

Geochemistry of Permian to Triassic igneous rocks from northern Chile (28°-30°15'S): Implications on the dynamics of the proto-Andean margin

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ABSTRACT. Permian to Triassic igneous rocks cropping out in the Coastal and Frontal cordilleras in northern Chile between 28°00'S and 30°15'S have long been interpreted to represent products of magmatism related to an extensional tectonic setting, either as the result of crustal anatexis or asthenospheric mantle decompression melting, in a passive continental margin. Eighty-six samples of plutonic (61) and volcanic (25) rocks from this region are characterized petrographically and geochemically. They are Permian to Early Jurassic in age, but the majority of the studied rocks correspond to the Lower to Middle Triassic Chollay Plutonic Complex, the volumetrically most important unit in the area. The rock samples have features typical of magmas derived from flux-induced melting of a depleted mantle such as: broad range of petrographic composition with predominance of intermediate to acid members, highly porphyritic volcanic rocks, magnetite as the Fe-Ti oxide mineral phase, enrichment in LILE over HFSE, marked depletion in Nb, Ta, Ti, and P and moderate to no negative Eu anomalies. Few of the studied rock samples (<10%) have alkaline signature and trace element contents representative of anorogenic magmatism. In this work, we propose that subduction of an oceanic plate beneath the South American continent is responsible for the evolution of the margin from the Permian to Early Jurassic, at the studied latitudes. A preliminary interpretation of the margin architecture of the Andean margin from the Permian to the Triassic would be that the Chanchoquin and Chollay plutonic complexes represent the roots of a magmatic arc developed from the Permian to the Middle or early Late Triassic, whereas the Guanaco Sonso and Pastos Blancos formations would be the shallower parts of such arc. The La Totora Formation and some volumetrically minor Upper Triassic intrusive units represent magmatic products with alkaline signatures, which developed immediately before the establishment of the magmatic arc in the present-day Coastal Cordillera (during the Rhaetian to Early Jurassic).

Keywords: Triassic, Subduction, Pre-andean, Frontal cordillera, Geochemistry.

RESUMEN. **Geoquímica de rocas ígneas Permo-Triásicas del norte de Chile (28°-30°15'S): Implicancias en la dinámica del margen pre-Andino.** Las rocas ígneas del Permo-Triásico que afloran en las cordilleras de la Costa y Frontal en el norte de Chile, entre los 28°00' S y 30°15' S han sido interpretadas históricamente como productos de magmatismo asociados a un ambiente extensional, como el resultado de un proceso de anatexis cortical o bien fusión de manto astenosférico, en un margen pasivo. Se analizaron 86 muestras, de las cuales 61 corresponden a rocas plutónicas y 25 a rocas volcánicas, a las que se les hizo una caracterización petrográfica y geoquímica. Son de edad permica a jurásica inferior, pero la mayoría de las muestras de rocas analizadas corresponden al Complejo Plutónico Chollay, de

edad Triásico Inferior-Medio, siendo la unidad más importante en el área de estudio. Las muestras analizadas tienen características típicas de magmas derivados de fusión de un manto empobrecido como: amplio rango composicional con predominio de los componentes intermedio a ácidos, rocas volcánicas altamente porfídicas, magnetita como fase mineral principal de Fe-Ti, enriquecimiento en elementos LILE sobre HFSE, empobrecimientos en Nb, Ta, Ti y P, y moderada a inexistente anomalía negativa de Eu en las rocas estudiadas; algunas (<10%) tienen signatura alcalina y contenidos de elementos traza representativos de magmatismo anorogénico. En este trabajo, se propone que la subducción de una placa oceánica bajo el continente de Sudamérica es responsable de la evolución del margen entre el Pérmico y el Jurásico Inferior, a las latitudes estudiadas. Una interpretación preliminar de la arquitectura del margen Andino desde el Pérmico al Triásico puede ser que los complejos plutónicos Chanchoquín y Chollay representen las raíces de un arco magmático desarrollado entre el Pérmico y el Triásico Medio a Superior, mientras que las formaciones Guanaco Sonso y Pastos Blancos podrían ser porciones más superficiales de este arco. La Formación La Totora y algunos cuerpos menores de intrusivos del Triásico Superior representan productos con signatures alcalinas, los que se desarrollaron inmediatamente antes del establecimiento del arco magmático en la actual cordillera de la Costa (durante el Raetiano al Jurásico Inferior).

Palabras clave: Triásico, Subducción, Pre-andino, Cordillera frontal, Geoquímica.

1. Introduction

The Permian to Triassic is a controversial period for the southwestern Gondwana margin evolution since it is thought to represent a significant magmatic lull that resulted from lack of subduction after the orogenic collapse following the Permian “San Rafael” orogenic event (Nasi *et al.*, 1990; Mpodozis and Ramos, 1989; Mpodozis and Kay, 1992). The magmatic sources would have changed significantly, decreasing the crustal component, between the Late Permian and the Early Jurassic. This change, which occurred during the Triassic, is explained by some authors as the response to a shift from subduction in a compressive setting to an extensional continental rift-related tectonic setting due to Pangea breakup (Mpodozis and Kay, 1992; Hervé *et al.*, 2014), or as extensional deformation in the overriding plate, in a continuous subduction setting (Vásquez *et al.*, 2011; Poma *et al.*, 2014; Del Rey *et al.*, 2016).

In the Coastal and Frontal cordilleras of north-central Chile (the latter being that part of the Andes along the Chile-Argentina border between 28°20' and 31° S that features uplifted Paleozoic basement blocks), successive Cretaceous to Miocene deformation fronts within the current flat-subduction segment of the Andes have generated both thin- and thick-skinned deformation in a fold-and thrust belt (Moscoso and Mpodozis, 1988; Martínez *et al.*, 2012), exposing large portions of late Paleozoic and early Mesozoic basement between 27°00' and 30°00'S (Ribba *et al.*, 1988; Salazar *et al.*, 2013; Hervé *et al.*, 2014). Thus, the geological record representing the Gondwana and Early Andean stages of the evolution of the

South American margin are well exposed, although highly deformed. In particular, units cropping out in the Precordillera and Frontal Cordillera of northern Chile between 28°00' and 29°30', are a good record of this key time frame prior to the Andean subduction.

In Argentina, the Late Permian to Triassic period is characterized by the widespread magmatism represented by the Choiyoi group, whose origin had been attributed to crustal anatexis due to lithospheric extension associated to an orogenic collapse (Llambías and Sato, 1990; Llambías *et al.*, 1993). Acid explosive volcanism is well documented until the Early Triassic and followed by sedimentary rift deposits with basaltic rocks of anorogenic affinities, in the Cuyo and Ichigualasto basins (Ramos and Kay, 1991).

The geological cartography of northern Chile between 27°00' and 30°00' has been updated over the past decade with works performed, at 1:100.000 scale, by the Servicio Nacional de Geología y Minería (SERNAGEOMIN) (Welkner *et al.*, 2006, Arévalo and Welkner, 2008; Moscoso *et al.*, 2010; Salazar *et al.*, 2013; Creixell *et al.*, 2012; Creixell *et al.*, 2013; Martínez *et al.*, 2015; Ortiz and Merino, 2015; Salazar and Coloma, 2016). These works include large geochronological databases in addition to refined litho stratigraphic unit definitions. In particular, the Late Paleozoic to Triassic rock units has been significantly modified, incorporating several new units and redefining those previously known. Even though extensive outcrops of acidic volcanic and subvolcanic rocks from the Late Carboniferous to the Permian are exposed in the Precordillera and Frontal Cordilleras, and interpreted as equivalents to the Choiyoi Group. The Triassic rock units are

more diverse and include large plutonic complexes, explosive volcanic sequences of dacitic to rhyolitic composition, continental to marine sedimentary sequences with minor volcanic component, and volcanic sequences of basaltic-andesite to rhyolitic composition (Reutter, 1974; Nasi *et al.*, 1990; Salazar *et al.*, 2013; Ortiz and Merino, 2015; Salazar and Coloma, 2016). Thus, the development of a continental rift phase in the South American plate during the Triassic is not a straightforward from the geological record in northern Chile between 27° and 30° S. Furthermore, extensive geochemical data from the Triassic units is lacking, precluding a tectonic interpretation of the magmatism from its chemical signature.

In this paper, we present new petrographical and geochemical data for several, Late Paleozoic to Triassic, plutonic and volcanic units cropping out in the Coastal (28°00' S-29°30' S) and Frontal cordilleras of northern Chile (28°30' S-30°15' S). The geochronology of these units has been presented elsewhere (Creixell *et al.*, 2012; Valin, 2014; Vallejos, 2014; Salazar *et al.*, 2013; Creixell *et al.*, 2016; Ortiz and Merino, 2015; Salazar and Coloma, 2016). The new data allow us to revise previous models for the tectonic setting of the Paleozoic to Triassic magmatism, its sources and processes of generation.

2. Geological Setting

In the Coastal Cordillera (28°-29° S, Fig. 1), the Paleozoic basement is represented by the Devonian to Permian Punta de Choros Metamorphic Complex, composed by micaschists and metabasites (Creixell *et al.*, 2012) and Chañaral Epimetamorphic complexes, which consists mainly of metaturbidites and metasedimentary rocks (Godoy and Lara, 1998) and the Carboniferous to Permian Llano de Chocolate Beds (Creixell *et al.*, 2012, 2016). The latter is a sedimentary rock sequence, mainly continental, deposited in a delta environment with proximal volcanic deposits (Creixell *et al.*, 2016). These Paleozoic units are unconformably overlaid by Triassic rocks of the Canto del Agua Formation, a geographically restricted sedimentary sequence, and the volcanic Jurassic rocks included in the La Negra Formation, and intruded by several plutonic complexes ranging in age from the Upper Triassic to the Lower Cretaceous (Welkner *et al.*, 2006;

Arévalo and Welkner, 2008; Creixell *et al.*, 2012). Among the older Mesozoic intrusives are the Carrizal Bajo Plutonic complex, a suite of diorites, quartz diorites, granodiorites and granites bounded by synplutonic normal faults and an age range between 208 and 206 Ma, the Algodones Granite composed of monzogranites and granodiorites of 203-199 Ma and surrounded by amphibole mylonites (Welkner *et al.*, 2006; Arévalo and Welkner, 2008; Creixell *et al.*, 2012) and the Quebrada La Vaca Tonalite, composed of tonalites and quartz diorites ranging in age from 193 to 191 Ma (Welkner *et al.*, 2006; Creixell *et al.*, 2012).

Several Paleozoic and Mesozoic units are recognized in the Frontal Cordillera, the most relevant of which to the present study are listed in Table 1. The Permian and Triassic plutonic units have a distinct spatial distribution along the Frontal Cordillera, as two parallel, roughly N-S trending, belts. The western belt comprises Pennsylvanian to Cisularian granitoids of the Guanta and Chanchoquin plutonic complexes that intrude Late Devonian to Mississipian metamorphic rocks and penecontemporaneous volcanic deposits (Fig. 1). The eastern belt is composed mainly by outcrops of the Chollay Plutonic Complex, intruding Devonian metasediments, Carboniferous granitoids, Permian metamorphic rocks and tonalites, and penecontemporaneous volcanic deposits with minor components of Permian intrusives. In between the two belts, scattered outcrops of Carboniferous granitoids and high-grade gneiss and metaplutonic rocks are found (Salazar *et al.*, 2013; Ortiz and Merino, 2015; Salazar and Coloma, 2016) (Fig. 1).

The Guanta Plutonic Complex (Ortiz and Merino, 2015), equivalent to the Guanta unit of Nasi *et al.* (1985), is composed of leuco to mesocratic, coarse to medium-grained, partly foliated, biotite and amphibole tonalites and granodiorites, ranging in age from 300 to 280 Ma (Nasi *et al.*, 1985; Hervé *et al.*, 2014; Ortiz and Merino, 2015). In continuity to the north, the Chanchoquín Plutonic Complex is a suite of medium to coarse grained granitoids composed of two-mica granodiorites, monzogranites, biotite and amphibole tonalites and diorites, that ranges from 297 to 285 Ma in age (Salazar *et al.*, 2013). The Quebrada El Pintado Tonalites are small foliated plutonic bodies and correspond to tonalites and granodiorites of amphibole and biotite, of Middle Permian age (272-266 Ma, Salazar and Coloma, 2016). All the aforementioned units were previously assigned to

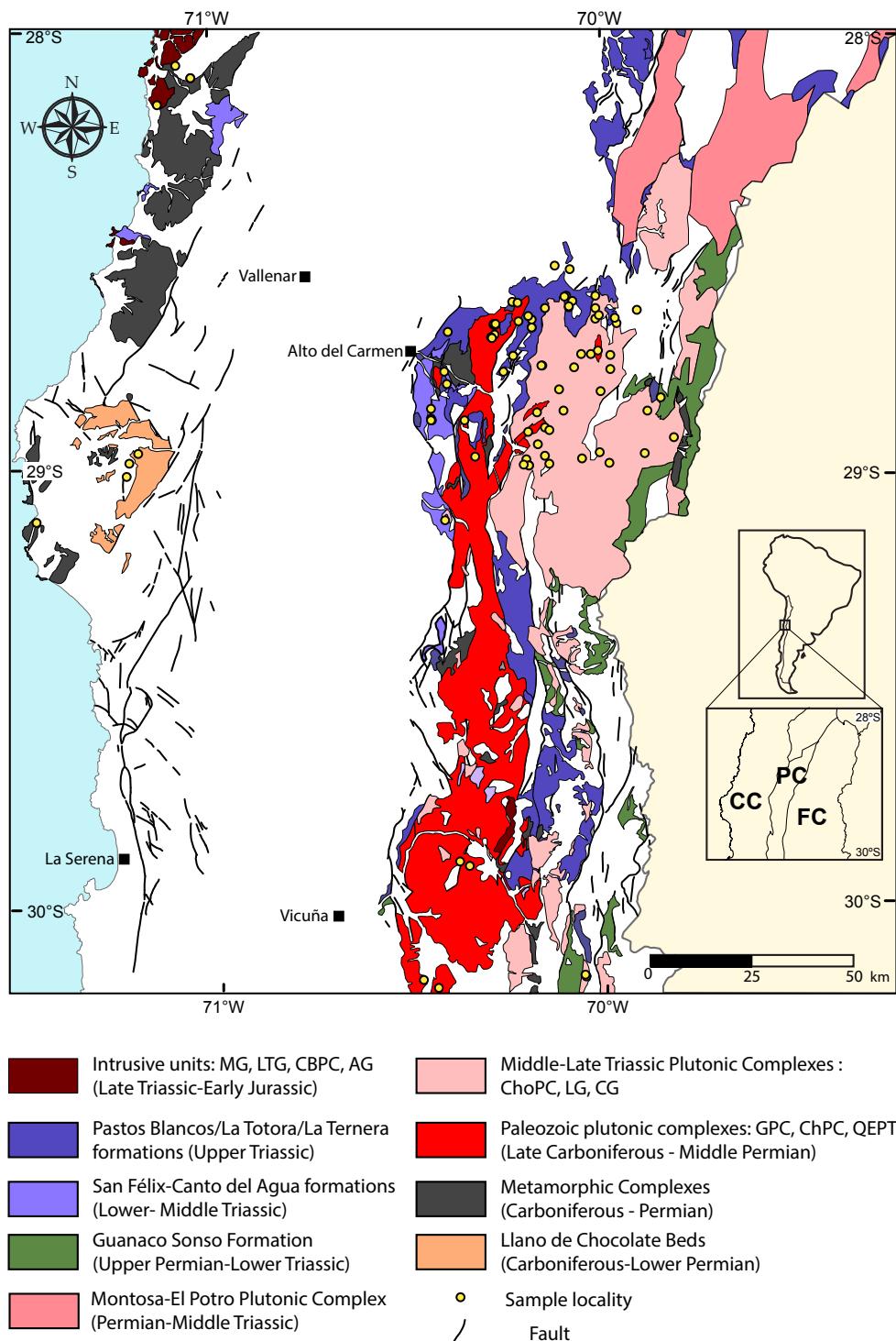


FIG. 1. Simplified geological map of the studied region including sample location. **GPC:** Guanta Plutonic Complex, **ChPC:** Chancho-quin Plutonic Complex, **QEPT:** Quebrada el Pintado Tonalites, **ChoPC:** Chollay Plutonic Complex, **LG:** La Laguna Gabbro, **CG:** Colorado Syenogranite, **MG:** Montegrande Granite; **LTG:** Los Tilos Pluton; **CBPC:** Carrizal Bajo Plutonic Complex; **AG:** Algodones Granite; **CC:** Coastal Cordillera, **PC:** Precordillera, **FC:** Frontal Cordillera.

