Across and along arc geochemical variations in altered volcanic rocks: Evidence from mineral chemistry of Jurassic lavas in northern Chile, and tectonic implications

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ABSTRACT

Postmagmatic processes mask the original whole-rock chemistry of most Mesozoic igneous rocks from the Andean arc and back-arc units preserved in Chile. Mineral assemblages corresponding to subgreenschist metamorphic facies and/or propylitic hydrothermal alteration are ubiquitous in volcanic and plutonic rocks, suggesting element mobility at macroscopic and microscopic scale. However, fresh primary phenocrysts of clinopyroxene and plagioclase do occur in some of the altered rocks. We use major and trace element chemistry of such mineral phases to infer the geochemical variations of four Jurassic arc and four back-arc units from northern Chile. Clinopyroxene belonging to rocks of the main arc and two units of the back-arc are augites with low contents of HFSE and REE; they originated from melting of an asthenospheric mantle source. Clinopyroxenes from a third back-arc unit show typical OIB affinities, with high Ti and trace element contents and low Sr. Trace elemental variations in clinopyroxenes from these arc and back-arc units suggest that olivine and clinopyroxene were the main fractionating phases during early stages of magma evolution. The last back-arc unit shows a broad spectrum of clinopyroxene compositions that includes depleted arc-like augite, high Al and high Sr–Ca diopsid (adakite-like signature). The origin of these lavas is the result of melting of a mixture of depleted mantle plus Sr-rich sediments and subsequent high pressure fractionation of garnet. Thermobarometric calculations suggest that the Jurassic arc and back-arc magmatism had at least one crustal stagnation level where crystallization and fractionation took place, located at ca. -8–15 km. The depth of this stagnation level is consistent with lower-middle crust boundary in extensional settings. Crystallization conditions calculated for high Al diopsides suggest a deeper stagnation level that is not consistent with a thinned back-arc continental crust. Thus minor garnet fractionation occurred before these magmas reached the base of the crust. The presented data support the existence of a heterogeneous sub arc mantle and complex magmatic processes in the early stages of the Andean subduction.

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1. Introduction

All the volcanic rocks that record the early Andean subduction system (Jurassic to Lower Cretaceous) exhibit some degree of hydrothermal alteration and or low grade metamorphism, part of which may have taken place in contact with seawater under submarine conditions, as well as subsequent contact and regional metamorphism related to the emplacement of later arc magmas (Aguirre et al., 1989; Levi et al., 1989; Losert, 1974; Oliveros et al., 2008; Robinson et al., 2004). The secondary mineral assemblages observed in lavas, dikes and related volcaniclastic rocks, (chlorite–epidote–quartz–calcite–titanite–sericite–actinolite–K-feldspar–zoisite–prehnite–pumpellylite) represent either propylitic hydrothermal alteration or greenschist or sub-greenschist facies low-grade metamorphic events that took place during the Mesozoic (Losert, 1974; Oliveros et al., 2006; Parada et al., 2007; Robinson et al., 2004; Tristá-Aguilera et al., 2006). Considering that under the above described metamorphic conditions large ion lithophile elements (LILE), low field strength elements (LFSE) and some high field strength elements (HFS) can have a mobile behavior, the original composition of the rocks may have been obliterated, which limits our ability to decipher their original elemental and isotopic characteristics, and prevents a robust petrogenetic interpretation for the Andean magmatism during the Mesozoic.

Most of the work discussing the petrogenesis of the Jurassic to Lower Cretaceous Andean volcanics has focused on the study of the less mobile
elements (i.e.: the rare earth and high field strength elements), the isotopic ratios of volcanic rocks and the comparison with the composition of co-genetic less altered intrusive bodies (Kramer et al., 2005; Lucassen et al., 2006; Oliveros et al., 2006, 2007; Palacios, 1978; Parada et al., 1999; Rogers and Hawkesworth, 1989; Vergara et al., 1995). This geochemical comparison to contemporaneous unaltered intrusions is not possible in the case of the Upper Jurassic back arc volcanics (Rossel et al., 2013), since back arc plutonic rocks, if they exist, are not exposed in this area.

The chemistry of primary magmatic mineral phases can be an important tool for the characterization of magmatism. Ever since the definition by Bowen (1928) of the continuous and discontinuous crystallization series in igneous rocks, there are numerous examples of successful methodologies that use mineral compositions to assess petrogenetic conditions; for instance the tectonic discrimination diagrams based on clinopyroxene composition in basalts (Lettier et al., 1982), the characterization of magmatism based on trace and rare earth elements (REE) compositions of clinopyroxenes and other primary mineral phases (Marks et al., 2004; Vannucci et al., 1993) and several thermo-barometers based on melt (whole rock)—mineral equilibrium (Putirka, 2005, 2008; Putirka et al., 2003). Therefore, if the chemistry of some primary igneous mineral phases is not changed during secondary processes, then their major and trace element compositions represent indirect petrogenetic proxies.

Jurassic volcanic rocks cropping out in the present-day Coastal Cordillera, Precordillera and High Andes of north-central Chile (26°–31°S) bear phenocrysts that are fresh or much less altered than the surrounding groundmass. Here we present in-situ mineral chemistry data in order to gain knowledge on the petrogenesis of altered Jurassic Andean magmatic rocks. We compare these results with data obtained from a companion study that focused on whole-rock chemistry (Rossel et al., 2013). In that paper, we showed that there is a progressive change in the geochemistry of the lavas from arc to back-arc, and linked it to variations in the magma sources. Those changes should be also traceable with the geochemistry of major and trace elements of primary minerals, such as clinopyroxene, allowing an improvement in the reconstruction of the sources and primary magmatic processes of the early stages of Andean subduction.

