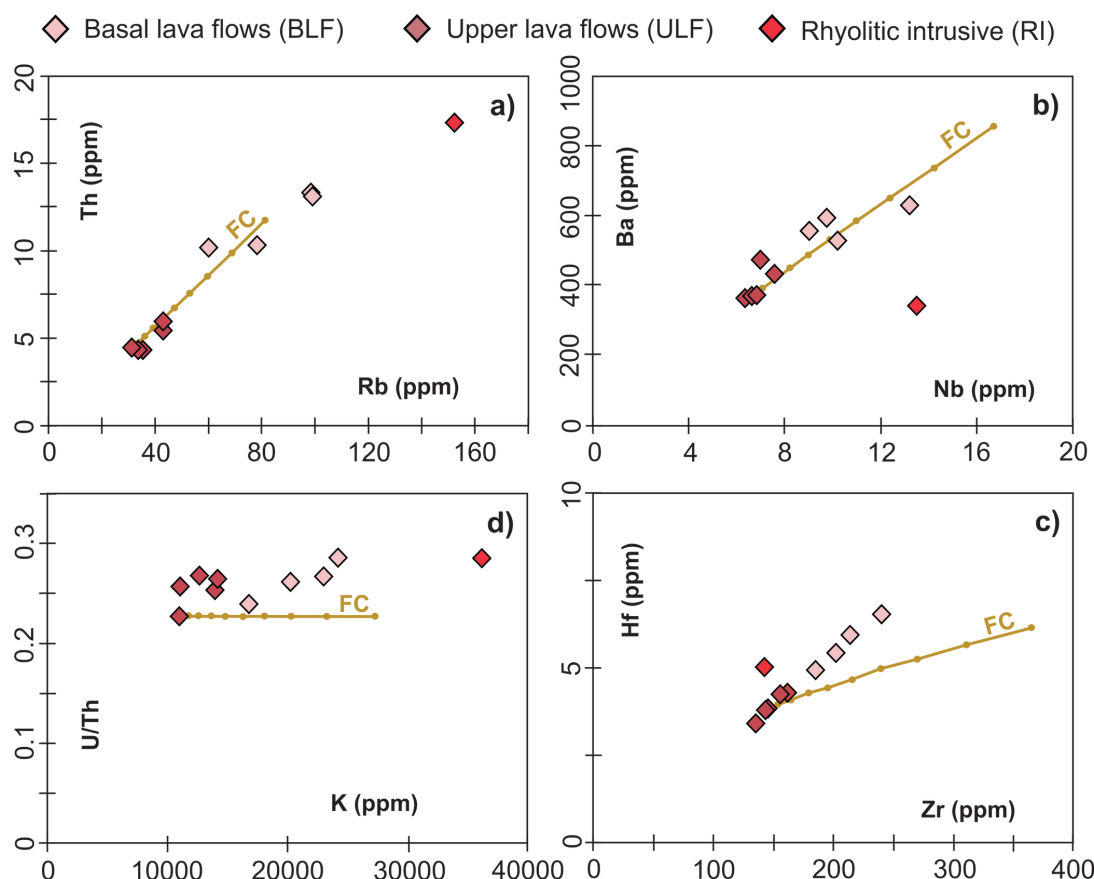


Figure 9. Geochemical modeling obtained using the FC-AFC- FCA modeler of Ersoy and Helvacı (2010). The modeling uses the partition coefficients for basic melt compositions and the sample TDM12 as the starting composition, as it is the least evolved VVF sample. The fractionating assemblage used to model the FC trend is plagioclase (50 %), olivine (20 %), clinopyroxene (15 %), and magnetite (15 %), consistent with the minerals present in samples of the ULF group (Supplementary Table S1). Increments represent the 7% and crystallization ends at 63%.

ing and crustal contamination (Kay, Burns, et al., 2006; Kay et al., 2004).