the Elqui Superunit, an association of Carboniferous to Permian tabular coarse grained plutonic bodies believed to reflect significant crystallization depths (Nasi *et al.*, 1985). The Chollay Plutonic Complex, equivalent to the Chollay unit of Nasi *et al.* (1985), range in ages from 249 to 236 Ma and is composed of five different lithofacies, with medium to very coarse grained plutons that include gabbro-diorite, tonalite, syenogranite, granodiorite and monzogranite, being the two latter the most abundant (Salazar *et al.*, 2013; Salazar and Coloma, 2016). The Colorado syenogranite corresponds to a group of hololeucocratic, fine-grained to porphyritic plutonic bodies of characteristic reddish color, that range in age from 225 to 219 (Nasi *et al.*, 1985; Salazar *et al.*, 2013; Maksaev *et al.*, 2014). In the same geographic position as the Colorado syenogranite, several dioritic and granodioritic units have been lately described by Ortiz and Merino (2015), with an age of *ca.* 215 Ma. Other upper Triassic intrusive rocks are the La Laguna Gabbro, Montegrande Granite, Los Tilos Granodiorite (also called Los Tilos Pluton after Nasi *et al.*, 1990; Hervé *et al.*, 2014) and mafic dike swarms (Mpodozis and Cornejo, 1988; Martin *et al.*, 1999; Creixell *et al.*, 2009; Hervé *et al.*, 2014). All these units were assigned to the Ingaguás Superunit by Nasi *et al.* (1985).

One of the oldest stratified units is the Upper Permian-Lower Triassic Guanaco Sonso Formation which is unconformably overlain by the Upper Triassic Pastos Blancos Formation (Nasi *et al.*, 1990; Martin *et al.*, 1999; Ortiz and Merino, 2015; Salazar and Coloma, 2016). These units were originally assigned to the Pastos Blancos Formation (Nasi *et al.*, 1990) or to the Guanaco Sonso and Los Tilos Sequences of the Pastos Blancos Group (Martin *et al.*, 1999). They consist mainly of pyroclastic and volcanoclastic rocks, of intermediate to acidic composition with minor basalts, (Martin *et al.*, 1999; Salazar *et al.*, 2013; Ortiz and Merino, 2015; Salazar and Coloma, 2016), but they are also including coarse sandstones, conglomerates and epiclastic rocks. While rocks of the Guanaco Sonso Formation unconformably overlie Paleozoic metamorphic basement, the rocks of Pastos Blancos Formation rest over the Chollay Plutonic Complex and is in turn intruded by the Colorado syenogranites and dykes. The San Félix Formation is a 6,000 m thick clastic continental-marine rock succession of Triassic age (Reutter, 1974) that contains a few crystalline and lithic lapilli tuffs levels in some

of its five members and basic to intermediate lavas in the uppermost member (Salazar *et al.*, 2013). Although the age range for this formation comprises the entire Triassic period, fossil content and U-Pb geochronology indicate that most of the sedimentation took place from the Lower to the Middle Triassic and only the uppermost member is Late Triassic in age, which is covered by and interfingers eastward with andesitic lavas of the La Totora Formation (Reutter, 1974; Salazar *et al.*, 2013). The La Totora Formation is a volcanic sequence composed of lavas and tuffs of basic and intermediate composition, ranging in age from 221 to 212 Ma (Reutter, 1974; Salazar *et al.*, 2013; Maksaev *et al.*, 2014; Salazar y Coloma, 2016). East from the outcrops of the San Félix Formation, La Totora Formation covers unconformably the Chollay Plutonic Complex and is covered by the marine Lower to Middle Jurassic rocks of the Lautaro Formation.

3. Samples and methods

The complete dataset includes eighty-six samples of plutonic (61) and volcanic (25) rocks (Table 1, Fig. 1) belonging to twelve different Paleozoic and Mesozoic units. For the purposes of this study, the volcanic rocks collected from outcrops of the uppermost member of the San Félix Formation are assigned to the La Totora Formation, according to the information given in the previous chapter. The lithologies of the selected samples are: basaltic, basaltic-andesite and dacitic lavas, crystal and lithic lapilli tuffs, granodiorites, tonalites, granites, gabbros and diorites. Sixty-five samples were collected during the geological mapping of the Precordillera and Frontal Cordillera between 28°30' and 29°00'S by a team of the Servicio Nacional de Geología y Minería (SERNAGEOMIN). The petrographic description and methods used in the geochemical analysis of these rock samples are detailed in Salazar *et al.* (2013) -they can be obtained from authors Coloma and Salazar upon request- and summarized here and in the following chapters. The remaining twenty-one samples were collected in the Coastal Cordillera and Precordillera between 28° S and 30°15' S for petrographic and geochemical analysis. The thin sections were analyzed under the polarized-light microscope for a textural and mineralogical characterization. The samples were crushed and fresh fragments handpicked under binocular microscope.

TABLE 1. GEOLOGICAL UNITS STUDIED IN THIS WORK WITH THEIR REPRESENTATIVE LITHOLOGIES AND AGE RANGE, ANALYZED SAMPLES FOR EACH UNIT AND THEIR ALTERATION DEGREE EXPRESSED AS % OF THE TOTAL VOLUME OF THE ROCK.

Unit	Samples	Lithologies	Alteration degree	Age range
Llano de Chocolate Beds	CPV-12-12, CPV-12-105, CPV-12-127	Rhyolite, Dacite, Rhyolitic tuff	0.24-0.8	318-285 Ma ¹
Chanchoquín Plutonic Complex and Guanta Unit	ST-04t, CT-310t, CT-311t, CT-312t, CT-333t, CT-340t, CT-91t, ST-70t, ST-71t, CT-236t, CT-334t, CT-337t, 07-15	Tonalite, Granodiorite	0.00-0.16	296-285 Ma ²
Upper Permian Dike	ST-69t	Undetermined	0.1	-
Quebrada del Pintado Tonalites	CT-160t, CT-202t, CT-296t, ST-97t	Tonalite	0.02-0.08	272-259 Ma ²
Guanaco Sonso Formation	CT-213t, CT-216t, ST-13t, ST-14t, CT-286t	Basalt, Basaltic Andesite, Dacite, Rhyolite	0.13-0.35	265-240 Ma ²
La Laguna Gabbro	07-10, 07-11	Gabbro	0.01-0.02	255 Ma ³
Chollay Plutonic Complex (Granodiorite)	CT-228t, ST-16t, CT-19t, CT-237t, CT-284t, ST-160t, CT-191t, CT-19Bt, CT-154t	Granodiorite	0.015-0.17	247-237 Ma ²
Chollay Plutonic Complex (Monzogranite)	SCL-02t, CT-146At, CT-158t, CT-161t, CT-196t, CT-199t, CT-233t, CT-289t, CT-290t, CT-291t, CT-294t, CT-303t, ST-80t, ST-98Bt, ST-17t	Monzogranite	0.03-0.12	247-233 Ma ²
Chollay Plutonic Complex (Tonalite)	SCL-09t, CT-164t, CT-167t, CT-173t, CT-250t, CT-255t, CT-300t, CT-35t	Tonalite	0.04-0.27	237-234 Ma ²
Chollay Plutonic Complex (Gabbro-Diorite)	CT-193t	Diorite	0.11	249-242 Ma ²
San Félix Formation	CPV-12-38, CPV-12-49b, CT-75At, ST-212At	Lithic tuff, Andesitic tuff, Tuff	0.1-0.7	254-212 Ma ^{2,4}
Upper Triassic dike	CT-74t		0.4	-
Colorado Syenogranite	SCL-14t, ST-9t	Syenogranite	0.05-0.09	229-219 Ma ²
La Totora Formation	ST-93At, ST-196t, ST-11t, ST-19t, CPV-12-23, CPV-12-24, CPV-12-60, SCL-26t, ST-62t, ST-175t, ST-43t	Andesitic tuff, Rhyolitic tuff, Andesite, Basalt, Tuff, Rhyolite, Rhyolitic tuff	0.08-0.89	221-210 Ma ^{2,5}
Montegrande Granite	07-07, 07-06	Granite, Granodiorite	0.01	215 Ma
Los Tilos Pluton	07-13	Granodiorite	0.01	215 Ma
Carrizal Bajo Complex	CPV-12-91A, CPV-12-91B, CPV-12-93	Diorite, Tonalite, Granodiorite	0.05-0.23	208-206 Ma ⁶
Algodones Granite	CPV-12-92	Diorite	0.4	203-199 Ma ⁶

¹Creixell *et al.* (2016); ²Salazar *et al.* (2013); ³Hervé *et al.* (2014); ⁴Vallejos (2014); ⁵Maksaev *et al.* (2014); ⁶Arévalo and Welkner (2008).

The selected fragments pulverized under 60 μm for chemical analyses of major and trace elements. Major element contents were determined through XRF (X rays fluorescence) whereas trace elemental concentrations were determined on a quadrupole single collector ICP-MS at the Geosciences Department of the University of Arizona. Analytical techniques, sample preparation procedures and standards were previously described in Chapman *et al.* (2015) and Rossel *et al.* (2013).

U-Pb geochronology of zircons was conducted by LA-MC-ICP-MS at the Arizona LaserChron Center (Gehrels *et al.*, 2008). The analyses involve ablation of zircon with a New Wave/Lambda Physik DUV193 Excimer laser (operating at a wavelength of 193 nm) using a spot diameter of 25 or 35 μm . The ablated material is carried with helium gas into the plasma source of a GV Instruments Isoprobe, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements are made in static mode, using Faraday detectors for ^{238}U and ^{232}Th , an ion-counting channel for ^{204}Pb , and either Faraday collectors or ion counting channels for $^{208-206}\text{Pb}$. Ion yields are $\sim 1 \text{ mV ppm}^{-1}$. Each analysis consists of one 20 s-integration on peaks with the laser off (for backgrounds), twenty 1 s-integrations with the laser firing, and a 30 s delay to purge the previous sample and to prepare for the next analysis. The ablation pit is $\sim 15 \mu\text{m}$ in depth.

For each analysis, the errors in determining $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ result in a measurement error of $\sim 1\%$ (at 2σ level) in the $^{206}\text{Pb}/^{238}\text{U}$ age. The errors in measurement of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ also result in $\sim 1\%$ (2σ) uncertainty in age for grains that are $>1.0 \text{ Ga}$, but are substantially larger for younger grains due to low intensity of the ^{207}Pb signal. For most analyses, the crossover in precision of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages occurs at $\sim 1.0 \text{ Ga}$. Common Pb correction is accomplished by using the measured ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers (1975) (with uncertainties of 1.0 for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.3 for $^{207}\text{Pb}/^{204}\text{Pb}$). The measurement of ^{204}Pb is unaffected by the presence of ^{204}Hg because backgrounds are measured on peaks (thereby subtracting any background ^{204}Hg and ^{204}Pb), and because very little Hg is present in the argon gas. Interelement fractionation of Pb/U is generally $\sim 20\%$, whereas fractionation of Pb isotopes is generally $<2\%$. In-run analysis of fragments of a

large Sri Lanka zircon crystal (generally every fifth measurement) with known age of $564 \pm 4 \text{ Ma}$ (2σ error) is used to correct for this fractionation (see Gehrels *et al.*, 2008). The uncertainty resulting from the calibration correction is generally $\sim 1\%$ (2σ) for both $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ages.

The reported ages are determined from the weighted mean of the $^{206}\text{Pb}/^{238}\text{U}$ ages of the concordant and overlapping analyses (Ludwig, 2003). The reported uncertainty (labeled “mean”) is based on the scatter and precision of the set of $^{206}\text{Pb}/^{238}\text{U}$ or $^{206}\text{Pb}/^{207}\text{Pb}$ ages, weighted according to their measurement errors (shown at 1σ). The systematic error, which includes contributions from the standard calibration, age of the calibration standard, composition of common Pb and U decay constants, is generally $\sim 1-2\%$ (2σ).

4. Petrography of the plutonic and volcanic rocks

The petrography of the studied samples was carried out mainly in thin sections, in which the main mineralogy, both primary and secondary, was distinguished. Some images from the thin sections are detailed in figure 2, and the details of these descriptions are in the Appendix 1.

4.1. Llano de Chocolate Beds

In this unit, the volcanic and pyroclastic rocks are interbedded in the dominantly sedimentary sequence (Vallejos, 2014; Creixell *et al.*, 2016) and they correspond to dacitic lavas and crystalline lapilli tuffs. The dacites have porphyritic texture, slightly seriated, with felsitic groundmass. The phenocrysts correspond to reabsorbed quartz, plagioclase and biotite. Alteration minerals represents up to 5% of the rock, with calcite and clay minerals replacing plagioclase, and biotite is replaced by epidote and chlorite. Quartz, biotite, calcite and sericite also occur in veinlets. The tuffs have fragmental texture with fiammes, and phenocrysts of quartz and plagioclase. Secondary calcite and biotite occur in veinlets.