2. Geologic background

During the Jurassic and Early Cretaceous, western South America was characterized by an extensional and transtensional tectonic regime (Charrier et al., 2007; Creixell et al., 2006; Grocott and Taylor, 2002; Scheuber and González, 1999) due to the oblique subduction of the dense and cold Phoenix plate (Jaillard et al., 1990; Scheuber and González, 1999). This geodynamic regime resulted in a roll-back of the slab and retreat of the trench, as well as progressive thinning of the upper plate (Charrier et al., 2007; Ramos, 1999). The convergent margin developed an arc region in the present-day Coastal Cordillera of southern Perú and northern-central Chile, and a series of back arc basins to the east of the arc, within the modern Chilean Precordillera and High Andes. The arc magmatism was voluminous (Kramer et al., 2005; Lucassen et al., 2006; Oliveros et al., 2006, 2007; Palacios, 1978; Rogers and Hawkesworth, 1989; Vergara et al., 1995), and led to the accumulation of volcanic sequences up to 7000 m in thickness with minor sedimentary intercalations, and subsequent intrusion of large plutonic bodies (Buchelt and Tellez, 1988; Muñoz et al., 1988). Among the units that represent the Jurassic arc are the La Negra Formation and its equivalents (Camarca and Oficina Viz Formations) in northern Chile (18°–29°S), and the Aguas Saladas Volcanic Complex (30°–31°S).

The back arc region developed in response to the progressive thinning of the continental crust (Charrier et al., 2007; Martínez et al., 2012), and it is composed of up to 4000 m of marine and continental sedimentary rocks that were deposited during the Jurassic and Early Cretaceous (Charrier et al., 2007; Martínez et al., 2012; Mpodozis and Ramos, 1989; Vicente, 2006). In this context, the Upper Jurassic geological units cropping out in the Precordillera and High Andes between 26° y and 31°S, the Quebrada Vicuñitas Beds and the Lagunillas, Picudo and Algarrobal formations (Fig. 1), represent a particular event in the evolution of the back arc basins, in which basic and intermediate volcanism and continental sedimentation dominated over protracted marine sedimentary conditions (Charrier et al., 2007).

Since the Late Cretaceous, the continuous shifting of the magmatic front to its present position in the high Andes (Charrier et al., 2007; Mpodozis and Ramos, 1989) resulted in the occurrence of numerous events of hydrothermal alteration or regional low grade metamorphism that modiﬁed to a greater or lesser extent the geochemical composition of the host rocks. These events are represented in all the studied units by burial metamorphism, in the Precordillera area by the intrusion of Palaeocene and mainly Eocene plutons (Cornejo et al., 1998; Iriarte et al., 1999; Mpodozis and Cornejo, 1986; Tomilson et al., 1999) while in the Coastal Cordillera the main thermal event affecting the arc rocks was the product of the intrusion of composite Lower Cretaceous plutons (Creixell et al., 2012; Dalimeyer et al., 1996; Emparán and Calderón, 2010; Emparán and Pineda, 2000; Grocott et al., 1994; Welkner et al., 2006). In addition, much of the Jurassic volcanism was developed in a submarine environment (Vergara et al., 1995; Vicente, 2005) that affected the geochemical composition of the host rocks (Kramer et al., 2005; Oliveros et al., 2007), hindering the clear interpretation of the genesis of the Jurassic Andean magmatism.

3. Sample selection and analytical methods

In order to properly characterize the magmatic sources and evolution of the arc and back arc volcanism in northern Chile, we selected eleven samples for chemical analyses of fresh pyroxene and plagioclase phenocrysts (Table 1). One sample of the Agua Salada Volcanic Complex (ASVC) represents the arc domain and two samples of the Quebrada Vicuñitas Beds, two samples of the Lagunillas formation, four samples of the Picudo formation and two samples of the Algarrobal formation represent the back arc domain. Although slightly altered, the selected samples are the most primitive and best preserved from the arc and back arc volcanic units, they have either low contents of silica or were classified as basalt, basaltic andesite or andesite based on their mineralogy and texture. Their bulk chemistry is presented in Rossel et al. (2013). Given that the olivine crystals in these rocks, when present, are completely replaced by iddingsite (mixture of Fe-rich phyllosilicates), the most primitive phases in equilibrium with the original melt that have their chemistry unaltered are the fresh clinopyroxene and to a lesser extent plagioclase.

Electron microprobe analyses were carried out using a CAMECA SX100 and a JEOL JXA-8600M electron microprobe at the University of Arizona and University of Concepción, respectively. Analytical conditions were 15 kV, 20 nA with a 1 µm beam size. Na and K were measured at 15 kV, 8 nA and the remaining elements at 15 kV, 20 nA, with typical detection limits of WDS (wavelength-dispersive spectrometry) in the range between 0.13% (SiO2) and 0.01% (K2O). Ion microprobe analyses were performed at Arizona State University SIMS (Secondary Ion Mass Spectrometry) facility, with a primary beam of 16O+ — at a current of 3 to 4 nA. For the measurements the approach of “conventional energy filtering” was used, as described by Shimizu et al. (1978), Hinton (1990) and Zimmer and Crozz (1986).

Major element composition for pyroxene and plagioclase of 20 samples from the volcanic rocks of the Jurassic arc cropping out between 18°30’ and 24°00’S, from Oliveros et al. (2007), are included in the database for comparison.

4. Bulk rock petrography and geochemistry of the studied units

The Jurassic to Lower Cretaceous volcano-sedimentary units in the Precordillera and high Andes of northern Chile, 26°–31°S
are relatively well characterized in terms of their petrography and geochemistry. In particular, the volcanic rocks representative of the Jurassic back arc domain have been studied in detail by Rossel et al. (2013). In spite of the variable alteration degree exhibited by these rocks, the presence of fresh clinopyroxene phenocrysts is not uncommon.