5.2. Regional Comparison with Pliocene to Pleistocene Magmatism

To fully understand the evolution of the Varvarco Volcanic Field, it is essential to consider the magmatic context in which it developed. Thus, the studied VVF sequence is compared with the contemporaneous Plio-Pleistocene magmatism in the Southern Central Andes (34–38°S) to understand how the particular tectonic context influenced their location and geochemical features. As discussed, Pliocene to Holocene magmatism is divided into three main groups: the main volcanic arc in the Andean axis, the western retroarc (WR), and the eastern retroarc (ER); the last one is further divided into northern (NER) and southern eastern retroarc (SER) magmatism (fig. 1). This division is mainly based on the spatial distribution of these magmatic groups relative to their distance from the trench, following previous studies in the area (Hickey-Vargas et al., 2016; Holm et al., 2016; Jacques et al., 2013; Muñoz Bravo et al., 1989; Søger et al., 2015).

In a longitudinal comparison at ~35–36°S, both the present-day volcanic arc and the studied VVF rocks display a similar arc-like geochemical signature, being the VVF sequence slightly enriched in incompatible elements (fig. 6A and B). In contrast, the VVF rocks are slightly less enriched in incompatible elements when compared to the southern eastern retroarc (SER). Particularly, the SER volcanism is enriched in Nb and Ta relative to the VVF rocks, suggesting a contribution from an OIB-like source in its genesis (Søger et al., 2013) (fig. 6A and B). The VVF rocks are more enriched in REE elements than the present-day volcanic arc rocks at 35–36°S, but less enriched than the SER rocks. All of them show higher contents of LREE relative to HREE. VVF rocks display an arc-like signature, with similar La/Ta and slightly lower Ba/Ta ratios than the basic to intermediate present-day volcanic arc rocks (fig. 6D, E, and F). On the other hand, the VVF lavas have higher La/Ta, Ba/Ta, and Ba/Nb ratios compared to the basic to intermediate SER volcanism, suggesting a stronger influence of slab fluids (fig. 6D, E, and F). Specifically, the rhyolitic intrusion (RI) displays positive abundance anomalies in Rb and Th, similar to the SER acidic rocks, due to fractionation of alkali feldspars (fig. 6C). The RI sample has higher concentrations of Ta and Nb, and similar contents of Zr, Hf, and Sm than

the more evolved rocks of the present-day volcanic arc, but lower than the acidic SER rocks (fig. 6C). This suggests a closer geochemical affinity with the present-day volcanic arc rocks. Although the RI presents more pronounced negative anomalies in Sr and Ti than those observed in the present-day arc rocks, both show a similar REE pattern (fig. 6C).

Overall, the VVF shows intermediate geochemical features between the southern eastern retroarc (SER) and the volcanic arc magmatism at 35–36°S, which can be explained by its position relative to the trench (fig. 1). The present-day arc volcanoes at 35–36°S display the strongest arc-like signature, while the SER volcanism shows OIB-type intraplate features, probably associated with the asthenospheric plume-like structure beneath this area (figs. 6 and 9) (Burd et al., 2014; Germa et al., 2010; Søger et al., 2013). This intraplate-like signature is not recognized in the VVF rocks whose geochemical features are more akin to the present-day arc.