4.2. Chanchoquín Plutonic Complex

The Chanchoquín Plutonic Complex is composed mainly of tonalites and granodiorites with minor monzogranites and diorites, the studied samples include only tonalitic and granodioritic lithologies. Granodiorites are fine to medium grained and contain

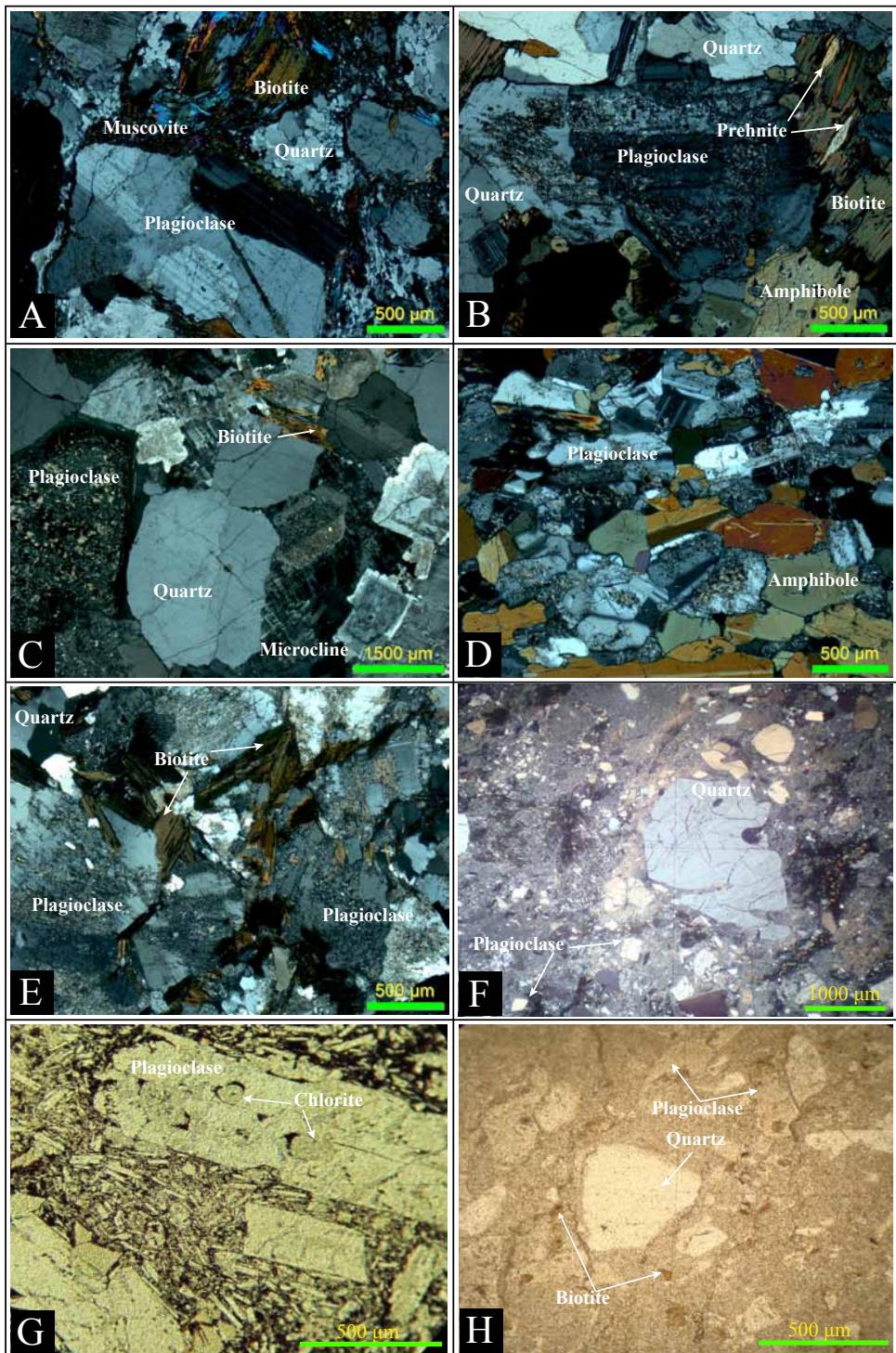


FIG. 2. Microphotographs of the most relevant lithologies of the studied units: **A**. Tonalite, Chanchoquín Plutonic Complex; **B**. Tonalite, Quebrada el Pintado Tonalites; **C**. Monzogranite, Chollay Plutonic Complex; **D**. Tonalite, Chollay Plutonic Complex; **E**. Granodiorite, Chollay Plutonic Complex; **F**. Dacite, Llano de Chocolate Beds; **G**. Andesitic clast in volcanic breccia, La Totora Formation; **H**. Crystalline tuff, San Félix Formation.

quartz with undulatory extinction, plagioclase, orthoclase, biotite and minor muscovite or amphibole; accessory minerals are Fe-Ti oxides (mainly magnetite) and sphene. Perthitic texture is observed in some feldspar crystals. These lithologies are slightly altered (less than 10% volume of the rock) with sericite replacing feldspars and prehnite and epidote replacing biotite. Tonalites are medium to fine grained, they contain quartz with undulatory extinction and polycrystalline, zoned plagioclase, orthoclase, biotite, muscovite, minor amphibole, with Fe-Ti oxides and apatite as accessory minerals. Alteration minerals are generally less than the 8% of the rock, but in three samples they reach the 15%, with sericite replacing feldspars and chlorite, epidote and prehnite replacing mafic minerals. At the outcrop scale, the rocks are foliated to variable degrees.

4.3. Los Tilos Granodiorite

This unit is characterized by the presence of cordierite in its mineralogy, with allotromorphic inequigranular texture; its composition varies between granite and granodiorite and is composed by quartz, alkali feldspar, plagioclase, biotite, white mica with slight deformation, and cordierite. The quartz has undulatory extinction and locally shows a granoblastic texture, biotite is altered to chlorite and epidote, and shows slight deformation, similar to the white mica.

4.4. Quebrada El Pintado Tonalites

The rocks of this units are grey fine to medium grained tonalites with local millimetric to centimetric foliation. They contain polycrystalline quartz with undulatory extinction, plagioclase, minor orthoclase, biotite, amphibole, pyroxene, muscovite and Fe-Ti oxides, with apatite as accessory minerals. Myrmekitic and perthitic textures are observed in the feldspars. Secondary mineral represent less than the 6% of the volume of the rock, with sericite replacing feldspars, and chlorite and epidote replacing biotite.

4.5. Guanaco Sonso Formation

This volcanic and sedimentary unit is volumetrically important in the Frontal Cordillera (Fig. 1) and it is composed mainly of dacitic to rhyolitic, partly welded tuffs and lava flows of basaltic, dacitic and rhyolitic composition. Minor sedimentary beds of

volcarenites, siliciclastic laminated conglomerate and medium to coarse grained sandstone are found, along with scarce outcrops of lacustrine mudstone and chert. The main lithology is crystal and lithic-bearing vitric lapilli tuffs, with plagioclase, quartz and amphibole phenocrysts, acid volcanic fragments and pumice of millimetric to centimetric size.

4.6. Chollay Plutonic Complex

The Chollay Plutonic Complex is the largest intrusive unit in the studied area (Fig. 1) and it is composed mainly of monzogranite and granodiorite, along with diorite to gabbro, tonalite and syenogranite. The monzogranites are pink and coarse grained rocks, which contain quartz with undulatory extinction and locally polycrystalline, sometimes zoned plagioclase, orthoclase with perthitic texture, minor microcline, biotite, muscovite, with Fe-Ti oxides (mainly magnetite) and sphene as accessory minerals; alteration minerals represent up to the 10% of the rock volume, with sericite replacing feldspars, and chlorite and epidote replacing biotite. The granodiorites are grayish white, fine to medium grained rocks, with zoned plagioclase, quartz with undulatory extinction and locally polycrystalline, orthoclase with perthitic texture, biotite, amphibole and muscovite, with sphene, apatite and rutile as accessory minerals, the alteration minerals can reach 15% in volume of the rock, with mainly sericite replacing feldspars and chlorite replacing biotite, while epidote and prehnite are also observed replacing mafic minerals. The diorites and gabbros are dark grey, medium to fine grained rocks, they contain zoned plagioclase and variable amount of olivine and clinopyroxene, the latter with amphibole rims, minor biotite, and Fe-Ti oxides, apatite and rutile as accessory minerals; alteration minerals can reach 12% of the volume of the rock, with sericite replacing plagioclase and scarce chlorite and prehnite. The tonalites are medium to fine grained, grey rocks, contain quartz with undulatory extinction, zoned plagioclase, scarce orthoclase, biotite, hornblende, and Fe-Ti oxides (mainly magnetite), with apatite and sphene as accessory minerals, and alteration minerals represent between 7 to 25% of the total volume of the rock, with sericite replacing plagioclase (4-15%), chlorite replacing biotite and amphibole (3-12%) and disseminated epidote. The syenogranites are orange, medium grained rocks, contain scarce

plagioclase, orthoclase with peritic texture, quartz with undulatory extinction, scarce Fe-Ti oxides, and zircon as accessory mineral.

4.7. Colorado Syenogranites

The lithologies in this plutonic unit vary from syenogranites to monzogranites with myrmekitic and graphic textures in the feldspars. The rocks are pink-orange, coarse to medium grained, with porphyric to phaneritic texture. Quartz with undulatory extinction, orthoclase, plagioclase and biotite are the main minerals with scarce opaque minerals (Fe-Ti oxides), and apatite and rutile as accessory minerals; alteration is weak and secondary minerals phases represent less than the 6% of the total volume of the rock, with sericite replacing plagioclase, chlorite replacing biotite and disseminated epidote.

4.8. San Félix Formation

The pyroclastic deposits are interbedded in the mainly siliciclastic rock sequence (Reutter, 1974; Ribba, 1985; Salazar *et al.*, 2013; Vallejos, 2014), and they correspond to centimeter thick beds of lapilli and ash tuffs. The volcanic rocks have fragmental texture and locally eutaxitic, silicic alteration affected the matrix and plagioclases phenocrysts are replaced by sericite and clays, fine veins filled with sericite, biotite and quartz crosscut the rock.

4.9. Montegrande Granite

The Montegrande granite is an NNW elongated intrusive with an area of *ca.* 16 km² (Parada, 1984). The granite is allotriomorphic inequigranular and is composed by alkali feldspar, quartz, plagioclase and minor amphibole, clinopyroxene, biotite and white mica. Alkali feldspar is anhedral and perthitic, while amphibole is interstitial, anhedral and often includes oxidized pyroxene, biotite and white mica are also interstitial. Locally, the amphibole is completely replaced by chlorite with minor biotite. The plagioclase is subhedral, with minor secondary sericite and often is rimmed by albite.

4.10. La Laguna Gabbro

It consists of small stocks with few hundreds of meters in diameter (Mpodozis and Cornejo,

1988, this work). The gabbros are coarse-grained with hypidiomorphic inequigranular texture with plagioclase, interstitial clinopyroxene, orthopyroxene, opaque minerals, and minor quartz and interstitial orthoclase. Locally, the rocks exhibit graphic texture. Clinopyroxene could be present as reaction rims which enclose opaque minerals. The alteration in these rocks is scarce, pyroxenes are altered to chlorite, epidote and opaque minerals whereas plagioclase are slightly altered to sericite.

4.11. La Totora Formation

This volcanic unit is composed by andesitic lava flows, volcanic breccias and a tuff level interbedded in the sequence. The lavas are reddish-violet andesites and basalts, with aphanitic to slightly porphyritic texture, occasional vesicles and amygdales. The phenocrysts correspond to pyroxene and plagioclase with sieve texture, and the groundmass is hyalopilitic, locally intergranular, with plagioclase, pyroxene and olivine. The glass is altered to chlorite and Fe-Ti oxides. Secondary minerals represent up to 15% of the rock, with clay minerals, epidote and calcite replacing plagioclase, calcite in microveins, calcite and zeolite filling vesicles. The breccias are andesitic in composition. The clasts represent 15 to 40% of the total volume. They are lavas with porphyric and hyalophytic textures, plagioclase phenocryst (sieve textures) and glass, replaced by chlorite and Fe-Ti oxides. The matrix is similar in composition. The rocks are altered to calcite, quartz and clay minerals. Calcite is replacing plagioclase phenocrysts and fill veinlets with quartz.

4.12. Carrizal Bajo Plutonic Complex and Algodones Granite

These plutonic bodies have a rather restricted distribution in the Coastal Cordillera (Welkner *et al.*, 2006; Arévalo and Welkner, 2008) (Fig. 1). The samples of the Algodones granite correspond to medium grained quartz diorites, with plagioclase, quartz, clinopyroxene and biotite. These lithologies are slight to strongly altered (5 to 40% vol), chlorite and amphibole replace clinopyroxene, epidote and chlorite replace biotite and plagioclase crystals are replaced by sericite and clay minerals. The samples of the Carrizal Bajo Plutonic Complex correspond to medium to fine grained, equigranular biotite

tonalites and granodiorites, and amphibole tonalite. They are slight to moderately altered, with chlorite and epidote replacing mafic minerals, and sericite and clay minerals replacing feldspars.

4.13. Dikes

They are hypabisal rocks with subophitic texture and basaltic-andesitic to andesitic in composition. The phenocrysts are principally plagioclase, with moderate alteration to sericite and clay minerals, Fe-Ti oxides and pyroxene, which is often altered to amphibole and chlorite.

5. Geochronological results and interpretation

Isotope chronology data have been published elsewhere for most of the studied rock units (see Martin *et al.*, 1999; Welkner *et al.*, 2006; Salazar *et al.*, 2013; Hervé *et al.*, 2014; Creixell *et al.*, 2016; Ortiz and Merino, 2015; Salazar and Coloma, 2016) and summarized in Table 1. In this work, four samples of small intrusive rock units were selected for U-Pb dating in igneous zircons (Fig. 3). The detailed results are listed in the Appendix 2.

One sample from the Guanta unit (O7-15), equivalent to the Chanchoquín Plutonic Complex, displays an age distribution pattern with a single-peak, for which the best estimated age is 297.0 ± 4.0 Ma. One sample from a body assigned to Los Tilos pluton (O7-13) also yielded a single-peak age distribution pattern with a best estimated age of 290.3 ± 3.0 Ma. In both cases, there are no discordant ages from individual grains. The age of the Guanta unit agrees with previous reported data (Nasi *et al.*, 1985; Hervé *et al.*, 2014; Maksaev *et al.*, 2014). In contrast, the Los Tilos pluton has been before assigned to the Ingaguás Superunit (Nasi *et al.*, 1985) and dated at 215.6 ± 1.9 Ma (Hervé *et al.*, 2014) discordant with the result obtained in this work (290.3 ± 3.0 Ma). Given that there are no younger single-grain ages, either concordant or discordant, in the analyzed sample, it is difficult to discard the result obtained for sample O7-13, but it is possible that it does not belong to the Los Tilos Pluton since the other data point to a Late Triassic rather than Early Permian age.

On the other hand, sample O7-07 from the Montegrande Granite yielded a best estimated age of 214.6 ± 1.5 Ma, with one single grain age of 260.3 ± 25.2 Ma, suggesting possible assimilation

of older crustal rocks during magma generation or evolution. This age is in agreement with the geochronological data previously reported, which range between 192 ± 11 and 215.6 ± 1.4 Ma (Brook *et al.*, 1987; Hervé *et al.*, 2014). In the case of the La Laguna Gabbro (sample O7-11), crustal assimilation by the Triassic magma is also a likely process since the rock exhibit a bimodal age distribution with peaks at 218.8 ± 8.3 Ma and 265.0 ± 2.4 Ma. Hervé *et al.* (2014) reported an age of 255.2 ± 1.8 Ma but these authors discarded two younger single-grain ages at *ca.* 215 Ma and 225 Ma. We therefore think that the Late Triassic age is a plausible date for igneous crystallization of the gabbroic rocks, although some crustal material might have been assimilated in the process.

6. Geochemistry

Major and trace elements abundances for the studied volcanic and plutonic rocks are listed in Table 2 and in Salazar *et al.* (2013). Prior to the description of the geochemical results, the issue of the secondary alteration processes that affected the studied rocks is addressed.