Fig. 1. Simplified geological map of the studied area including sample locations. QVB: Quebrada Vicuñita Beds. LF: Lagunañas Formation. PF: Picudo Formation. AF: Algarrobal Formation. ASVC: Agua Salada Volcanic Complex. DZ Max. age: maximum depositional age obtained through U–Pb dating of detrital zircons. IZ: crystallization age of rocks obtained through U–Pb dating of igneous zircons. Modified after SERNAGEOMIN (2003).
4.1. Algarrobal Formation

This Upper Jurassic back arc unit crops out between ~30 and 31°S. The selected samples of this formation have porphyritic textures with seriate euhedral phenocrysts of plagioclase (~25% of rock volume) that can reach ~7 mm along their major axis, and minor amounts (~7%) of euhedral to subhedral clinopyroxene, ranging in size between 1 and 2 mm. Completely altered euhedral crystals of olivine

Table 1
Main features of the analyzed samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unit</th>
<th>Lithology</th>
<th>Coordinates (UTM E/N)</th>
<th>wt.%SiO₂</th>
<th>#Mg</th>
<th>Main mineralogy</th>
<th>Main alteration</th>
<th>First Ca phase</th>
<th>Cpx composition</th>
<th>Bulk-rock ¹⁸⁷Sr/¹⁸⁶Sr(i)*</th>
<th>Bulk-rock εNd(i)*</th>
<th>Analysis</th>
<th>Measured minerals</th>
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</thead>
<tbody>
<tr>
<td>PR-09-19</td>
<td>QVB BA</td>
<td>457666/7036398</td>
<td>–</td>
<td>–</td>
<td>Plg, Cpx, Fe–Ti oxides</td>
<td>Chl</td>
<td>Plg</td>
<td>Augite</td>
<td>–</td>
<td>–</td>
<td>EMPA</td>
<td>Cpx, Plg</td>
<td></td>
</tr>
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<td>Plg</td>
<td>Augite</td>
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<td>4.1</td>
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<td>Cpx, Plg</td>
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<tr>
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<td>53</td>
<td>Ol, Plg, Cpx, Fe–Ti oxides</td>
<td>Id-Cc</td>
<td>Cpx = Plg</td>
<td>Plg?</td>
<td>Ti-subsilic diopside</td>
<td>0.704</td>
<td>2.8</td>
<td>EMPA, SIMS</td>
<td>Cpx</td>
</tr>
<tr>
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<td>444163/6929847</td>
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<td>43</td>
<td>Ol, Plg, Cpx, Fe–Ti oxides</td>
<td>Id-Cc</td>
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<td>Plg?</td>
<td>Ti-subsilic diopside</td>
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<td>Cpx</td>
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<td>Plg</td>
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<td>Cpx</td>
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<tr>
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<td>47</td>
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<td>Plg</td>
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<td>Plg?</td>
<td>Diopside</td>
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<td>–</td>
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<td>Chl</td>
<td>Cpx = Plg</td>
<td>Plg?</td>
<td>Diopside</td>
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<td>3.8</td>
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<td>Plg</td>
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<td>Chl</td>
<td>Plg</td>
<td>Augite</td>
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<td>EMPA</td>
<td>Cpx</td>
<td></td>
</tr>
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<td>56</td>
<td>Plg/Cpx/Fe–Ti oxides</td>
<td>Chl</td>
<td>Plg</td>
<td>Augite</td>
<td>0.704</td>
<td>2.7</td>
<td>EMPA, SIMS</td>
<td>Cpx</td>
<td></td>
</tr>
</tbody>
</table>


* Rossel et al. (2013)

Fig. 2. Back-scattered electron (BSE) and second electron (SE) images of typical compositional and textural features observed in the studied rocks. BSE images of a) Large clinopyroxene (Cpx) crystal with opaque inclusions (Fe–Ti Ox.) and b) clinopyroxene phenocryst and large plagioclase (Plg) crystal with poikilitic clinopyroxene inclusions from the Algarrobal Formation from sample M-14; c) SE image of clinopyroxene phenocryst from sample PR-09-19 from Quebrada Vicuña Beds; d) BSE image of equigranular arrangement of plagioclase and clinopyroxene with interstitial olivine (Ol) from sample PR-10-80 of the Lagunillas Formation.
are present but in small amounts (<3%). They range in size from 0.5 to 1 mm and can occur either as phenocrysts or in the groundmass.

Plagioclase and clinopyroxene mostly occur as isolated phenocrysts, but clinopyroxene can also occur as inclusions in large plagioclase poikilocrysts (Fig. 2b). Alteration affecting plagioclase phenocrysts results in the development of sericite and minor amounts of epidote, but is common to find fresh crystals, or at least a fresh area inside the phenocrysts. On the other hand, clinopyroxene phenocrysts can be divided in almost completely fresh and completely chloritized crystals. No zonation is observed by optical microscope or backscattered electron (BSE) images into feldspars or pyroxenes. The groundmass usually has a pilotaxitic texture and it is composed of euhedral plagioclase, clinopyroxene, Fe–Ti oxides and minor amounts of olivine. A low-grade metamorphism or hydrothermal alteration overprint is evidenced by the greenish color of the groundmass under the optical microscope, the albitionization of plagioclase microcrystals and the presence of completely chloritized clinopyroxenes. The most common secondary phases in the matrix are chlorite and clays.