A comparison of the geochemistry of Plio-Pleistocene magmas between 34 and 38°S, clearly reveals a trend from volcanic arc rocks with high Ba/Nb and Ba/La ratios, typical of orogenic andesites, towards an E-MORB composition in the northern eastern retroarc (NER), and in the southern eastern retroarc (SER) rocks with lower Ba/La and higher Ba/Nb ratios (fig. 10A). The Ba/La vs. Nb/La ratios of studied VVF rocks are consistent with present-day arc magmatism represented by the Orogenic Andesites field, although they show lower Ba/La ratios, similar to the contemporaneous western retroarc (WR) rocks (fig. 10A). The transitional behavior between the SER, NER, and present-day volcanic arc magmatism is more evident when considering Th/Hf and Ta/Hf ratios (fig. 10B). The SER rocks exhibit the highest Ta/Hf and lowest Th/Hf ratios, indicative of an intraplate-like source. In contrast, the NER magmatism displays a transitional composition between SER and WR rocks. Specifically, there is a decrease in Ta/Hf and an increase in Th/Hf ratios from the northern eastern retroarc (NER) towards the western retroarc (WR) rocks, including the studied VVF sequence (Ta/Hf: 0.1–0.2; Th/Hf: 1.1–3.4). The present-day volcanic arc rocks have Ta/Hf ratios lower than 0.2, consistent with an arc-like geochemical signature (fig. 10B). The enrichment signature seen in the southern eastern (SER) region is also evident in the Nb/Y vs. Zr/Y diagram, where the SER volcanism shows a tendency towards the plume source field with an OIB-like composition (fig. 10C) (Kay, Burns, et al., 2006; Kay & Copeland, 2006; Søger et al., 2013, 2015). In contrast, the WR rocks present a geochemical behavior similar to the volcanic arc, consistent with the arc-like compositional field, while the studied VVF magmatism shows transitional features between both groups (fig. 10C). Additionally, the RI sample plots within the volcanic arc granites field of the discrimination plot for evolved rock compositions, similar to the evolved rocks from the main arc and the WR at the Transitional Southern Volcanic Zone (TSVZ) (fig. 10D). Instead, the evolved rocks from the SER are instead richer in Y+Nb, being more akin to the within-plate granites compositional field (fig. 10D) (Pearce et al., 1984).

Increasing arc-like signatures are observed from the eastern retroarc (ER) belt to the main volcanic arc axis in the TSVZ between 34 and 38°S, consistent with the previous longitudinal comparison at the studied latitudinal range (35–36°S). This geochemical behavior is best explained by the distance of each N-S magmatic belt to the trench. Specifically, eastern retroarc (ER) magmatism records compositional differences from south to north, showing an intraplate-like geochemical signature in the southern eastern retroarc (SER) (36–38°S), which decreases and disappears to the northern eastern retroarc (NER) (34–36°S) (Espanon et al., 2016; Holm et al., 2014; May et al., 2018; Søger et al., 2013). This compositional variation might be associated with the presence of the asthenospheric anomaly at ~37–38°S (Burd et al., 2014; Rojas Vera et al., 2014).

Furthermore, Plio-Pleistocene Loncopué Trough magmatism is included for comparison (fig. 10) as it developed in the western retroarc (WR) at the studied latitudinal range and particularly above the Nazca plate tearing at 38°S (fig. 1). The southernmost Loncopué basaltic and rhyolitic rocks show an intraplate-like signature similar to the southern eastern retroarc (SER) rocks. This is evidenced by their lower Ba/La, higher Nb/La, higher Ta/Hf, and higher Nb/Y compared to the present-day volcanic arc rocks and the rest of the WR sequences, including the studied VVF rocks (fig. 10A, B, and C). This signature suggests that the Loncopué Trough magmatism may be influenced by the upwelling of the asthenospheric anomaly in the area where the Nazca plate tearing developed. However, the plume-like influence did not affect the studied VVF magmatism as it is located northwards.

In summary, the geochemical evolution of the Plio-Pleistocene magmatism between 34° and 38°S shows that an intraplate-like geochemical signature dominates in the southern eastern retroarc (SER), while magmatism in the northern eastern retroarc (NER) presents less pronounced intraplate-like features. In contrast, the western retroarc (WR) rocks, including the studied Varvarco Volcanic Field, show no intraplate-like influence, except for the southernmost Loncopué rocks (Rojas Vera et al., 2014; Varekamp et al., 2010) and other eruptive centers such as the Palao and Tromen volcanos in the southeastern extreme of the Las Loicas Trough (Pallares et al., 2019; Traun et al., 2024) (fig. 1). This pattern is best explained by their proximity to the surface projection of the tearing in the Nazca plate and the plume-like asthenospheric anomaly at ~38°S, which results in the direct influence of the upwelling alkaline magmas. Instead, the present-day volcanic arc along the main Andean axis shows the strongest slab-fluids influence due to its closest position to the trench.