6.1. Alteration

Secondary minerals are very common in the studied samples (see Table 1 and Appendix 1). The alteration minerals in the volcanic rocks can be up to the 25% of the total volume of the rock, whereas in the plutonic rocks is generally less than the 10%, with some exceptions up to 40% (Algodones granites). The exception are: sample CPV-12-105 (Llano de Chocolate beds), a silicified rhyolite or rhyolitic tuff for which the recognized volume of secondary quartz reaches the 85%; sample CPV-12-38 (San Félix Formation), a lithic tuff with a total volume of alteration minerals, mainly secondary quartz, of 39%; four samples of Coastal Cordillera intrusives (CPV-12-91A, CPV-12-92, CPV-12-93 and CPV-12-03) with total volume of alteration minerals ranging from 26 to 12%, being chlorite the main secondary phase; and four samples of the Chollay Plutonic Complex (CT-164q, CT-173q, CT-184q, CT-191q) with total volume of alteration minerals ranging from 26 to 12%, being sericite the main secondary phase. In addition, three samples of pyroclastic rocks (sample CPV-12-38 and CPV-12-49b, San Félix Formation;

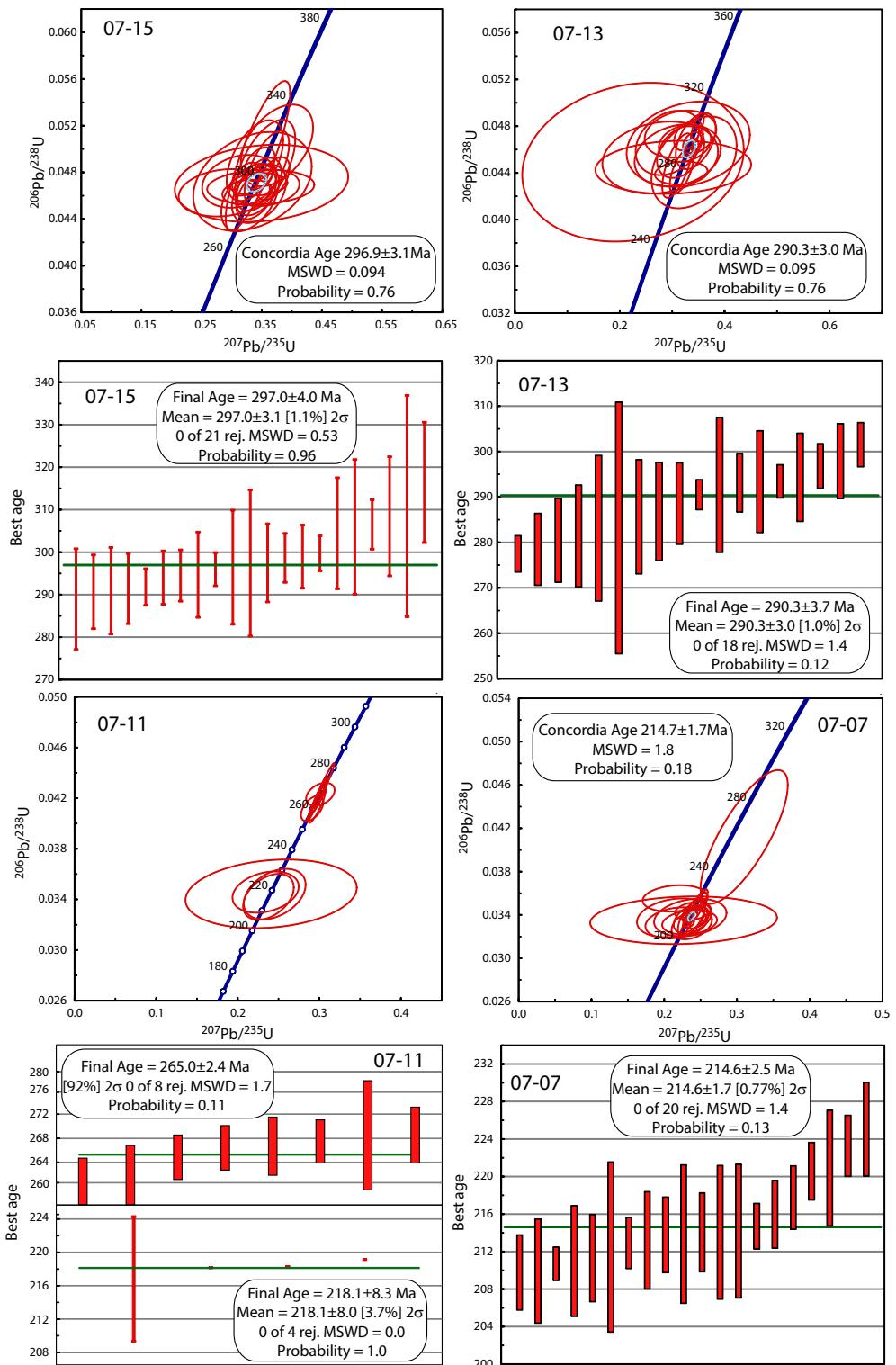


FIG. 3. Tera-Wasserburg concordia and estimated best U-Pb age plots for analyzed samples belonging to the Guanta Unit (O7-15), the Los Tilos Pluton (O7-13), the La Laguna Gabbro (O7-11) and the Montegrande Granite (O7-07).

TABLE 2. XRF AND ICP-MS GEOCHEMICAL DATA FOR THE ANALYZED SAMPLES.

Sample Unit	CPV-12-105 Llano de Chocolate Beds	CPV-12-12 Llano de Chocolate Beds	CPV-12-127 Llano de Chocolate Beds	O7-15 Guanta Unit	O7-10 La Laguna Gabbro	O7-11 La Laguna Gabbro	SCL-02q Chollay Plutonic Complex
Lithology	Rhyolite	Dacite	Tuff rhyolitic	Tonalite	Gabbro	Gabbro	Monzogranite
UTM East	286,402	289,084	287,052	366,163	396,451	396,266	410,948
UTM North	6,789,103	6,794,562	6,792,338	6,697,056	6,669,570	6,669,913	6,804,964
SiO₂ %	67.42	72.24	68.71	56.25	47.44	46.25	77.72
TiO₂	<0.01	0.16	0.28	0.75	1.48	1.25	0.09
Al₂O₃	9.50	9.87	12.41	13.33	17.08	17.30	11.89
FeO	0.00	0.77	0.65	0.83	0.95	1.04	0.19
MnO	0.04	0.06	0.04	0.09	0.08	0.08	0.05
MgO	0.18	0.53	0.58	3.24	4.21	4.72	0.08
CaO	0.31	1.13	1.23	5.57	10.70	9.59	0.27
Na₂O	3.96	2.10	2.35	2.66	2.72	2.51	3.92
K₂O	4.61	3.53	3.91	2.06	1.00	1.40	3.94
P₂O₅	0.02	0.05	0.06	0.19	0.63	0.89	0.02
LOI	12.79	7.98	8.45	7.34	7.78	8.06	0.40
Total %	98.82	99.96	99.98	97.87	100.43	100.01	98.95
La ppm	4.3	38.0	38.6	8.4	27.2	26.3	13.3
Ce	6.9	66.7	67.6	31.9	56.0	53.5	25.5
Pr	1.4	6.1	11.1	3.2	7.2	5.1	2.9
Nd	8.0	29.8	28.1	18.0	31.4	28.4	10.0
Sm	1.8	6.1	5.5	4.3	7.0	6.0	1.9
Eu	0.4	1.3	1.0	1.0	2.4	1.7	0.3
Gd	1.9	5.8	5.1	4.3	6.7	5.7	1.6
Tb	0.3	0.9	0.9	0.7	1.0	0.8	0.3
Dy	1.8	5.2	4.7	4.1	5.6	4.6	2.1
Ho	0.4	1.1	1.0	0.8	1.1	0.9	0.5
Er	1.0	3.2	3.1	2.4	3.0	2.5	1.3
Tm	0.1	0.5	0.5	0.3	0.4	0.3	0.2
Yb	0.9	3.2	3.4	2.2	2.6	2.1	1.6
Lu	0.1	0.5	0.5	0.3	0.4	0.3	0.2
Y	7.6	20.0	18.5	18.8	29.4	14.8	14.1
Sc	1.6	5.5	6.4	13.0	18.8	12.7	2.0
Hf	1.2	2.8	3.3	0.6	5.1	3.0	2.2
Nb	4.1	9.8	9.9	7.6	8.1	6.4	9.5
Ta	0.3	0.7	0.9	0.5	0.4	0.4	1.0
Th	5.1	13.7	27.7	4.2	6.0	6.4	8.6
Zn	117.8	583.1	20.1	59.7	82.4	74.4	<30
Co	0.4	3.5	3.3	17.9	44.3	25.7	<1
Ni	8.0	3.0	2.1	24.3	37.9	33.4	<20
Ba	299.8	2,075.6	624.0	377.2	427.9	431.0	677.0
Cr	53.1	15.2	6.9	18.8	18.8	22.4	<20
V	11.1	2.6	27.2	28.7	12.0	10.2	75.0
Se	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Br	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cu	15.3	3.6	4.3	8.8	52.8	60.4	10.0
Sr	44.7	167.1	67.1	236.3	530.8	420.2	42.0
Zr	21.9	72.5	85.2	5.9	219.2	118.2	61.0
Rb	38.8	153.3	177.1	54.7	19.2	26.2	138.0
As	0.0	0.0	0.0	0.0	0.0	0.0	<5
Be	0.0	0.0	0.0	0.0	0.0	0.0	3.0
Sb	2.1	0.5	1.2	0.1	0.9	0.3	0.4
Sn	2.3	6.1	7.9	4.5	3.6	3.8	1.0
U	1.6	2.6	3.2	1.7	1.8	1.8	2.3
W	1.8	2.3	2.5	5.4	0.8	0.7	1.2
Bi	0.0	0.0	0.0	0.0	0.0	0.0	<0.1
Cd	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Cs	1.6	2.3	14.6	2.0	3.1	2.5	2.0
Ga	6.9	33.1	17.4	18.4	27.4	20.0	13.0
Ge	0.1	0.4	0.4	0.9	1.3	1.1	2.8
In	0.0	0.0	0.0	0.0	0.0	0.0	<0.1
Mo	0.9	0.1	0.2	1.2	0.5	0.4	<2
Pb	61.5	4.1	12.2	15.9	11.9	10.3	9.0
Ag	0.0	0.0	0.0	0.0	0.0	0.0	1.2
Tl	0.0	0.0	0.0	0.0	0.0	0.0	0.7

Table 2 continued.

Sample Unit	SCL-09q Chollay Plutonic Complex	CPV-12-38* San Félix Formation	CPV-12-49b* San Félix Formation	CPV-12-23 La Totora Formation	CPV-12-24 La Totora Formation	CPV-12-60 La Totora Formation	SCL-26q* La Totora Formation
Lithology	Tonalite	Tuff lithic	Tuff lithic	Andesite	Andesite	Basalt	Tuff
UTM East	410.315	362.530	359.174	376.484	383.333	382.348	414.172
UTM North	6.794.865	6.778.657	6.805.415	6.814.323	6.826.718	6.827.655	6.808.064
SiO₂ %	68.47	86.59	72.23	56.61	43.06	44.81	81.32
TiO₂	0.46	0.17	0.14	1.34	1.58	1.10	0.11
Al₂O₃	14.55	5.40	13.20	14.61	16.33	15.21	9.93
FeO	1.02	0.00	0.25	1.61	1.81	1.43	0.40
FeO	2.54	0.00	0.50	5.38	9.05	7.16	0.79
MnO	0.07	0.02	0.03	0.11	0.19	0.14	0.01
MgO	1.43	0.12	0.62	2.17	9.09	8.96	0.15
CaO	3.46	0.13	0.27	5.57	7.50	8.86	0.57
Na₂O	3.59	0.31	1.86	3.55	3.77	4.82	1.69
K₂O	2.92	1.95	3.50	1.30	0.08	0.29	3.76
P₂O₅	0.10	0.00	0.03	0.43	0.37	0.33	0.01
LOI^a	1.16	5.18	7.34	7.31	7.17	6.81	1.94
Total %	99.78	99.87	99.99	99.99	99.99	99.92	100.69
La ppm	23.7	8.9	37.8	26.1	1.3	8.9	31.2
Ce	44.3	31.0	73.4	52.8	6.3	28.5	62.8
Pr	5.0	2.8	12.0	5.1	0.8	3.7	7.2
Nd	18.1	13.7	32.6	28.4	5.0	17.7	26.8
Sm	3.4	3.0	7.0	6.2	1.4	3.6	4.8
Eu	0.8	0.6	1.4	2.0	0.5	1.1	0.3
Gd	2.7	3.3	6.8	6.3	1.4	3.3	3.6
Tb	0.5	0.6	1.1	1.0	0.2	0.5	0.7
Dy	2.6	3.2	6.7	5.6	1.3	2.3	4.2
Ho	0.5	0.6	1.3	1.1	0.3	0.4	0.9
Er	1.7	1.6	3.9	3.2	0.7	1.6	2.6
Tm	0.3	0.2	0.5	0.4	0.1	0.1	0.4
Yb	1.6	1.4	3.6	2.8	0.6	1.0	3.1
Lu	0.3	0.2	0.5	0.4	0.1	0.1	0.4
Y	15.8	12.1	42.8	33.3	2.5	13.3	24.5
Sc	9.0	2.1	4.8	12.0	6.2	20.5	3.0
Hf	4.8	1.1	4.8	6.0	2.7	1.9	4.5
Nb	6.7	6.6	15.6	9.3	3.7	4.8	11.9
Ta	0.6	0.3	0.9	0.5	0.2	0.2	0.9
Th	8.7	5.9	27.2	3.1	0.3	2.0	14.6
Zn	50.0	9.4	20.1	92.9	101.6	114.6	< 30
Co	7.0	2.1	1.1	16.1	43.4	35.1	< 1
Ni	< 20	3.7	6.7	5.1	102.1	153.7	< 20
Ba	794.0	467.8	1662.7	391.7	17.8	43.4	471.0
Cr	< 20	16.4	17.2	5.7	103.8	550.8	< 20
V	157.0	15.0	7.5	4.9	203.8	120.6	6.0
Se	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Br	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cu	30.0	3.0	2.2	18.1	769.8	7.8	< 10
Sr	249.0	6.6	151.0	444.2	146.5	199.2	41.0
Zr	189.0	19.8	98.8	280.7	127.8	78.9	127.0
Rb	111.0	105.1	136.8	20.8	0.1	3.2	105.0
As	< 5	0.0	0.0	0.0	0.0	0.0	< 5
Be	2.0	0.0	0.0	0.0	0.0	0.0	2.0
Sb	0.3	13.3	0.3	0.0	0.2	0.1	0.4
Sn	2.0	4.3	8.9	3.9	2.5	1.1	4.0
U	1.6	1.1	3.7	0.7	0.2	0.1	2.2
W	2.3	1.8	1.6	0.3	0.2	0.1	1.5
Bi	< 0.1	0.0	0.0	0.0	0.0	0.0	< 0.1
Cd	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cs	2.7	21.1	2.7	0.5	0.0	0.8	2.3
Ga	16.0	14.3	33.8	20.5	13.7	16.3	11.0
Ge	2.5	0.1	0.3	1.0	1.8	1.2	1.4
In	< 0.1	0.0	0.0	0.0	0.0	0.0	< 0.1
Mo	< 2	0.2	0.4	0.9	0.3	0.3	< 2
Pb	13.0	2.5	12.9	8.9	10.4	9.3	17.0
Ag	2.0	0.0	0.0	0.0	0.0	0.0	2.2
Tl	0.7	0.0	0.0	0.0	0.0	0.0	1.0

Table 2 continued.