According to their mineralogy, with abundant of mafic constituents (mostly clinopyroxene) and the absence of primary quartz, K-feldspars or hydrated minerals, the Algarrobal Formation rocks can be classified mainly in the range between basalts and andesites. However, due to the intense silicic alteration affecting these lavas, the apparent compositional range indicated by whole-rock chemistry varies from basaltic andesite to rhyodacite (Rossel et al., 2013). These rocks have typical geochemical features of subduction-related magmatism: calc-alkaline affinities, with no early enrichment of FeO, Mg# ranging between 30 and 56, enrichment in LILE and light rare earth elements (LREE), depletion in HFSE and Nb (La/NbN = 2–3), REE patterns flatter than those of the other back arc units (LaN/NbN between 3 and 10), high concentrations of YbN (13–23) and a flat tail in the REE diagrams normalized to the chondritic reservoir (DyN/YbN ≤ 2).

4.3. Quebrada Vicuña Beds

This Upper Jurassic back-arc unit crops out between ~26° and 27°S. The rocks of the Quebrada Vicuña Beds are very homogeneous in composition, corresponding to porphyritic basaltic andesites, with plagioclase and clinopyroxene phenocrysts (Fig. 2c). In the selected samples of this unit plagioclase phenocrysts are euhedral and up to 10 mm in size, and represent approximately 80% of coarse fraction, whereas clinopyroxenes are subhedral, usually less than 2 mm in size, and can occur grouped as glomerocrysts up to 5 mm in diameter. The pilotaxitic groundmass represents approximately 70–75% of the volume of the rock and is composed of plagioclase, Fe–Ti oxides and minor clinopyroxene microcrystals. Hydrothermal alteration overprint is mostly recorded in the feldspars: large plagioclase phenocrysts can be partially replaced by sericite, whereas groundmass microclits are either albitized or replaced by brownish-greenish fine clay. Clinopyroxenes may exhibit thin chloritized rims in phenocrysts or in the groundmass. A particular alteration feature recognized in one of the selected samples is the presence of amphibole crystals closely related to areas where the replacement of the groundmass by brownish-greenish fine clay is more intense. Ar–Ar dating of the altered groundmass yielded an age of 72.9 ± 0.3 Ma (Rossel et al., 2013), that probably reflects a thermal event due to intrusion of Upper Cretaceous to Paleocene plutons (Cornejo et al., 1998), affecting the Quebrada Vicuña Beds rocks.

The geochemistry of Quebrada Vicuña Beds lavas indicates a transitional affinity for the volcanism, between calc-alkaline and tholeiitic, with a marked enrichment in FeO, Mg# that range between 37–52 and incompatible element contents similar to those of the Jurassic arc rocks (Rossel et al., 2013). Spider diagrams of these units show typical features of subduction-related magmas with deep Nb-Ta troughs (LaN/NbN = 2–11), REE patterns flatter than those of the other back arc units (LaN/NbN between 3 and 10), high concentrations of YbN (13–23) and a flat tail in the REE diagrams normalized to the chondritic reservoir (DyN/YbN ≤ 2).

4.4. Lagunillas Formation

This formation is the easternmost Upper Jurassic back arc unit and crops out as a discontinuous belt between ~27° and 30°S. The volcanic rocks of the Lagunillas Formation are exclusively olivine basalts lava flows with a typical massive central part and a vesicular top; they have a fine grained equigranular texture, although minor (~5%) plagioclase and olivine phenocrysts are observed. Plagioclase is the most abundant mineral phase, representing approximately ~80% of the rocks by volume (Fig. 2d). Olivine usually represents about ~10% of the volume of the rock, it can reach 2 mm in size and is always completely replaced by iddingsite (mixture of Fe-rich phyllosilicates). Plagioclase crystals are weakly altered to sericite and range in size from 0.5 to 1 mm; they can also occur as isolated phenocrysts (2 mm) in sample PR-10-80. The clinopyroxene occurs as crystals intergrown with plagioclase; it represents less than 5% of the volume of the sample and shows no evidence of alteration. Finally Fe–Ti oxides occur as interstitial crystals but commonly they do not constitute more than 1 or 2% of the volume of the rocks. Locally, the volcanic rocks of this unit are pervasively altered to calcite, which replaces plagioclase and olivine phenocrysts and fills numerous amygdules. The strongly altered samples were not included in this work.

The selected rocks of Lagunillas Formation have alkaline affinities, with no early enrichment of FeO, Mg# that ranges between 32 and 61 and the lowest concentrations of SiO2 of all the back-arc units, ranging between 45 and 49 wt.%. Spider diagrams of these lavas show patterns similar to those of the ocean island basalts (OIBs), with no Nb–Ta anomalies (LaN/NbN < 1). The REE diagrams exhibit a marked enrichment in LREE relative to HREE (LaN/YbN = 5–17) and low concentration of HREE respect to chondritic reservoir (YbN ≤ 10), suggesting the presence of garnet as a residual phase in the magma source.
4.5. Agua Salada Volcanic Complex

This Upper Jurassic arc unit crops out between ~30° and 31°S in Coastal Cordillera of northern Chile. The rocks of this unit are mostly volcanic and subvolcanic basaltic andesites strongly affected by contact metamorphism related to the intrusion of large granitoids of Lower Cretaceous age (Emparan and Pineda, 2000). The rocks have porphyritic textures with up to 40% of phenocrysts. Plagioclase is the main primary crystal-grained samples, but these phases likely formed during contact metamorphism.

The volcanic rocks from this complex have calc-alkaline/transitional petrographic affinities, like most of the Jurassic arc rocks, but with no clear enrichment of FeO, that is ppd. Clinopyroxene is the main primary mineral phase representing up to 80% of the volume of the rocks; the crystals are strongly but not completely altered to sericite and epidote. Clinopyroxene is a subordinate phase representing no more than 5% of the crystals are strongly but not completely altered to sericite and epidote.