5.3. Tectonomagmatic Evolution of the Plio-Pleistocene Magmatism

Since Pliocene times, the Southern Central Andes between 34 and 38°S have been characterized by extensional conditions related to the steepening of the Nazca plate, after the Payenia shallow subduction period between 16 and 3.5 Ma (fig. 11A) (Dyhr et al., 2013; Kay, Mancilla, et al., 2006;

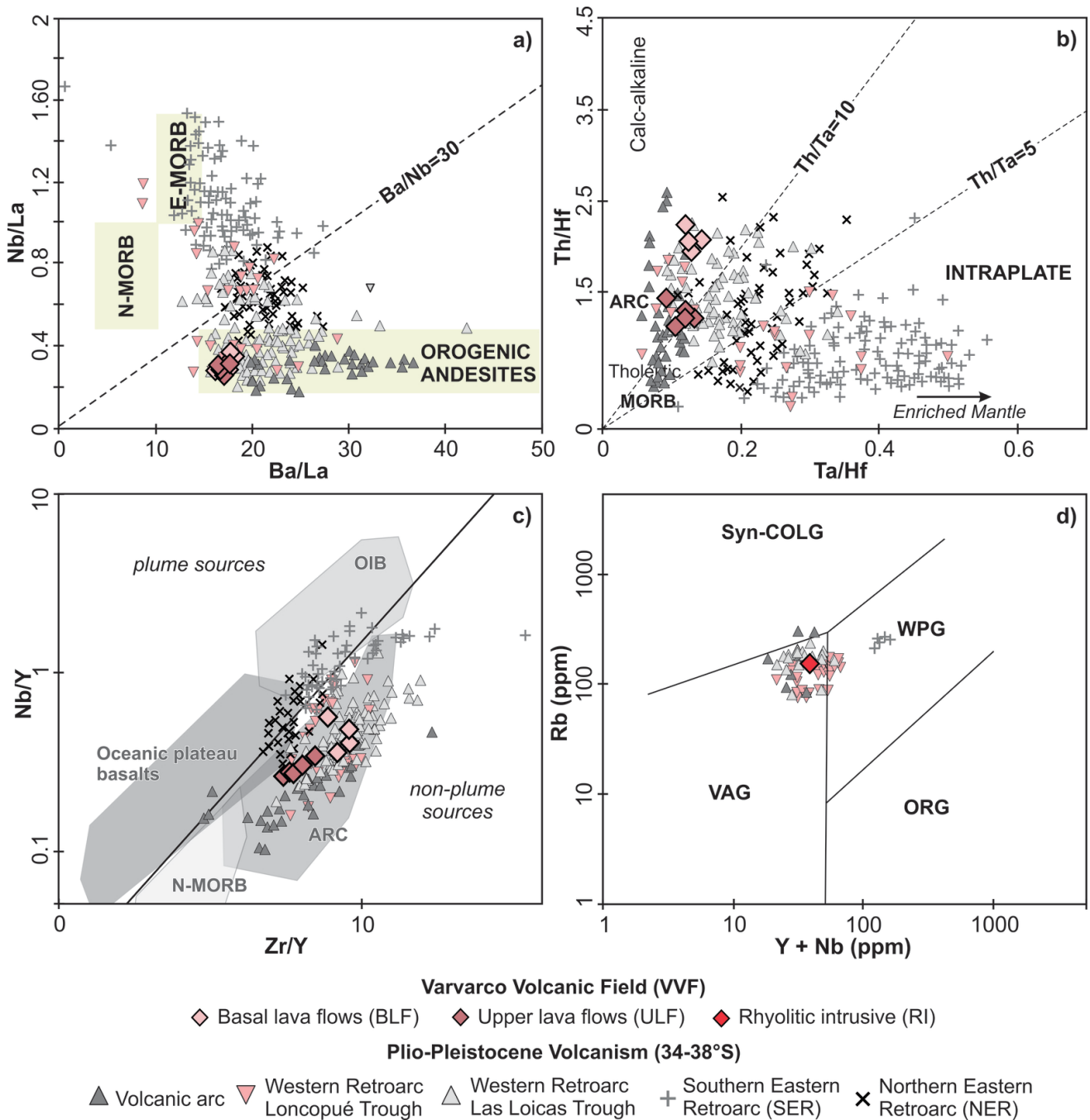


Figure 10. Regional comparison between studied Varvarco Volcanic Field samples and published geochemical data from the Pliocene to Holocene main arc, western retroarc (WR), and eastern retroarc (ER) volcanic rocks of the Southern Central Andes (34–38°S). A) Nb/La vs. Ba/La diagram showing the fields for Orogenic Andesites, N-MORB, and E-MORB compositions (Aragón et al., 2011). B) Th/Hf vs. Ta/Hf diagram considering typical Arc, MORB, and Intraplate compositions (Kay, Burns, et al., 2006). C) Nb/Y vs. Zr/Y diagram. The compositional fields for N-MORB, Oceanic plateau basalts, Arc, and OIB are plotted following Condie (2005) and Fitton et al. (1997). D) Rb (ppm) vs. Y+Nb (ppm) discrimination diagram for Southern Central Andes acidic rocks after Pearce et al. (1984); syn-COLG = syn-collisional granites, WPG = within-plate granites, VAG = volcanic-arc granites and ORG = ocean-ridge granites. For diagrams A), B), and C) only basic to intermediate volcanic rocks are plotted, while diagram D) only shows acidic volcanic rocks. Geochemical data of the main arc, western retroarc, and eastern retroarc belts is taken from Frey et al. (1984), Hickey et al. (1986), Futa and Stern (1988), Tormey et al. (1991, 1995), Ferguson et al. (1992), Miranda et al. (2006), Hildreth et al. (1999), Costa and Singer (2002), Germa et al. (2010), Sruoga et al. (2012, 2016), Jacques et al. (2013), Kay et al. (2013), Søager et al. (2013), Rojas Vera et al. (2014), Wehrmann et al. (2014), Pallares et al. (2016, 2019).