Sample Unit	O7-13 Los Tilos	O7-07 Monte Grande Unit	O7-06 Monte Grande Unit	CPV-12-91A Carrizal Bajo Plutonic Complex	CPV-12-91B Carrizal Bajo Plutonic Complex	CPV-12-93 Carrizal Bajo Plutonic Complex	CPV-12-92 Algodos Granite
Lithology	Granite (two mica)	Granite	Granite	Diorite	Tonalite	Granodiorite	Diorite
UTM East	368.473	361.047	357.424	301.526	301.526	288.859	298.038
UTM North	6.695.942	6.666.761	6.668.630	6.884.546	6.884.546	6.878.634	6.887.501
SiO₂, %	67.80	67.42	74.31	51.74	68.22	67.83	53.61
TiO₂	0.08	b.d.l.	0.08	1.33	0.41	0.12	0.91
Al₂O₃	12.71	9.50	9.53	12.62	8.73	10.44	13.59
Fe₂O₃	0.35	0.15	b.d.l.	1.56	1.04	0.37	1.73
FeO	1.15	1.02	b.d.l.	7.79	2.09	0.74	5.76
MnO	0.06	0.04	0.03	0.11	0.05	0.04	0.10
MgO	0.52	0.18	0.20	4.23	0.52	0.33	4.36
CaO	1.85	0.31	0.61	7.32	2.20	1.01	6.21
Na₂O	3.41	3.96	2.76	2.88	2.70	3.63	3.18
K₂O	1.91	4.61	4.70	1.44	1.25	3.96	1.58
PO₄	0.07	0.02	b.d.l.	0.50	0.11	0.07	0.26
LOI^a	9.44	8.03	8.93	8.44	12.54	11.12	8.62
Total %	99.36	95.24	101.14	99.96	99.87	99.65	99.90
La ppm	25.9	45.5	5.2	11.3	57.1	11.5	9.8
Ce	44.1	86.6	7.2	42.4	106.6	38.9	36.1
Pr	4.6	12.1	0.9	4.9	16.6	3.2	3.6
Nd	16.7	38.4	3.9	24.0	45.1	15.7	19.7
Sm	2.8	8.2	0.6	6.1	8.5	3.9	4.5
Eu	0.9	0.9	1.4	1.6	1.5	0.5	1.1
Gd	2.4	7.5	0.5	6.6	7.9	4.2	4.2
Tb	0.3	1.1	0.1	1.2	1.1	0.8	0.6
Dy	1.3	6.1	0.3	7.0	5.2	4.7	3.6
Ho	0.2	1.2	0.1	1.4	1.0	1.0	0.7
Er	0.6	3.4	0.2	4.2	2.8	3.0	2.0
Tm	0.1	0.5	0.0	0.6	0.4	0.5	0.3
Yb	0.5	3.2	0.2	3.9	2.4	3.3	1.8
Lu	0.1	0.5	0.0	0.6	0.4	0.5	0.3
Y	4.3	25.8	1.1	43.0	26.0	33.6	12.3
Sc	2.1	1.9	2.0	17.4	3.8	2.6	10.9
Hf	0.3	0.9	0.3	1.3	2.8	2.4	0.7
Nb	6.6	8.5	7.5	14.3	6.1	6.8	4.0
Ta	0.4	0.4	0.4	0.8	0.3	0.6	0.3
Th	3.2	3.4	2.1	7.7	55.8	14.4	4.2
Zn	55.6	72.0	16.2	67.9	22.2	31.6	61.9
Co	1.9	0.2	0.5	23.8	3.4	2.4	21.1
Ni	3.2	1.3	2.7	31.2	3.6	3.9	30.3
Ba	598.5	505.0	1561.6	233.0	432.9	231.4	214.0
Cr	112.1	4.7	88.9	74.1	5.8	5.5	68.4
V	2.9	1.2	1.0	182.8	22.6	7.1	178.4
Se	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Br	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cu	3.2	1.2	3.1	24.4	36.6	2.7	44.9
Sr	335.9	8.8	101.1	206.6	130.3	50.0	318.9
Zr	3.7	8.0	6.1	25.6	102.1	74.7	7.3
Rb	30.3	37.7	121.0	33.1	27.6	234.2	18.2
As	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Be	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sb	0.1	0.1	0.0	0.3	0.2	0.0	0.1
Sn	1.9	3.4	1.1	3.9	5.6	10.3	3.0
U	0.4	0.7	0.3	1.6	1.7	3.8	0.7
W	0.2	0.2	0.4	0.8	0.5	0.2	0.4
Bi	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cd	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cs	1.3	0.9	1.4	0.6	0.9	8.2	0.3
Ga	20.1	21.8	27.4	17.3	17.7	15.2	14.8
Ge	0.4	0.4	0.1	1.1	0.5	0.3	0.8
In	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mo	0.3	0.6	0.1	0.4	0.5	0.4	0.3
Pb	15.6	15.4	29.8	8.5	14.9	20.5	5.5
Ag	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tl	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* Strongly altered volcaniclastic samples, with minor lithic content.

SCL-26q, La Totora Formation) are strongly altered and lithic fragments were not separate, which implies that these samples have not been considered in the interpretation of the tectonic implications. Calcite and sericite are ubiquitous alteration mineral phases in the volcanic rocks, whereas clay minerals, chlorite and sericite are the dominant secondary minerals in the plutonic rocks. Sericite and clay minerals replace plagioclase phenocrysts and calcite occurs in fractures, amygdules or as replacement of phenocrysts. The high loss on ignition in some of the volcanic and plutonic rocks is consistent with the widespread occurrence of calcite (Table 2).

Given that the discrimination of the convergent margin and within plate tectonic settings for igneous rocks is largely based in the content of incompatible (alkaline, large radii lithophile and high field strength) elements of the analyzed samples, and taking into account that some of these elements are mobile in hydrothermal processes, it is necessary to test the extent of mobility for the studied rocks. A comparison between the total alkalis *versus* silica (TAS) and Zr/Ti *versus* Nb/Yb classification diagrams was made (Figs. 4c, 4d). Slight enrichment in alkalis is observed in the volcanic rocks, which plot near the alkaline/sub-alkaline boundary. However, the classification based on the more immobile elements discards the alkaline character of the same rocks, with the exception of sample CPV-12-24, a basalt from the La Totora Formation. The potential bias of some mobile major and trace elements along with the high amount of material loss on ignition, that affects particularly the major elements, imply that the interpretations of the tectonic setting of the magmas that generated the studied rocks must be done with caution and based on the behavior of the less mobile elements, such as the rare earth (REE) and high field strength (HFSE) elements. In this work, we only considered for tectonic implications the rocks with less than 10 % of total volume of alteration minerals.

6.2. Major Elements

The contents of SiO_2 (on anhydrous basis) of the volcanic rocks with variable alteration grade range between 48% and 91% (Fig. 4c). The pyroclastic rocks of the La Totora and San Félix Formations and the Llano de Chocolate Beds that have the highest SiO_2 content are strong altered. This is consistent

with the dispersion of the alkalis displayed for these samples in Fig. 4c. Although the number of studied samples precludes a significant statistical approach, a bimodal distribution of the volcanic rock within the different units is not observed, at least for the major element content. The alkali content of the rocks range from 3 to 8 wt% (oxide), and in general it increases with higher SiO_2 content. Exceptions to this pattern are samples CPV-12-38 and CPV-12-105 with 2% and 10% alkalis, respectively. According to their SiO_2 and K_2O content the studied rocks would have calc-alkaline and high-K calc-alkaline affinities (Fig. 4c)(Peccerillo and Taylor, 1976; Irvine and Baragar, 1971) The wt% of TiO_2 , MgO and FeO_{t} vary from 0.08 to 2.20, 0.49 to 16.00 and from 0.30 to 13.50, respectively. The dispersion for these elements is much less than for the alkalis and in general their concentration decreases with increasing SiO_2 content. The Al_2O_3 content ranges between 8.83 and 18.50 wt%, decreasing, first very slightly and then progressively, with increasing SiO_2 content. The systematic decrease in the contents of TiO_2 , FeO_{t} , MgO , Al_2O_3 and CaO is compatible with progressive fractionation of plagioclase, Fe-Ti oxides, olivine and clinopyroxene, which is consistent with the observed mineralogy in the studied rocks (Appendix 1).

6.3. Trace elements

As observed in the multi-element diagrams (Fig. 5) most of the studied samples show enrichment in LILE compared to HFSE, relative to primitive mantle concentrations. High contents of Pb as well as a depletion in Nb-Ta, Ti and P are observed in rocks of all units. The volcanic rocks show a much larger dispersion in LILE than any of the plutonic lithologies, especially Cs and Rb. Such pattern is likely due to hydrothermal alteration or very low grade metamorphism. The rocks of the La Totora Formation have the lowest LILE contents but still enriched in this groups of elements compared to HFSE.

Both plutonic and volcanic units show rather steep chondrite-normalized REE patterns (Fig. 5), with $(\text{La}/\text{Yb})_{\text{N}}$ ranging from 3.4 to 52.2 for Permian rocks to 3.1 to 43.4 for Triassic rocks. Eu anomalies in volcanic rocks show a moderately negative correlation to SiO_2 in all units, suggesting a modest contribution of plagioclase fractionation to magma

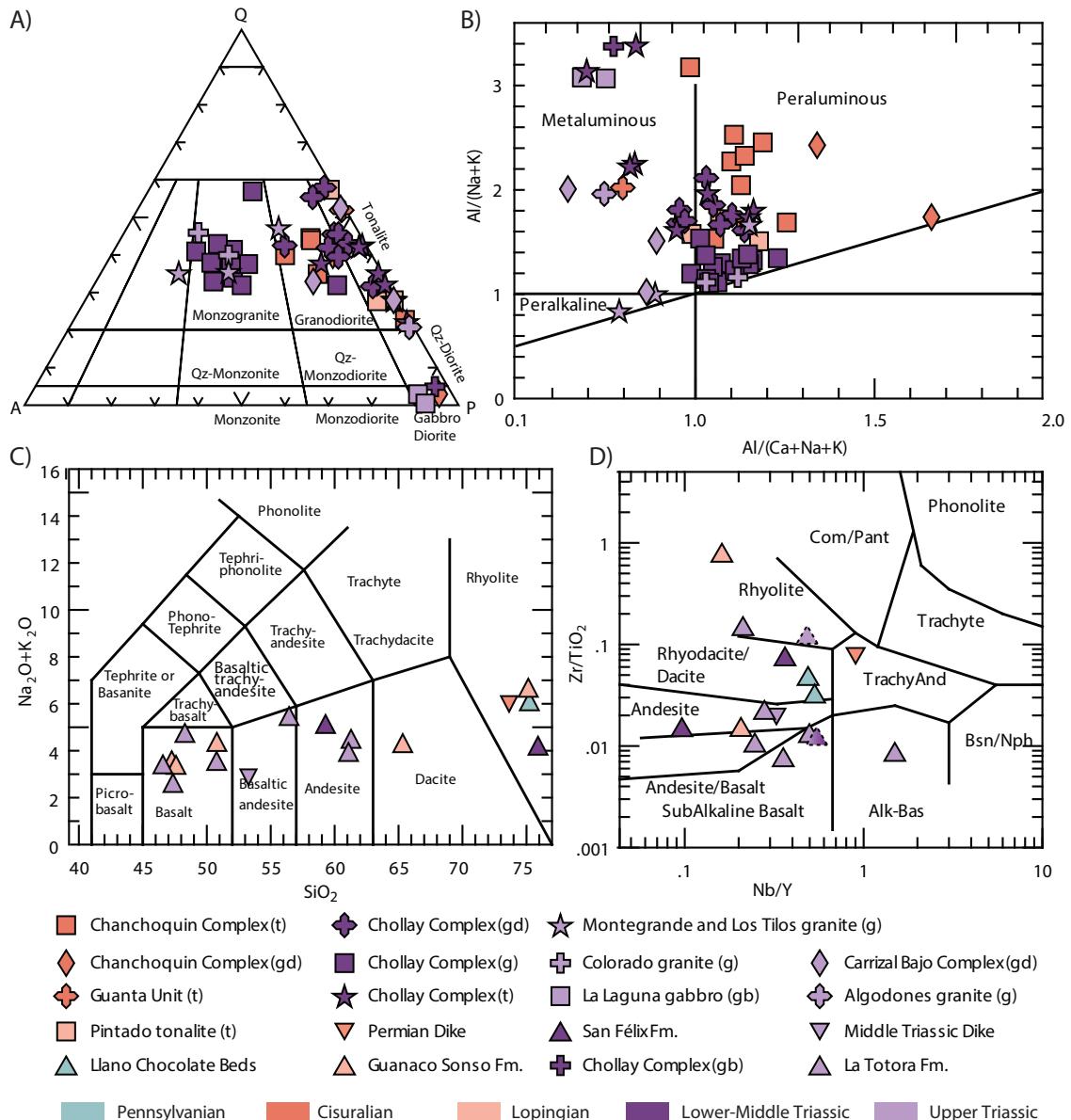


FIG. 4. A. QAP classification and B. alumina saturation index diagrams for plutonic rocks (Shand, 1927), C. TAS (Lebas *et al.*, 1986) and D. Nb/Y versus Zr/TiO_2 (Winchester and Floyd, 1977) classification diagrams for volcanic rocks. Symbols with dashed lines and color gradient represent the two strongly altered samples of volcaniclastic rocks from the San Félix (CPV-12-38) and La Totora (SCL-26Q) formation.

evolution. The Eu/Eu^* ranges from 0.6 to 1.2 in most of the volcanic rocks, and it around 1.0 for the majority of Triassic rocks (Fig. 6a), suggesting relatively high oxygen fugacity conditions for those magmas. The plutonic rocks also lack significant negative Eu anomalies but have a wider range of

Eu/Eu^* between 0.2 and 1.8 (Fig. 7a). The Upper Triassic intrusives, both in the Coastal and Frontal cordilleras, exhibit the most marked negative anomalies and most positive as well, whereas the Chollay complex and the Permian intrusions have Eu/Eu^* values around 1.