5. Pyroxene chemistry

5.1. Major elements

Major element chemistry of the clinopyroxenes is listed in Table 2 and detailed in the Table A (Suppl. content). Pyroxene description and classification are based on atoms per formula unit (a.p.f.u.) normalized to 6 oxygens (Morimoto et al., 1988) and include data from this work and previously analyzed pyroxenes from Oliveros et al. (2007).

Most of the clinopyroxenes from the Picudo and Lagunillas formations are aluminous. They have higher contents of Ca, Na, Ti and lower contents of Si, Mg than pyroxenes from the Algarrobal Formation, Quebrada Vicuña Beds and those of the Jurassic arc rocks. In particular, clinopyroxenes from sample PR-10-72 (Lagunillas Formation) can be classified as subcalcic and titanian, defining a completely different fractionation trend compared to the other units in the Ti vs Mg\# diagram (Fig. 3), with Ti contents over or very close to 0.1 a.p.f.u. Clinopyroxene Mg\# ranges between 50 and 85, with those from back arc samples having a more restricted range, mostly between 67 and 85 (Fig. 3). The highest Mg\# are from samples PR-10-45 of the Picudo Formation, the lowest are from crystals of the Jurassic arc rocks, and the more restricted range is observed in clinopyroxenes of Lagunillas Formation (69–74). Clinopyroxenes in basaltic samples PR-10-45 from Picudo and PR-10-72 and PR-10-80 from Lagunillas formations, and PR-11-168 from Picudo Formation are diopside, whereas in the other arc and back arc samples the pyroxenes are augites (Fig. 4a).

Three low-Wo clinopyroxenes from the Jurassic arc rocks can be classified as pigeonite. Clinopyroxene have Mg\# ranging between 65 and 78, the most primitive are those from sample PR-10-41 (Figs. 3, 4a). A few analyzed pyroxenes from the Agua Salada Volcanic Complex are augites with Mg\# that ranges between 67 and 70; their composition is very similar to the clinopyroxene phenocrysts of the Jurassic arc rocks (Oliveros et al., 2007).

Scarc orthopyroxene crystals were found in evolved samples of the Picudo Formation. (PR-09-05 and PR-10-41) and in the Jurassic arc samples (Oliveros et al., 2007) and they correspond to enstatites.

5.2. Trace element chemistry

Trace element chemistry of the clinopyroxenes is listed in the Table B (Suppl. content); REE concentration and ratios were normalized to the chondrite composition of Sun and McDonough (1989). The REE patterns display a convex-upward shape with the highest enrichments between Nd and Eu. Unlike the clinopyroxenes from the Agua Salada Volcanic Complex (arc domain), the minerals from back arc samples show no negative Eu anomalies (Fig. 5), suggesting that there was no major previous fractionation of plagioclase in those melts, even when petrographic analysis suggest that plagioclase is commonly the first phase to crystallize. The Ceb/Smn (LREE) and Gd\#/Yb\# (HREE) ratios vary significantly between 0.1–1.5 and 0.2–3.2, but most of the samples are between 0.3 to 0.6 and 0.9 to 1.9. However, the ratios obtained in one alkali basalt from Lagunillas Formation (0.7 to 0.9 and 2.5 to 3.2 in Mg\# (Mg + Fe) abundances in a.p.f.u.)
6.1. Major elements

Major element chemistry of feldspars is listed in Table 3 and detailed in Table C (Suppl. content). Description and classification is in atoms per formula unit (a.p.f.u.) normalized to eight oxygens. Previously analyzed samples from the Camaraca, Oficina Viz, La Negra Formations (Jurassic arc, Oliveros et al., 2007) are included in the calculations and diagrams. Most of the studied feldspars are bytownite to andesine plagioclase (Fig. 4b). Some anorthite-rich bytownites are found in lavas of the Picudo Formation and these samples exhibit a rather continuous fractionation trend from An_{85} to An_{90}. The sample with the most anorthitic plagioclase (An_{85–64}) is the Picudo Formation basalt (PR-10-45) and that with the least anorthitic plagioclase is PR-11-168 (An_{90–71}).

Feldspars from the other units show a restricted range of composition (An_{83–90}), with a few isolated bytownite and andesine crystals from Quebrada Vizcuña Beds and Algarrobal Formation lavas. Olivine and plagioclase from the Lagunillas Formation lavas. On the other hand, the plagioclases in the Jurassic arc lavas (Camaraca, Oficina Viz, La Negra Formations and Agua Salada Volcanic Complex) are mainly labradorite, although they exhibit a broad range of composition, ranging from An_{74} to An_{52}.

Alkali feldspars are minor constituents of the studied rocks and they can be found as microlites in a few evolved arc anodesites (VO175 and VO169 from Camaraca and Oficina Viz formations respectively), a sample of the Picudo Formation (PR-10-41; not shown) and in the alkali basalts of the Lagunillas Formation (Fig. 4b). In the latter, they correspond mainly to anorthoclase crystals, with a few sandines (Fig 4b).