Litvak et al., 2015, 2019; Ramos et al., 2014). During this period, a WNW-ESE tearing developed in the Nazca plate at $\sim 38^\circ\text{S}$ (Pesicek et al., 2012). Slab steepening began in the southern eastern retroarc region (SER) of the Payenia eastern retroarc and progressively extended to the northern eastern retroarc (NER) area (Gudnason et al., 2012) (figs. 1 and 11B). The steepening, along with the consequent tearing, triggered the upwelling of a hotter asthenospheric mantle, which influenced the mantle nearby the southern eastern retroarc (SER) area at $\sim 37\text{--}38^\circ\text{S}$ (Astort et al., 2019; Burd et al., 2014; Pesicek et al., 2012; Rojas Vera et al., 2014). Thus, only the SER volcanism, together with the southernmost coeval magmatic units of the western retroarc (WR), such as Las Loicas (Tromen and Palao volcanoes) and Loncopué Troughs, show an enriched geochemical signature and OIB-type magmatic sources associated with the upwelling of the plume-like asthenospheric structure (Germa et al., 2010; Hernando et al., 2012; Holm et al., 2016; Rojas Vera et al., 2014; S  ager et al., 2013; Traun et al., 2024; Varekamp et al., 2010). As the steepening progressed, arc-related magmatism migrated westwards, forming parallel N-S magmatic belts, ending with the establishment of the present-day volcanic arc along the main Andean axis (fig. 1) (Dungan et al., 2001; Hickey-Vargas et al., 2016; Sell  s et al., 2004; Singer et al., 2014; Sruoga et al., 2012).