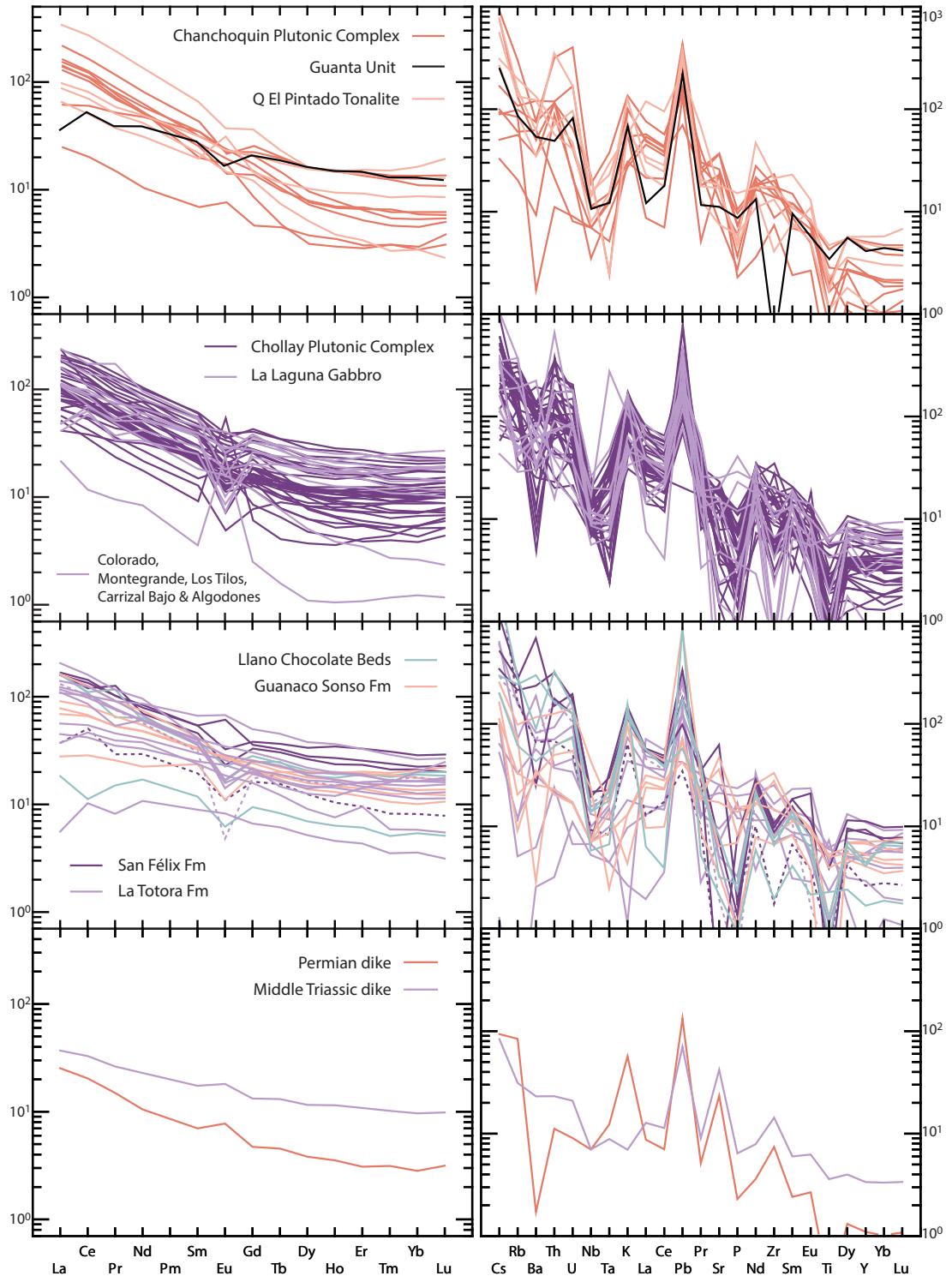


FIG. 5. Spider diagrams of chondrite-normalized rare earth (left) and primitive mantle-normalized (right) trace elements abundance in the studied rocks. Normalizing values are from Sun and McDonough (1989). Dashed lines represent the two strongly altered samples of volcaniclastic rocks from the San Félix (CPV-12-38) and La Totora (SCL-26Q) formation.

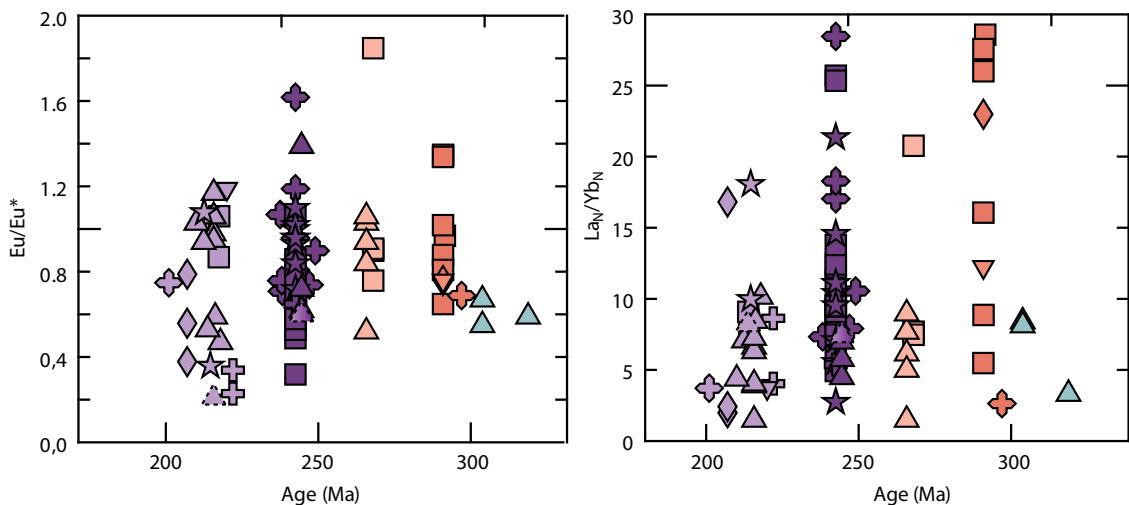


FIG. 6. Age versus Eu/Eu^* and $\text{La}_{\text{N}}/\text{Yb}_{\text{N}}$ for the studied samples. All REE values normalized to chondrite abundances (Sun and McDonough, 1989). Symbols with dashed lines and color gradient represent the two strongly altered samples of volcanoclastic rocks from the San Félix (CPV-12-38) and La Totora (SCL-26Q) formation.

7. Discussion

7.1 . Sources and evolution of the proto-Andean magmatism

The studied rocks are very heterogeneous both petrographically and from their major element composition. The trace elements content is also variable, but they display similar geochemical patterns (*e.g.*, REE) suggesting uniform chemical behavior (Fig. 5). In particular, the marked enrichment in LILE over HFSE is present in all the spider diagrams of figure 5, both for plutonic and volcanic rocks. The volcanic rocks are all subalkaline and plot within the calc-alkaline field of the AFM diagram (Fig. 7a). All but one of the basic and intermediate samples (CPV-12-24 of the La Totora Formation) have also HFSE contents representative of calc-alkaline affinities (Fig. 7b) and the more acidic rocks plot in the field of arc granites based on their LILE and HFSE contents (Fig. 7c, e). Although the number of analyzed volcanic rocks does not allow a robust statistical analysis, it is noteworthy to point out that they comprise the entire petrographic range for subalkaline volcanics, from basalt to rhyolites and there is no bimodal distribution in their composition (Fig. 4c, d). The plutonic rocks also lack bimodal distribution of their compositional ranges, and tonalite is the most abundant lithological

type, followed by monzogranite and grandiorite (Fig. 4a). Very few basic intrusions, such as gabbro or diorite, are found among the studied intrusive units (Fig. 4a). In the tectonic discrimination diagrams of Pearce *et al.* (1984), nearly all samples plot in the “Volcanic Arc Granite” field (Fig. 7d, f). Only two samples of the Colorado Syenogranite unit are outside this pattern, plotting in the field of “within plate magmatism” (Fig. 7d).

The Colorado Syenogranite, the La Laguna Gabbro and the Montegrande granite are among the intrusive units with alkaline within plate affinity that are described in the literature (Parada, 1981, 1982; 1988; Nasi *et al.*, 1985; Mpodozis and Kay, 1992) as representatives of the Upper Triassic magmatism. Taking into account the Colorado Syenogranite and the La Totora Formation samples analyzed in this study, it is clear that alkaline magmatism did occur during the Upper Triassic in the present-day Frontal Cordillera. Its volume and areal distribution however, seem to be significantly more restricted (Fig. 1) than that of the calc-alkaline magmatism as it was proposed before and it cannot be considered as representative of the main magmatic events or fluxes that built the continental crust during the Triassic. The origin of this alkaline magmatism may be related to the establishment of the arc in the present-day Coastal Cordillera (see below).

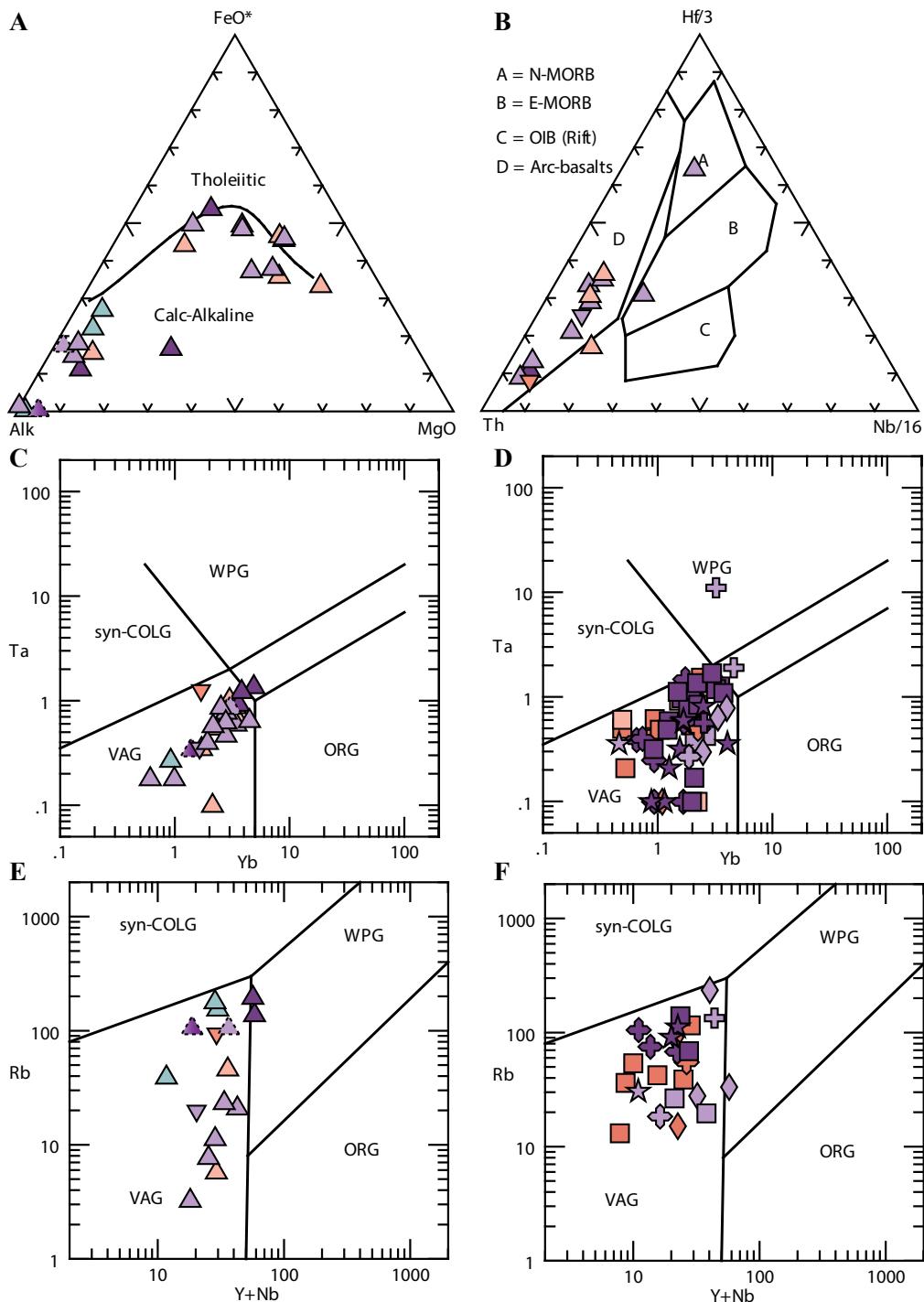


FIG. 7. Tectonic discrimination diagrams for the studied samples. **A**, AFM (Irvine and Baragar, 1971) and **B**, Th-Nb-Hf for basic and intermediate volcanic rocks; Yb versus Ta diagram (Pearce *et al.*, 1984) for **C**, acid volcanic and **D**, plutonic rocks; Yb+Nb versus Rb (Pearce *et al.*, 1984) for **E**, acid volcanic and **D**, plutonic rocks. Symbols with dashed lines and color gradient represent the two strongly altered samples of volcaniclastic rocks from the San Félix (CPV-12-38) and La Totora (SCL-26Q) formation.

All volcanic rocks are highly porphyritic, suggesting a probably elevated water content of the magmas that favored crystal growth over nucleation prior to volatile immiscibility or degassing (Cashman and Blundy, 2000; Winter, 2010). The ubiquitous presence of magnetite as the main Fe-Ti oxide mineral phase in both plutonic and volcanic rocks is also an indicator of rather elevated f_{O_2} conditions in the magmas (Buddington and Lindsley, 1964). Hydrated minerals such as amphibole and biotite occur in all the petrographic range of the plutonic rocks, from gabbro to syenogranite, which is an undoubtedly evidence that the magmas were hydrated. These petrographic and geochemical patterns are often interpreted as the result of flux-melting of an asthenospheric mantle source, a process that usually takes place at convergent margins where an oceanic plate is subducted under the continent (Stern, 2002 and references therein).

If the magmatic source was indeed a depleted mantle, subsequently metasomatized by fluids that enriched it in mobile elements released by mineral breakdown of hydrated minerals from the subducted slab, then an assimilation of the continental crust during the ascent of such mantle-derived melts is likely (Hildreth and Moorbarth, 1988), especially because the acid components in the plutonic and volcanic rocks are volumetrically dominant. The subduction-related signature is present in both peraluminous and metaluminous intrusives, suggesting that such signal is not only derived from crustal assimilation. Even though high SiO_2 , Na_2O , K_2O and REE contents are observed, evidences of fractional crystallization are not entirely coupled to this signal. For example the rocks with the highest REE contents lack the characteristic negative Eu-anomaly associated to fractionation of plagioclase during magma differentiation (Table 2). The degree of crustal assimilation during the Triassic must have been, however, restricted or at least lower than that of the Paleozoic magmatism. This is inferred from the alumina content of the plutonic rocks, which is generally lower for the Chollay and other Triassic intrusives than for the Permian plutons (Fig. 4b). A similar hypothesis has been presented by Hervé *et al.* (2014) and del Rey *et al.* (2016) for the plutonic rocks of the Frontal Cordillera at the same latitudes of the present study. Based on the coupled variation between $^{176}Hf/^{177}Hf$ and $d^{18}O$ and the crystallization age of zircons from these units, these authors concluded

that the crustal contamination of the magma sources decreased steadily from the Carboniferous to the Triassic. This is in agreement with the regional extension that should have taken place at continental margin as it has been proposed by several authors (Nasi *et al.*, 1985; Mpodozis and Ramos, 1989; Mpodozis and Kay, 1992) and can also be related to crustal thinning since La_N/Yb_N for Triassic rocks are lower than their Permian counterparts (Fig. 6b). The decrease of a crustal component in the magma sources during the Triassic therefore suggest that the geochemical signature of the studied rocks cannot be solely attributed to heritage from partial melting of a crustal protolith formed during the Gondwana orogeny or earlier.

7.2. Tectonic framework for the Triassic magmatism: passive or active continental margin?

Current models for the tectonic setting of the South American margin during the Triassic, propose that subduction ceased or it was significantly diminished due to global extensional forces operating on the tectonic plates at this time (Mpodozis and Ramos, 1989) or morphed into a soft collision due to accretion of an allochthonous terrain to the continental margin (Mpodozis and Kay, 1992). Evidences supporting these models come both from field geology and geochemistry of Permian to Triassic rocks cropping out in Chile and Argentina. However, in light of the recently updated geological cartography and the more robust geochemical databases for relevant units, alternative tectonic setting cannot be ruled out (Del Rey *et al.*, 2016).

The lines of evidence for the extensional-setting model in present-day Argentinean territory are in summary: **a.** the existence of huge volume of acid magmatism genetically related to crustal anatexis, represented by the Choiyoi group, a unit that is located along the eastern flank of the Andes, between 20° and 40°S (Llambías and Sato, 1990, 1995; Llambías *et al.*, 1993, 2003); **b.** the generation of basaltic flows of alkaline or within plate geochemical signature, genetically related to the last stage of the Choiyoi Group magmatism (Ramos and Kay, 1991), **c.** the sedimentological and structural framework of rift activity in the Cuyo and Ichigualasto basins, both of Lower to Upper Triassic age (Spalletti, 1997; Spalletti *et al.*, 2006; Giambiagi and Martínez, 2008; Giambiagi

et al., 2011) and d) the petrological, sedimentological and structural framework of rift, and subduction-related, activity for the Uppermost Triassic-Lower Jurassic Pre-Cuyo group of the Neuquén Basin in Argentina (Spaletti, 1997; Franzese and Spaletti, 2001; Bechis *et al.*, 2010; D'Elia *et al.*, 2012a, b).