7. Thermobarometry of clinopyroxenes and plagioclases

Thermobarometry calculations using various equations (Putirka, 2005, 2008; Putirka et al., 2003) for plagioclase/whole rock, clinopyroxene/whole rock, clinopyroxene only and two pyroxenes equilibrium were performed on minerals from the Jurassic arc and back arc rocks (see Fig. 7a for location and unit names). Estimated crystallization temperatures and depth (pressures) for plagioclase/whole rock equilibrium in arc samples mostly fall (~50%) within a relative narrow range of 1160 to 1200 °C (Fig. 7b) and 18 to 26 km (Fig. 7c), with mean values of 1183 °C and 21.6 km. Clinopyroxene/whole rock equilibrium of the same units yielded lower crystallization temperatures, mostly between 1110 and 1150 °C, and depths between 8 and 18 km, with mean values of 1120 °C and 15.6 km. Otherwise, single clinopyroxene equilibrium of arc samples, suggest a narrow range of temperature mostly between 1150 and 1175 °C, with a mean value of 1162 °C, with the exception of pyroxenes in Camaraca Formation rocks that show lower values generally between 1130 and 1155 °C, but with a clear overlap of the upper 25% of the values of this unit respect to other arc units. Calculated crystallization depths using this method range mostly between 6 and 12 km, with a mean value of 9 km. Uncommon ortho/clinopyroxene equilibrium pairs from lavas of the Camaraca Formation (Fig. 7b) shown equilibration temperatures of ~1025 °C.
Crystallization temperatures estimated for back arc units (Fig. 7d,f) show that most of the used algorithms overlap between 1150 and 1200 °C, with higher mean values for plagioclase/whole rock equilibrium (1172 °C), followed by single clinopyroxene equilibration (1165 °C), and lower mean values for clinopyroxene/whole rock calculations (1150 °C). Anomalous behavior is observed in the plagioclase/whole rock equilibrium of the Picudo Formation samples. The obtained values range mainly between 1210 and 1240 °C, with the lower temperatures slightly overlapping the mean values calculated for the other back-arc samples (Fig. 7f). The clinopyroxene/whole rock equilibrium calculation yielded a wide range of temperatures following a bimodal distribution (Fig. 7f) with a peak at ~1200 °C grouping the results from the basaltic sample PR-10-45, and a lower peak at ~1080 °C group-
ing the rest of the analysis of this unit. The clinopyroxene only calculation for the Lagunillas Formation basalts yield temperatures (1050 to 1080 °C) which are anomalously lower than the rest of the back arc samples (Fig. 4d). Finally, a few ortho/clinopyroxene pairs from a basaltic andesite (PR-10-41) from Picudo Formation yielded a range of equilibration temperatures between ~975 and 1030 °C (Fig. 4d).

Crystallization pressures calculated for minerals from the back arc units (Fig. 7c,e) have a more complex behavior compared to tempera-
ture plots, but the results using the three different equations overlap in a range of depths between ~8 and 20 km. The most consistent results are those obtained on the basis of clinopyroxene composition solely,

Fig. 3. Mg# versus major cation abundances for the studied pyroxenes. Pyroxene composition of the Jurassic arc samples are after Oliveros et al. (2007) and this work. Dashed lines group different populations of measurements in Picudo and Lagunillas formations.
with a mean value of ~9.6 km (excluding the pyroxenes from the Picudo Formation basaltic sample PR-10-45, see Section 8.3). On the other hand, the plagioclase/whole rock barometer show higher values for the Lagunillas and Picudo formations crystals, but for the latter there is a large dispersion in the data (Fig. 7e,g). Particularly consistent are the results obtained in the Picudo Formation for clinopyroxene whole rock and clinopyroxene only barometers, with matching range of values, mean value and bimodal distribution of the data (Fig. 7d,f).

8. Discussion

8.1. Compositional variations in clinopyroxenes as proxies of magma sources

The major element composition of clinopyroxenes from the Jurassic arc and back arc units can be divided in two groups that follow distinct fractionation patterns. The first group, represented by pyroxenes from two samples of Picudo Formation (PR-10-45, PR-11-168) and the clinopyroxenes in Lagunillas formation lavas, is characterized by higher contents of Al, Ti, Ca, Na and lower contents of Si. The second group, which is represented by pyroxene from samples of the Quebrada Vicuñita Beds, Algarrobal Formation, Picudo Formation (PR-09-05) and Jurassic arc rocks, has low Al, Ti, Ca, Na and higher contents of Si. Clinopyroxenes in the remaining sample of Picudo Formation (PR-10-41) show features that resemble the second group, but they are slightly enriched in Al and Na.

According to the discrimination diagrams of Leterrier et al. (1982) the clinopyroxenes show a broad range of compositions, typical of subduction zones (Fig. 8). The Lagunillas Formation crystals define a particular pattern due to their high Ti contents, with clear alkaline affinities (Fig. 8a), while pyroxenes from the other units have compositions that resemble the clinopyroxenes from the MORB and the basalts from spreading centers such as back-arc basins (Fig. 8b), but with a clear fingerprint of subduction-related magmas (Fig. 8c). The clinopyroxenes of the Picudo Formation exhibit a significant alkaline component (Fig. 8a inset), but plot near to or within the field of calc-alkaline affinity (Fig. 8c). Thus, there are slight differences in the genesis of this unit with respect to the Algarrobal Formation, the Quebrada Vicuñita Beds and the Jurassic arc rocks for which the alkaline component is negligible (Fig. 8a). The likely factors that control the observed differences between the groups of studied pyroxenes are: i) variations in the pressure/temperature crystallization conditions and/or composition of a common parental magma, ii) different degrees of melting of a homogeneous mantle source, iii) compositional heterogeneities in the magma source, iv) previous fractionation of mineral phases, or a combination of the above.

The Mg# of clinopyroxene increases with increasing crystallization temperature (Trigila and DeBenedetti, 1993) and is independent of pressure (Putirka et al., 1996). On the other hand, Si in clinopyroxene is generally replaced by Al in the equilibrium exchange of Jd (NaAlSi2O6)–DiHd (Ca(Mg,Fe)Si2O6) and CaTs (CaAl2SiO6)–DiHd, which is sensitive to pressure. Experimental results show that Al in clinopyroxenes increases with decreasing temperature and increasing pressure (Putirka et al., 1996; Trigila and DeBenedetti, 1993), whereas Si increases with increasing temperature and decreasing pressure. The Mg#, Al and Si contents in the clinopyroxenes of the first group (pyroxenes from samples of the Lagunillas and Picudo formations) suggest that these minerals crystallized from a melt that was either colder or deeper-stable than from which the second group of pyroxenes crystallized. However, equilibration conditions calculated for the basaltic sample from the Picudo Formation (PR-10-45; Fig. 7e,f) suggest that the stagnation level of this back arc melt was at greater depths and higher temperatures than that of the magmas represented by other samples from arc and back arc (see Section 8.2). Thus, the high content of Al in the pyroxenes from the Picudo Formation basalt could be the result of higher pressure, not lower temperature, of crystallization.