During the Late Miocene to Early Pliocene, shallowing subduction of Nazca plate was associated with the migration and expansion of arc-related magmas towards the eastern retroarc (ER) area. However, volcanism in the main Andean arc axis continued during the Late Miocene to Early Pliocene, though with a volumetrically minor development (Burns et al., 2006; Kay, Burns, et al., 2006). As steepening of the Nazca plate occurred during the Pliocene, the arc-like influence in the eastern retroarc (ER) decreased and eventually disappeared. In contrast, arc-related magmatic activity became more prominent along the Andean axis, resulting in the formation of extensive rhyolitic calderas and eruptive centers that define the present-day volcanic arc (Litvak et al., 2015; Ramos et al., 2014).

Between the present-day volcanic arc in the Andean axis and the Payenia eastern retroarc (ER), the VVF developed as part of the western retroarc (WR) magmatic belt during Plio-Pleistocene times. The initial magmatic pulse (BLF) of the VVF sequence shows a calc-alkaline composition with an arc-like signature and some evidence of sediment influence and/or crustal assimilation. In contrast, the latest lava pulses (ULF) display a less evolved composition with minimal sedimentary signal, although the arc-like signature remains. This magmatic evolution aligns with the steepening of the Nazca plate and the associated increase in subduction angle, which established an extensional tectonic regime in the upper plate. This tectonic setting allowed the rapid ascent of magmas from the mantle source through the crust, leading to the more primitive geochemical signature observed in the upper lava flows (ULF) of the VVF. In this context, the potential influence of a sediment-like input seen in the initial magmatic pulses of the VVF has also been described in other volcanoes of the Transitional

Southern Volcanic Zone (TSVZ) and linked to the presence of the Mocha Fracture Zone (L  pez-Escobar, Parada, et al., 1995; Sell  s et al., 2004). The Mocha Fracture Zone subduction would have influenced the magmatic evolution in this area, as evidenced by the sediment-like geochemical signature, which may reflect a more hydrated subducted slab. However, the possibility of crustal contamination from a metasedimentary basement cannot be excluded. Subsequently, rhyolitic intrusions (RI) affected the VVF lava flows, potentially linked to crustal melts favored by the underplating of hotter asthenospheric melts at the base of the crust.

From a regional perspective, the geochemical differences observed between the N-S magmatic belts can be attributed to their relative positions to the trench along a W-E transect. Specifically, magmas from the present-day Transitional Southern Volcanic Zone (TSVZ) in the main Andean axis exhibit higher slab-fluids influence, which progressively decrease towards the western retroarc (WR) rocks, and nearly disappears in the eastern retroarc (ER) area. The westward shift of arc-like magmatism, from the eastern retroarc (ER) to the main volcanic arc since the Pliocene clearly explains the varying slab-fluid signal observed between these areas. Additionally, the regional comparison presented in this work provides evidence that the upwelling of the asthenospheric anomaly is mainly present in the southern eastern retroarc (SER) magmas of the Payenia region. However, in the western retroarc (WR), the intraplate-like signature is only identified in the southeastern magmatic products of the Las Loicas (Tromen and Palao volcanoes) and Loncop   Troughs, which are located immediately above the Nazca plate tearing at $\sim 38^\circ\text{S}$.