Along the western flank of the Andes and the forearc region of northern Chile between 28 and 31° S, however, the magmatic units that can be related to rift activity are scarce. Bimodal magmatism with crustal or intraplate signature has been reported in the Middle to Upper Triassic Pichidangui Formation (Morata *et al.*, 2000) and in the Limarí Complex (Parada *et al.*, 1991, 1999) at the Coastal Cordillera of north central Chile; and bimodal intrusions of Upper Triassic age had long been recognized in the Frontal Cordillera (~29–30° S) (Parada, 1982, 1988; Nasi *et al.*, 1985; Mpodozis and Kay, 1992; Hervé *et al.*, 2014). In both cases, the volume of magmatism is restricted to the total volume of volcanism and plutonism of the Triassic period (see Fig. 1). Some of the Permian to Lower Triassic volcanic units that are considered to be equivalent to the Choiyoi Group (La Tabla, Pantanoso and Guanaco Sonso/Pastos Blancos formations) do not exhibit geochemical features of extensive crustal contribution, furthermore, the available isotopic data from the literature, would favor the hypothesis of mixed magma sources, a depleted mantle and the continental crust (Parada, 2013; Hervé *et al.*, 2014; Del Rey *et al.*, 2016). Alkaline and/or tholeiitic basalts associated to the late stages of this acid magmatism, and commonly interpreted as dry primitive volcanism resulting from low degrees of decompression melting of the ascending asthenospheric mantle in a rift context, is not found. Basaltic and basaltic-andesitic flows that could correspond to rift activity are described in units such as the La Totora, La Ternera and Quebrada del Salitre Formation in the Precordillera and Frontal cordillera between 27° and 30° S, but they lack alkaline geochemical signature and their age is constrained to the Late Triassic (Reutter, 1974; Ribba *et al.*, 1988; Blanco, 1996; Cornejo and Mpodozis, 1997), more than 20 Ma after ceasing of the Choiyoi-related acid volcanism (Llambías *et al.*, 1993). Recent works have reported Triassic ages for some of the accretionary prisms in northernmost Chile (Casquet *et al.*, 2014), suggesting that generation of an accretionary wedge as the result of subduction of an oceanic plate at the continental margin was an

ongoing process at least until the Triassic and did not stop prior to the Carboniferous as it has been proposed before (Parada *et al.*, 1999)

The differences in the magmatic products at both sides of the Andean range are thus important and call for likely distinct patterns of lithospheric evolution during the Triassic. In the continental interior, stretching of the lithosphere induced crustal anatexis due to ascent of the asthenospheric mantle generating well developed NW-oriented depocenters that accommodated the rift deformation (Spaletti, 1997; Llambías *et al.*, 2003; Giambiagi *et al.*, 2011). The geochemical and petrological characteristics of the volcanic and plutonic rocks studied in this paper strongly suggest that they were generated in a subduction setting and the subduction was a continuous process that generated most of the magmatism in the arc region (Fig. 8a).

7.3. Permian to Triassic margin architecture in the studied segment

Even though evidences supporting the idea that continental margin was subjected to active subduction of an oceanic plate during the Triassic have been collected from petrology and geochemistry, the architecture of the supra-subduction zone is still undetermined. The Llano de Chocolate beds have been interpreted as forearc magmatism occurred during the Permian because of their location close to the coeval accretionary prism (Creixell *et al.*, 2016). Given the texture and composition of the Chancoquin and Chollay plutonic complexes (coarse grained, mainly granodioritic to tonalitic, biotite and hornblende-bearing intrusives), they can be interpreted as representative of the root of an active continental magmatic arc developed from the Permian to the Middle Triassic (Pitcher *et al.*, 1985; Pitcher, 1993; Winter, 2010). The Triassic Guanaco Sonso and Pastos Blancos formations would then represent shallower parts of the arc region, and the San Félix Formation would represent a proximal forearc basin that was active at least until the Early Triassic. Both units are composed of rhyolithic volcanic rocks similar in texture and composition to the subduction-related Miocene to recent acid volcanism emplaced in the same segment of the Andean arc (Kay and Mpodozis, 2001, 2002; Kay *et al.*, 2013).

The La Totora Formation on the other hand, is composed of more undifferentiated volcanics and

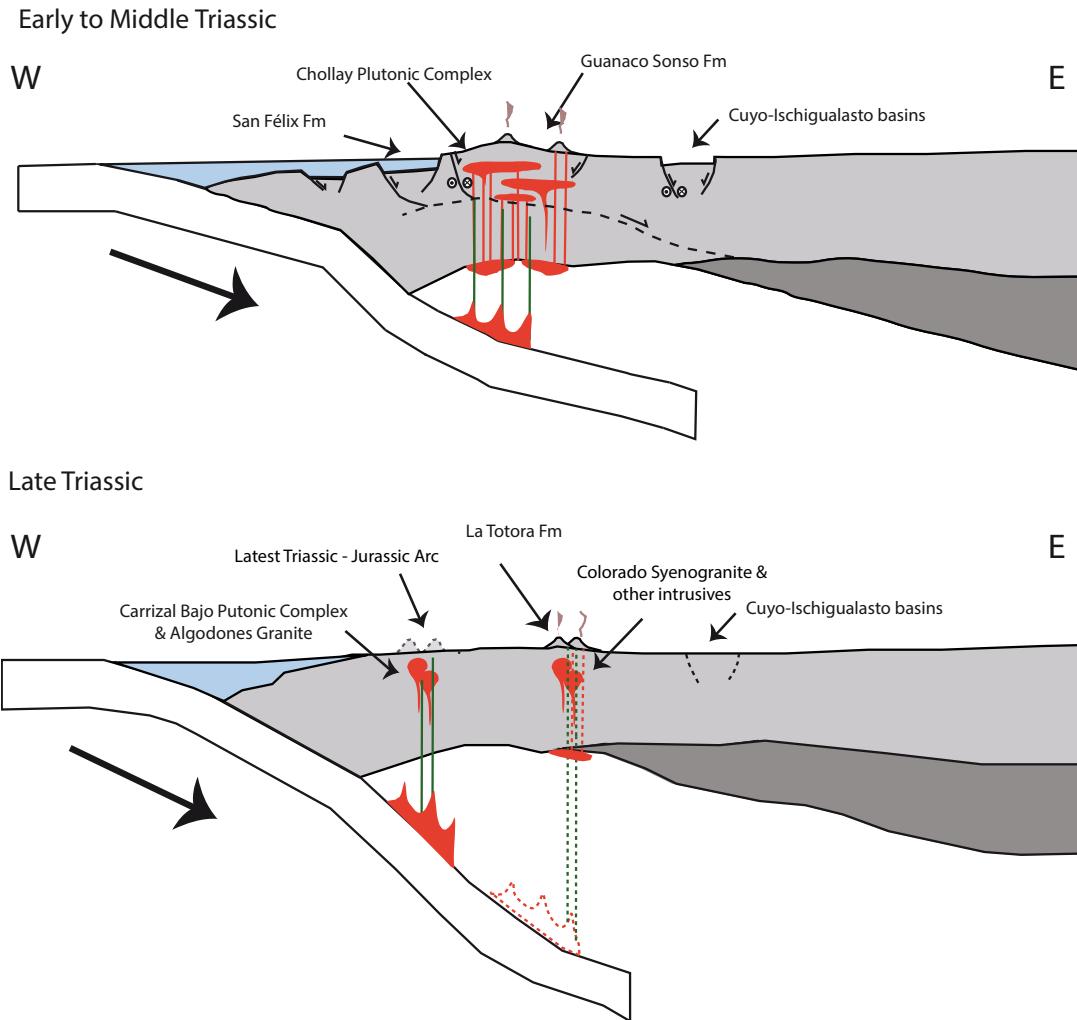


FIG. 8. Proposed tectonic setting for the Triassic magmatism at 28°-30°15' S in the South American margin.

restricted to the Norian-Raethian, although it still retains the subduction-related geochemical and petrological signature. During the Upper Triassic plutonic bodies with alkaline or within plate affinities were intruded (La Laguna Gabbro, Colorado Syenogranite, Montegrande granite). The data presented in this study indicate that these units also have the geochemical signature of arc magmas, but along with the La Totora Formation they comprise the time frame prior to the establishment of the arc at the Coastal Cordillera during the Hettangian (Mpodozis and Ramos, 1989; Parada *et al.*, 1999) (Fig. 8b). The first pulses of the well-known early Andean arc are represented by the La Negra Formation

and its equivalents (Rogers and Hawkesworth, 1989; Pichowiak *et al.*, 1990; Pichowiak, 1994) but given the signature of the Coastal Cordillera plutonic bodies studied in this work, they may have been the result of the earliest arc activity in the present-day coastal region. Furthermore, recent studies have reported Rhaetian volcanism in the Coastal Cordillera at 20°-22° S (Sepúlveda *et al.*, 2014). Changes in the geometry of the subducted lithosphere or in tectonic conditions of the upper plate may have induced shift in the arc locus from the Frontal Cordillera to the Coastal Cordillera, but the precise timing and origin of such shifting is yet unknown.

8. Concluding remarks

The Triassic magmatism at the present-day Coastal and Frontal Cordilleras between 28°00' and 29°30' S is mainly represented by plutonic units comprising tonalitic to monzogranite rocks, with scarce syenogranites and more basic rocks such as gabbro and diorite, of which the Chollay Plutonic Complex is the volumetrically most important. Volcanic sequences are more restricted but not uncommon, and they are composed of rocks ranging from basalt to rhyolite, being more abundant the differentiated rocks.

The Permian to Jurassic rocks have petrological and geochemical characteristics typical of subduction-related magmas: calc-alkaline or volcanic arc granite affinities, mafic hydrated minerals as major constituent of the rocks, highly porphyritic texture in the volcanics, magnetite as the main Fe-Ti oxide mineral phase, systematic enrichment of LILE versus HFSE when compared to primitive mantle abundances and Nb-Ta troughs. Although alkaline magmatism of within plate affinities is also found, it is significantly more restricted in terms of total volume and areal distribution and unlikely to be representative of the main Triassic magmatic events.

The detailed architecture of the Andean margin from the Permian to the Triassic is relatively unknown. The Chanchoquín and Chollay plutonic complexes would represent the roots of a magmatic arc developed from the Permian to the Middle or early Late Triassic, whereas the Guanaco Sonso and Pastos Blancos formations would be the shallower parts of the volcanic arc. The San Félix formation likely represent a forearc basin developed throughout the Triassic. The La Totora Formation and some intrusive units that may have slight intraplate or transitional geochemical signature are products of a magmatism developed immediately before the establishment of the magmatic arc in the present-day coastal cordillera, which took place at some time during the Rhaetian to Early Jurassic.

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References

- Arévalo, C.; Welkner, D. 2008. Geología del área Carrizal Bajo-Chacritas, Región de Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 111: 67 p., 1 mapa 1:100.000.
- Bechis, F.; Giambiagi, L.; García, V.; Lanés, S.; Cristallini, E.; Tunik, M. 2010. Kinematic analysis of a transtensional fault system: The Atuel depocenter of the Neuquén basin, southern Central Andes, Argentina. *Journal of Structural Geology* 32: 886-899. doi: 10.1016/j.jsg.2010.03.009.
- Blanco, N. 1996. Sedimentología y ambientes depositacionales de la Formación La Ternera, Triásico Superior de la Precordillera Andina de Copiapó, Región de Atacama, Chile, Memoria de Título (Inédito), Universidad de Concepción: 250 p. Concepción.
- Brook, M.; Pankhurst, R.; Sheperd, G.; Spiro, T. 1987. Anderhon: Andean geochronology and metallogenesis. British Geological Survey, Overseas Development Administration (unpublished open file report): 137 p. London.
- Buddington, A.F.; Lindsley, D.H. 1964. Iron-titanium oxide minerals and synthetic equivalents. *Journal of Petrology* 54: 310-357.
- Cashman, K.; Blundy, J. 2000. Degassing and crystallization of ascending andesite and dacite. *Philosophical Transactions of the Royal Society of London Series A*, 358 (1770): 1487-1513.
- Casquet, C.; Hervé, F.; Pankhurst, R.J.; Baldo, E.; Calderón, M.; Fanning, C.M.; Rapela, C.W.; Dahlquist, J. 2014. The Mejillonia suspect terrane (Northern Chile): Late Triassic fast burial and metamorphism of sediments in a magmatic arc environment extending into the Early Jurassic. *Gondwana Research* 25: 1272-1286.
- Chapman, A.D.; Ducea, M.N.; McQuarrie, N.; Coble, M.; Petrescu, L.; Hoffman, D. 2015. Constraints on plateau architecture and assembly from deep crustal xenoliths, northern Altiplano (SE Perú). *Geological Society of America Bulletin* 127: 1777-1797.
- Cornejo, P.; Mpodozis, C. 1997. El rift Triásico-Sinemuriano de Sierra Exploradora, Cordillera de Domeyko (25°-26°): asociaciones de facies y reconstrucción tectónica. In Congreso Geológico Chileno, No. 8, Actas 1: 550-554. Antofagasta.
- Creixell, C.; Parada, M.A.; Morata, D.; Roperch, P.; Arriagada, C. 2009. The genetic relationship between mafic dike swarms and plutonic reservoirs in the Mesozoic of central Chile (30°33'45'' S): Insights from AMS and geochemistry. *International Journal of Earth Sciences* 98: 177-201.