Furthermore, the most evolved samples of the Picudo Formation (PR-09-05 and PR-10-41) have low Al contents (Fig. 3) suggesting crystallization pressures similar to the pyroxenes from the Quebrada Vicuñita Beds, the Algarrobal Formation and the Jurassic arc rocks (depleted second group). This is consistent with the two populations of temperatures calculated for the Picudo clinopyroxenes (Fig. 7e) and the crystallization order of clinopyroxene and plagioclase observed in each sample, which suggest that the magmas of the Picudo Formation may have experienced complex transport and storage histories prior to their emplacement during late Jurassic.

The observed variations in Na and other incompatible elements in the clinopyroxenes could be due to different degrees of melting of a common magma source, such as a depleted sub-arc mantle. The high contents of Na and REE, and the high Sm/Yb ratios in the clinopyroxenes of the Picudo and Lagunillas formations, along with the restricted volume of volcanism in these two units compared to the Jurassic arc rocks and Algarrobal Formation, are in agreement with a lower degree of partial melting as proposed by Rossel et al. (2013). The high contents of Ti, Zr, Nb and Hf in pyroxene crystals from the Lagunillas Formation,
compared to the other arc and back arc units studied in this work, suggest that the parental magmas of this formation derive from an OIB-type source (Figs. 3, 6a,b, 8a).

Clinopyroxene in OIBs (Bohrson and Clague, 1988; Clague, 1988; Chen et al., 1992; Fedor and Galar, 1997; Tracy, 1980) and continental alkali basalt (Aoki, 1968, 1970; Arai et al., 2000, 2001; Ho et al., 2000; Kovács et al., 2004) usually have high contents of Na and Ti. For a given concentration of SiO₂, the continental alkali basalt clinopyroxenes have lower Mg# (70–86) than the clinopyroxene in the OIB (79–89) or volcanic arcs (85). The Mg# in the Lagunillas Formation pyroxenes ranges between 69 and 74, suggesting a close relationship of these lavas to a continental intraplate mantle source. This is consistent and confirms the results of Rossel et al. (2013), who propose the existence of an OIB-like mantle as the source of the Lagunillas Formation lavas based on whole rock geochemistry and radiogenic isotopes.

The Zr vs Sr and Sr vs Yb variations among clinopyroxenes of the second group (low Al, Ti, Ca, Na) can be explained by fractionation of similar proportions of clinopyroxene and olivine and minor amounts of plagioclase (Fig. 9). The compositional pattern of pyroxenes from the Picudo Formation basalt (PR-10-45) suggests the same fractionation assemblage as the second group, but the Na and Al enrichment in these crystals must be related to differences in the source. The high-Sr pyroxenes from one basaltic andesite in the same unit (PR-11-168) suggest a source that was either Sr-rich or lacked of plagioclase fractionation (see discussion in Section 8.3). The compositional variation trends of pyroxenes from this sample suggest that fractionation of clinopyroxene and minor plagioclase is the most likely process for magma evolution (Fig. 9b).

8.2. Mineral–liquid (whole rock) equilibrium and thermobarometry implications

The thermobarometric results on clinopyroxene for each studied unit, calculated with the same equation, display a Gaussian distribution.

Fig. 5. Chondrite normalized REE patterns for the clinopyroxenes of the Picudo Formation, Quebrada Vicuña Beds, Lagunillas Formation and Agua Salada Volcanic Complex. Two analyzed orthopyroxenes in sample PR-09-05 (basalt from the Picudo Formation) show typical LREE depleted pattern. Normalizing values are from Sun and McDonough (1989).
with a well-defined peak for both P and T. This behavior can be interpreted as indicative of preferred or protracted crystallization conditions for the clinopyroxenes, suggesting the existence of levels of stagnation for the magmas before eruption, which is consistent with the porphyritic nature of most of the analyzed samples. The magma stagnations levels could have been favored by compositional discontinuities in the mantle and crust during the Jurassic.

The inferred temperature and depth of these apparent stagnation levels (i.e., the crystallization conditions for the clinopyroxene and plagioclase) seem to be highly dependent on the equation used (Fig. 10), especially in the arc samples. In general, calculations based on plagioclase chemistry show higher values than those based on pyroxene, which is consistent with petrographic observations that suggest an early crystallization of olivine, when present, followed by plagioclase and finally pyroxene. Otherwise, the gap between the P–T conditions calculated for plagioclase or pyroxene could be in part due to the porphyritic nature of the lavas or to the alteration degree of the rocks. Given that the results based on clinopyroxene only geothermobarometry show more narrow and concordant ranges than the rock/mineral methods, it is likely that the alteration processes affecting the bulk-rock chemistry biased the thermobarometric calculations.