Variations in the position of arc-related magmatism can be influenced not only by the slab dip (Kay, Burns, et al., 2006), but also by other parameters, such as the convergence rate, variations in the corner flow dynamics, and crustal thickness of the upper plate, which impact the thermal structure of both the slab and the asthenospheric wedge (England & Katz, 2010; Grove et al., 2009; Peacock, 2020). In light of this, the development of Andean magmatism at the studied latitudinal range, between Late Miocene to Pleistocene times, should also be evaluated considering these parameters. Although the causes of the Late Miocene Payenia shallow subduction regime remain under debate, the decreasing convergence rate from 15 cm/yr to 10 cm/yr that began in the Late Early Miocene, (Somoza & Ghidella, 2012), could also have influenced the eastward expansion of the arc-related magmatism. A reduction in convergence rate can promote a decrease in the corner flow, which in turn may alter the thermal structure of the asthenospheric wedge and trigger a migration of the arc-front from the trench towards the east (England & Katz, 2010). However, since Miocene times, the convergence rate has continued to decrease until reaching its present-day velocity of ~ 7 cm/yr at 5 Ma (Somoza & Ghidella, 2012). Therefore, the main control on the thermal structure might be more significantly influenced by an increasing slab dip rather than by the convergence rate, in explaining the position of the arc-

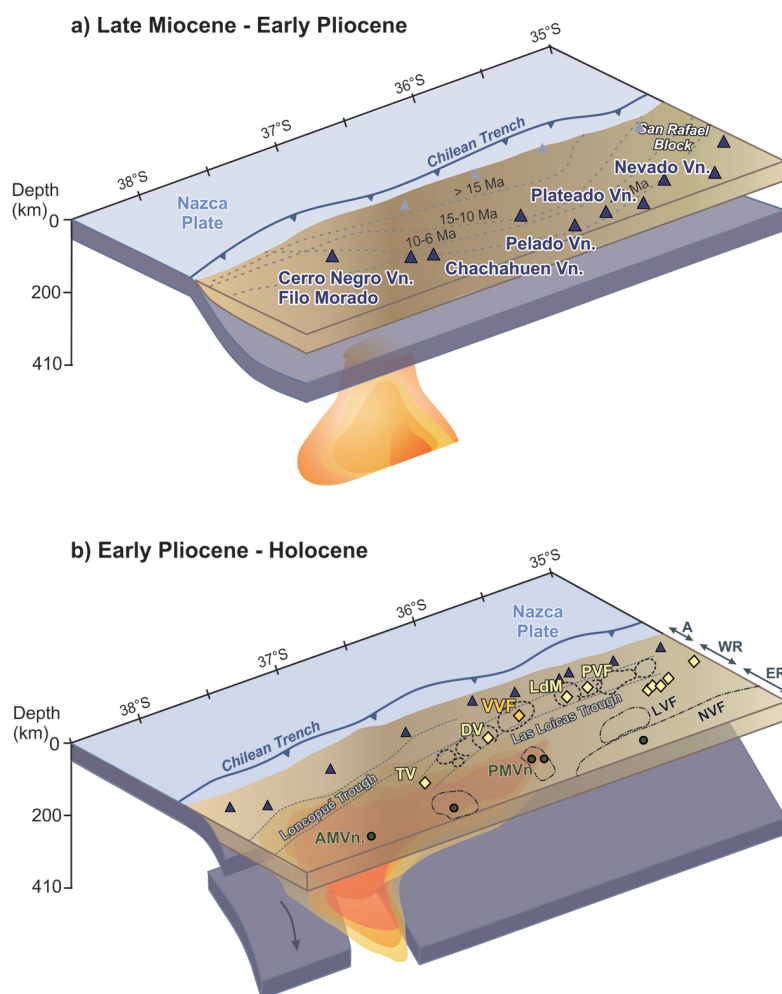


Figure 11. Schematic 3D diagrams showing the evolution of the Andean margin between the Late Miocene to the present. A) During the Late Miocene Payenia shallow subduction regime arc-related magmatism progressively expanded to the east (indicated with dashed lines). B) The steepening of the slab by Early Pliocene times promotes the development of N-S oriented magmatic belts from east to west, together with the upwelling of an asthenospheric plume-like structure that only affected the southern eastern retroarc (ER) magmatism and the western retroarc (WR) magmatism in their southernmost extreme. Based on Folguera et al. (2009), Pesicek et al. (2012), Burd et al. (2014), Litvak et al. (2015), and Gianni et al. (2017). (A: arc, WR: western retroarc, ER: eastern retroarc, AMVn: Auca Mahuida Volcano, PMVn: Payún Matru Volcano, TV: Tromen Volcano, DV: Domuyo Volcano, VVF: Varvarco Volcanic Field, LdM: Laguna del Maule, PVF: Puelche Volcanic Field, LVF: Llanquanelo Volcanic Field, NVF: Nevado Volcanic Field).

related rocks and the westward development of the Plio-Pleistocene N-S magmatic belts (Grove et al., 2009).