- Creixell, C.; Ortiz, M.; Arévalo, C. 2012. Geología del área Carrizalillo-El Tofo, Regiones de Atacama y Coquimbo. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 133-134: 82 p., 1 mapa 1:100.000.
- Creixell, C.; Labbé, M.; Arévalo, C.; Salazar, E. 2013. Geología del área Estación Chañar-Junta de Chingoles, Regiones de Atacama y Coquimbo. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 150: 85 p., 1 mapa escala 1:100.000. Santiago.
- Creixell, C.; Oliveros, V.; Vásquez, P.; Navarro, J.; Vallejos, D.; Valin, X.; Godoy, E.; Ducea, M.N. 2016. Geodynamics of Late Carboniferous Early Permian forearc in north Chile ($28^{\circ}30'-29^{\circ}30' S$). Journal of the Geological Society 173 (5): 757-772. doi:10.1144/jgs2016-010.
- Del Rey, A.; Arriagada, C.; Dekart, K.; Martínez, F. 2016. Resolving the paradigm of the late Paleozoic-Triassic Chilean magmatism: Isotopic approach. Gondwana Research 37: 172-181. doi: 10.1016/j.gr.2016.06.008.
- D'Elia, L.; Muravchik, M.; Franzese, J.R.; Bilmes, A. 2012a. Volcanismo de sin-rift de la Cuenca Neuquina, Argentina: relación con la evolución Triásico Tardío-Jurásico Temprano del margen Andino. Andean Geology 39 (1): 106-132. doi: 10.5027/andgeoV39N1-a06.
- D'Elia, L.; Muravchik, M.; Franzese, J.R.; López, L. 2012b. Tectonostratigraphic analysis of the Late Triassic-Early Jurassic syn-rift sequence of the Neuquén Basin in the Sanico depocentre, Neuquén Province, Argentina. Andean Geology 39(1): 133-157. doi: 10.5027/andgeoV39N1-a07.
- Franzese, J.R.; Spalletti, L.A. 2001. Late-Triassic-Early Jurassic continental extension in southwestern Gondwana: tectonic segmentation and pre-break-up rifting. Journal of South American Earth Sciences 14: 257-270. doi:10.1016/S0895-9811(01)00029-3.
- Gehrels, G.E.; Valencia, V.A.; Ruiz, J. 2008. Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry: Geochemistry Geophysics Geosystems, Q03017. doi: 10.1029/2007GC001805.
- Giambiagi, L.; Martínez, A. 2008. Permo-Triassic oblique extension in the Potrerillos-Uspallata area, western Argentina. Journal of South American Earth Sciences 26: 252-260. doi: 10.1016/j.jsames.2008.08.008.
- Giambiagi, L.; Mescua, J.; Bechis, F.; Martínez, A.; Folguera, A. 2011. Pre-Andean deformation of the Precordillera southern sector, southern Central Andes. Geosphere 7: 219-239. doi: 10.1130/GES00572.1.
- Godoy, E.; Lara, L. 1998. Hojas Chañaral y Diego de Almagro, Región de Atacama. Servicio Nacional de Geología y Minería, Mapas Geológicos 5-6, 1 mapa escala 1:100.000.
- Hervé, F.; Fanning, C.M.; Calderón, M.; Mpodozis, M. 2014. Early Permian to Late Triassic batholiths of the Chilean Frontal Cordillera ($28^{\circ}-31^{\circ}S$): SHRIMP U-Pb zircon ages and Lu-Hf and O isotope systematics. Lithos 184-187: 436-446. doi:10.1016/j.lithos.2013.10.018.
- Hildreth, W.; Moorbath, S. 1988. Crustal contributions to arc magmatism in the Andes of Central Chile. Contributions to Mineralogy and Petrology 98: 455-489.
- Irvine, T.; Baragar, W. 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences 8: 523-548.
- Kay, S.M.; Mpodozis, C. 2001. Central Andean ore deposits linked to evolving shallow subduction systems and thickening Crust. GSA Today 11: 4-9.
- Kay, S.M.; Mpodozis, C. 2002. Andean Adakites: Three Ways to Make Them. Acta Petrologica Sinica 18: 303-311.
- Kay, S.M.; Mpodozis, C.; Gardeweg, M. 2013. Magma sources and tectonic setting of Central Andean andesites ($25.5-28^{\circ}S$) related to crustal thickening, forearc subduction erosion and delamination. In Orogenic Andesites and Crustal Growth (Gómez-Tuena, A.; Straub, S.M.; Zellmer, G.F.; editors). Geological Society, Special Publication 385: 303-334. London.
- Lebas, M.J.; Lemaitre, R.W.; Streckeisen, A.; Zanettin, B. 1986. A Chemical Classification of Volcanic-Rocks Based on the Total Alkali Silica Diagram. Journal of Petrology 27: 745-750.
- Llambías, E.J.; Sato, A.M. 1990. El Batolito de Colangüil, cordillera frontal de Argentina: estructura y marco tectónico. Revista Geológica de Chile 17 (1): 89-108. doi: 10.5027/andgeoV17n1-a04.
- Llambías, E.J.; Sato, A.M. 1995. El Batolito de Colangüil: transición entre orogénesis y anorogénesis. Revista de la Asociación Geológica Argentina 50 (1-4): 111-131. Buenos Aires.
- Llambías, E.J.; Kleiman, L.E.; Salvarredi, J.A. 1993. El Magmatismo Gondwánico. In Geología y Recursos Naturales de Mendoza (Ramos, V.; editor). Congreso Geológico Argentino, No. 12 y Congreso de Exploración de Hidrocarburos, No. 2. Relatorio: 53-64. Mendoza.

- Llambías, E.J.; Quenardelle, S.; Montenegro, T. 2003. The Choiyoi Group from central Argentina: a sub-alkaline transitional to alkaline association in the craton adjacent to the active margin of the Gondwana continent. *Journal of South American Earth Sciences* 16: 243-257.
- Ludwig, K.R. 2003. Isoplot/EX version 3.0, a geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center, Special Publication.
- Maksaev, V.; Munizaga, F.; Tassinari, C. 2014. Timing of the magmatism of the paleo-Pacific border of Gondwana: U-Pb geochronology of Late Paleozoic to Early Mesozoic igneous rocks of the north Chilean Andes between 20° and 31°S. *Andean Geology* 41 (3): 447-506. doi: 10.5027/andgeoV41n3-a01
- Martin, M.W.; Clavero R., J.; Mpodozis, M., C. 1999. Late Paleozoic to Early Jurassic tectonic development of the high Andean Principal Cordillera, El Indio Region, Chile (29-30°S). *Journal of South American Earth Sciences* 12: 33-49.
- Martínez, F.; Arriagada, C.; Mpodozis, C.; Peña, M. 2012. The Lautaro Basin: A record of inversion tectonics in northern Chile. *Andean Geology* 39 (2): 258-278. doi: <http://dx.doi.org/10.5027/andgeoV39n2-a04>.
- Martínez, F.; Peña, M.; Arriagada, C. 2015. Geología del área Iglesia Colorada-Cerro del Potro y Cerro Mondaquita, región de Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 179-180, 1 mapa escala 1:100.000. Santiago.
- Morata, D.; Aguirre, L.; Oyarzún, M.; Vergara, M. 2000. Crustal contribution in the genesis of the bimodal Triassic volcanism from the Coastal Range, central Chile. *Revista Geológica de Chile* 27 (1): 83-98. doi: 10.5027/andgeoV27n1-a06.
- Moscoso, R.; Mpodozis, C. 1988. Estilos estructurales en el norte chico de Chile (28-31°S), regiones de Atacama y Coquimbo. *Revista Geológica de Chile* 15 (2): 151-166. doi: 10.5027/andgeoV15n2-a04.
- Moscoso, R.; Mpodozis, C.; Nasi, C.; Ribba, L.; Arévalo, C. 2010. Geología de la Hoja El Tránsito, Región de Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Preliminar 7: 17 p., 1 mapa escala 1:250.000. Santiago.
- Mpodozis, C.; Cornejo, P. 1988. Hoja Pisco Elqui, Región de Coquimbo. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 68: 120 p., 1 mapa escala 1:250.000. Santiago.
- Mpodozis, C.; Ramos, V. 1989. The Andes of Argentina and Chile. In *Geology of the Andes and its relation to hydrocarbon and mineral resources* (Erickson, G.E.; Cañas Pinochet, M.T.; Reinemund, J.A.; editors). Circumpacific Council for Energy and Mineral Resources, Earth Science Series 11: 59-90.
- Mpodozis, C.; Kay, S. 1992. Late Paleozoic to Triassic evolution of the pacific Gondwana margin: evidence from Chilean frontal Cordilleran batholiths. *Geological Society of America Bulletin* 104: 999-1014.
- Nasi, C.; Mpodozis, C.; Moscoso, R.; Maksaev, V.; Cornejo, P. 1985. El Batolito Elqui-Limarí (Paleozoico Superior-Triásico): características petrográficas, geoquímicas y significado tectónico. *Revista Geológica de Chile* 25-26: 77-111. doi: 10.5027/andgeoV12n2-3-a06.
- Nasi, C.; Moscoso, R.; Maksaev, V. 1990. Hoja Guanta. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 67: 141 p., 1 mapa escala 1:250.000.
- Ortiz, M.; Merino, R.N. 2015. Geología de las áreas Río Chollay-Matancilla y Cajón del Encierro, regiones de Atacama y Coquimbo. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 175-176, 1 mapa escala 1:100.000.
- Parada, F. 2013. Geoquímica de las rocas ígneas del Carbonífero-Triásico de la Alta Cordillera, Región de Atacama, Chile. Memoria de Título (Inédito), Universidad de Chile, Departamento de Geología: 93 p. Santiago.
- Parada, M.A. 1981. Lower Triassic Alkaline Granites of Central Chile (30°S) in the High-Andean Cordillera. *Geologische Rundschau* 70: 1043-1053.
- Parada, M.A. 1982. Petrology of the Lower Triassic anorogenic granites in the High Andes (30°S), Chile. Ph.D. Thesis (Unpublished). Tohoku University, 165 p. Japan.
- Parada, M.A. 1984. La asociación de granitos subsolvus e hipersolvus del plutón Monte Grande (Chile 30°S) y el desarrollo de sus pertitas. *Revista Geológica de Chile* 23: 69-77. doi: <http://dx.doi.org/10.5027/andgeoV11n3-a05>.
- Parada, M.A. 1988. Pre-Andean peraluminous and metasilicic leucogranitoid suites in the High Andes of Central Chile. *Journal of South American Earth Sciences* 1 (2): 211-221.
- Parada, M.A.; Levi, B.; Nyström, J.O. 1991. Geochemistry of the Triassic to Jurassic plutonism of central Chile (30 to 33°S); Petrogenetic implications and a tectonic discussion. *Geological Society of America, Special Paper* 265: 99-112. doi: 10.1130/SPE265-p99.

- Parada, M.A.; Levi, B.; Nyström, J.O. 1999. Multiple sources for the Coastal Batholith of central Chile (31-34°S): geochemical and Sr-Nd isotopic evidence and tectonic implications. *Lithos* 46: 505-521. doi: 10.1016/S0024-4937(98)00080-2.
- Pearce, P.A.; Harris, N.B.W.; Tindle, A.G. 1984. Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks. *Journal of Petrology* 25: 956-983. doi: 10.1093/petrology/25.4.956.
- Peccerillo, A.; Taylor, S.R. 1976. Geochemistry of eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. *Contributions to Mineralogy and Petrology* 58: 63-81.
- Pichowiak, S.; Buchelt, M.; Damm, K.W. 1990. Magmatic activity and tectonic setting of early stages of Andean cycle in northern Chile. *Geological Society of America, Special Paper* 241: 127-144.
- Pichowiak, S. 1994. Early Jurassic to Early Cretaceous magmatism in the Coastal Cordillera and the Central Depression of North Chile. In *Tectonics of the Southern Central Andes* (Reutter, K.J.; Scheuber, E.; Wigger, P.; Editors). Springer: 203-217. Heidelberg.
- Pitcher, W.S. 1993. *The Nature and Origin of Granite*. Blackie: 321 p. London.
- Pitcher, W.S.; Atherton, M.P.; Cobbing, E.J.; Beckensale (editors). 1985. *Magmatism at a Plate Edge. The Peruvian Andes*. Springer: 328 p. Berlin.
- Poma, S.; Zappettini, E.O.; Quenardelle, S.; Santos, J.O.; Koukharsky, M.; Belousova, E.; McNaughton, N. 2014. Geochemistry, U-Pb SHRIMP zircon dating and Hf isotopes of the Gondwanan magmatism in NW Argentina: petrogenesis and geodynamic implications. *Andean Geology* 41: 267-292. doi: 10.5027/andgeoV41n2-a01.
- Ramos, V.A.; Kay, S.M. 1991. Triassic rifting and associated basalts in the Cuyo basin, central Argentina. In *Andean magmatism and its tectonic setting* (Harmon, R.S.; Rapela, C.W.; editors). Geological Society of America, Special Papers 265: 79-91. Boulder.
- Reutter, K.J. 1974. Entwicklung und Bauplan der chilenischen Hochkordillere im Bereich 29° südlicher Breite. *Neues Jahrbuch für Geologie und Palaontologie* 146: 153-178.
- Ribba, L. 1985. *Geología Regional del Cuadrángulo El Tránsito, Región de Atacama. Memoria de Título (Inédito)*, Universidad de Chile: 203 p. Santiago.
- Ribba, L.; Mpodozis, C.; Hervé, F.; Nasi, C.; Moscoso, R. 1988. El basamento del valle del Tránsito, Cordillera de Vallenar: eventos magmáticos y metamórficos y su relación con la evolución paleozoica de los Andes Chileno-Argentinos. *Revista Geológica de Chile* 15 (2): 129-149. doi: 10.5027/andgeoV15n2-a03.
- Rogers, G.; Hawkesworth, C.J. 1989. A geochemical traverse across the North Chilean Andes: Evidence for crust generation melt from the mantle wedge. *Earth and Planetary Science Letters* 91: 271-285.
- Rossel, P.; Oliveros, V.; Ducea, M.; Charrier, R.; Scaillef, S.; Retamal, L.; Figueroa, O. 2013. The Early Andean Subduction system as an analogue to island arcs: evidence from across-arc geochemical variations in northern Chile. *Lithos* 179: 211-230. doi: 10.1016/j.lithos.2013.08.014.
- Salazar, E.; Coloma, F.; Creixell, C. 2013. *Geología del área El Tránsito-Lagunillas, Región de Atacama*. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 149: 121 p., 1 mapa 1:100.000.
- Salazar, E.; Coloma, F. 2016. *Geología del área Cerros de Cantaritos-Laguna Chica, Región de Atacama*. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 181: 171 p., 1 mapa 1:100.000.
- Sepúlveda, F.; Vásquez, P.; Quezada, A. 2014. *Cartas Patillos y Oficina Victoria, Región de Tarapacá*. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 167-168: 1 mapa 1:100.000.
- Shand, S.J. 1927. *The eruptive rocks*. John Wiley: 488 p. New York.
- Spallètti, L.A. 1997. Western Argentinian Triassic basin: origin and evolution. *Acta Geologica Hispanica* 32: 29-50.
- Spallètti, L.A.; Fanning, C.M.; Rapela, C.W. 2006. Dating the Triassic continental rift in the southern Andes: the Potrerillos Formation, Cuyo Basin, Argentina. *Geologica Acta* 6: 267-283. doi: 10.1344/105.00000256.
- Stacey, J.S.; Kramers, J.D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters* 26: 207-221.
- Stern, R.J. 2002. Subduction zones. *Reviews in Geophysics* 40: 1012. doi: 10.1029/2001RG000108.
- Sun, S.S.; McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geological Society, Special Publication* 42: 313-345.
- Valin, X. 2014. *Geoquímica de las unidades del Triásico a Jurásico Inferior en el norte de Chile (28°00'-29°30'S): implicancias para el inicio de la subducción*. Memoria

- de Título (Inédito), Universidad de Concepción, Departamento de Ciencias de la Tierra: 104 p. Concepción.
- Vallejos, D. 2014. Estudio sedimentológico y estructural de la Formaciones Canto de Agua, San Félix, La Totora y Estratos del Verraco: implicancia en la evolución triásica del margen andino. Memoria de Título (Inédito), Universidad de Concepción, Departamento de Ciencias de la Tierra: 104 p. Concepción.
- Vásquez, P.; Glodny, J.; Franz, G.; Frei, D.; Romer, R.L. 2011. Early Mesozoic plutonism of the Cordillera de la Costa (34°-37°S), Chile: Constraints on the onset of the Andean Orogeny. *The Journal of Geology* 119 (2): 159-184.
- Welkner, D.; Arévalo, C.; Godoy, E. 2006. Geología del área Freirina-El Morado, Región de Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 100: 50 p., 1 mapa 1:100.000.
- Winchester, J.A.; Floyd, P.A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology* 20: 325-343.
- Winter, J.D. 2010. An introduction to igneous and metamorphic petrology, 2nd ed. Pearson Prentice Hall: 702 p. New Jersey.

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