Finally, the crustal thickness of the upper plate can also influence the thermal structure of the asthenospheric wedge, thereby affecting the position of the arc. However, at the studied latitudinal range, the geochemical signature of arc-related rocks during the Late Miocene to Pliocene shallow subduction regime shows that they have been equilibrated within a crust of normal thickness, similar to the present-day values (~30 km) (Litvak et al., 2015; Tassara & Echaurren, 2012).

6. CONCLUSIONS

During Plio-Pleistocene times, after the Payenia shallow subduction regime, the subduction angle of the Nazca plate increased, leading to the westward migration of arc-related magmatism from the eastern retroarc (ER) to the present-day arc in the main Andean axis. This tectonic change triggered the emplacement of an N-S striking western retroarc (WR) magmatic belt characterized by calderas and strato-volcanoes, among which is the studied Varvarco Volcanic Field (VVF), one of the largest magmatic fields dating to this time.

The geochemistry of the VVF sequence records the evolution of the Plio-Pleistocene magmatism in a western

retroarc position. It is characterized by a succession of basic to intermediate lava flows, interbedded pyroclastic flows, and rhyolitic intrusives. The initial magmatic pulses Basal Lava Flows (BLF) are calc-alkaline basaltic andesites to andesites with a geochemical signature indicative of minor metasedimentary crustal assimilation and/or contamination with trench sediments, potentially associated with the Mocha Fracture Zone in the subducted plate. The later magmatic pulses Upper Lava Flows (ULF) of the VVF exhibit a less evolved chemical composition, represented by tholeiitic basalts to basaltic andesites, showing reduced sediment-derived contributions and/or crustal assimilation compared to the earliest phases (BLF). The main geochemical differences between BLF and ULF rocks are associated with variable degrees of fractional crystallization from an NMORB-type mantle and, to a lesser extent, with variable sediment or crustal influence. The transition from calc-alkaline to more primitive, tholeiitic magmas is consistent with the progressive steepening of the Nazca plate by the Pliocene, which triggered extension of the upper plate and enabled the rapid ascent of magmas characterized by reduced fractional crystallization. The latest stage of magmatism is characterized by rhyolitic intrusives (RI), whose evolved nature can be associated with the underplating of hotter asthenospheric melt at the base of the crust, a process likely enhanced by the steepening of the Nazca plate.

The VVF sequence shows a consistently arc-like geochemical signature, although less pronounced than the neighboring volcanoes in the main Andean axis. Regionally, the Early Pleistocene VVF magmatism is associated with the contemporaneous volcanism in the western retroarc (WR) zone. This magmatism evolved within an extensional tectonic setting during the steepening of the Nazca plate and the upwelling of a mantle plume-like structure in the eastern retroarc (ER) area, spatially coincident with a slab tearing at 38°S. While this asthenospheric anomaly did not significantly influence the VVF or the northern western retroarc (WR) magmatism, it notably affected the south-

eastern magmatic products, including those in the Las Loicas and Loncopué Troughs. The variable arc-like signatures observed along the present-day volcanic arc, the western retroarc (WR), and the eastern retroarc (ER) magmatism are associated with their respective distances from the trench relative to the main Andean axis, and directly linked to the degree of slab fluids influence and the geometry of the subducting slab.

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Supplementary Information

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SUPPLEMENTARY MATERIALS

Supplementary Information

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