Furthermore, few measurements of the studied minerals plot on the equilibrium line, which is the method proposed by Putirka et al. (2003) for testing the validity of the thermobarometric results (Fig. 10a). Only four samples plot on the equilibrium line which matches measured and predicted composition for the clinopyroxene, and therefore the calculated pressures and temperatures probably approach their crystallization conditions. These are two lavas from the La Negra Formation in the arc domain, VO04 and VO69 (Oliveros et al., 2007), and two lavas from the back arc domain, PR-10-45 (Picudo Formation) and PR-10-72 (Lagunillas formation). In order to evaluate the reliability of the remaining calculations, we performed a comparison between the measured REE contents on back arc samples and the predicted REE chemistry of these rocks based on clinopyroxene REE composition (Fig. 10b). The basalt and andesite of the Picudo Formation (PR-10-45 and PR-09-05, respectively) along with one sample of the Quebrada Vicuñita Beds (PR-10-32) show a good fit between measured whole-rock and clinopyroxene based REE contents, suggesting lower degrees of alteration for these samples. For the other analyzed samples and for the plagioclase/whole rock equation, which yielded systematically higher P–T values, there is no further means to assess the reliability of the obtained results.

The obtained temperatures and depths of equilibrated samples from the arc are ~1100 °C and ~6–18 km (Fig. 7b,c); the mean temperature for all samples and measurements calculated using the clinopyroxene/}

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**Table 3**

Mean and range of values for EMP analysis of feldspar crystals from the studied units and the previously published Jurassic arc samples (Oliveros et al., 2007).

<table>
<thead>
<tr>
<th></th>
<th>Lagunillas Formation</th>
<th>Quebrada Vicuñita Beds</th>
<th>Picudo Formation</th>
<th>Algarrobal Formation</th>
<th>Jurassic Arc</th>
</tr>
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<tbody>
<tr>
<td>N</td>
<td>9</td>
<td>9</td>
<td>38</td>
<td>8</td>
<td>220</td>
</tr>
<tr>
<td>SiO₂</td>
<td>Mean: 58.13 Range: 53.27/64.93</td>
<td>Mean: 53.66 Range: 48.06/59.24</td>
<td>Mean: 52.05 Range: 47.04/53.94</td>
<td>Mean: 53.39 Range: 53.00/53.94</td>
<td>Mean: 54.79 Range: 41.27/69.66</td>
</tr>
<tr>
<td>FeO</td>
<td>0.48 Range: 0.28/0.64</td>
<td>0.87 Range: 0.55/0.98</td>
<td>0.74 Range: 0.40/1.22</td>
<td>1.01 Range: 0.91/1.17</td>
<td>0.89 Range: 0.00/15.63</td>
</tr>
<tr>
<td>CaO</td>
<td>7.39 Range: 2.42/11.55</td>
<td>11.8 Range: 6.73/16.52</td>
<td>12.87 Range: 7.26/17.34</td>
<td>11.51 Range: 10.91/12.12</td>
<td>11.03 Range: 0.00/20.42</td>
</tr>
<tr>
<td>Na₂O</td>
<td>6.13 Range: 4.93/7.74</td>
<td>4.74 Range: 2.18/7.53</td>
<td>4.04 Range: 1.86/8.81</td>
<td>4.81 Range: 4.56/5.13</td>
<td>4.76 Range: 0.22/11.77</td>
</tr>
<tr>
<td>K</td>
<td>2.09 Range: 0.34/6.07</td>
<td>0.32 Range: 0.11/0.79</td>
<td>0.39 Range: 0.17/1.17</td>
<td>0.37 Range: 0.34/0.41</td>
<td>0.75 Range: 0.00/28.39</td>
</tr>
<tr>
<td>SiO₂</td>
<td>2.62 Range: 2.41/2.91</td>
<td>2.43 Range: 2.20/2.66</td>
<td>2.36 Range: 2.15/2.86</td>
<td>2.44 Range: 2.41/2.47</td>
<td>2.48 Range: 2.09/3.00</td>
</tr>
<tr>
<td>Al</td>
<td>1.37 Range: 1.08/1.58</td>
<td>1.54 Range: 1.33/1.78</td>
<td>1.62 Range: 1.12/1.84</td>
<td>1.52 Range: 1.48/1.55</td>
<td>1.49 Range: 1.01/1.91</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0.16 Range: 0.009/0.022</td>
<td>0.03 Range: 0.02/0.04</td>
<td>0.03 Range: 0.02/0.05</td>
<td>0.04 Range: 0.03/0.04</td>
<td>0.03 Range: 0.00/0.61</td>
</tr>
<tr>
<td>Ca</td>
<td>0.36 Range: 0.07/0.56</td>
<td>0.57 Range: 0.32/0.81</td>
<td>0.63 Range: 0.13/0.85</td>
<td>0.56 Range: 0.54/0.59</td>
<td>0.55 Range: 0.00/1.10</td>
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<td>Na</td>
<td>0.54 Range: 0.43/0.67</td>
<td>0.42 Range: 0.19/0.66</td>
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<td>0.41 Range: 0.00/2.98</td>
</tr>
<tr>
<td>K</td>
<td>0.12 Range: 0.02/0.35</td>
<td>0.02 Range: 0.01/0.05</td>
<td>0.02 Range: 0.01/0.33</td>
<td>0.02 Range: 0.02/0.04</td>
<td>0.04 Range: 0.00/1.09</td>
</tr>
<tr>
<td>Ab</td>
<td>52.8 Range: 42.7/65.2</td>
<td>41.2 Range: 19.2/64.0</td>
<td>35.4 Range: 13.8/59.1</td>
<td>42.2 Range: 39.7/44.9</td>
<td>41.88 Range: 1.83/98.95</td>
</tr>
<tr>
<td>An</td>
<td>35.4 Range: 67.6/53</td>
<td>36.9 Range: 31.6/80.2</td>
<td>62.4 Range: 13.0/58.5</td>
<td>55.7 Range: 52.9/58.3</td>
<td>53.75 Range: 0.01/90.96</td>
</tr>
<tr>
<td>Or</td>
<td>11.8 Range: 20.3/41</td>
<td>1.8 Range: 0.6/4.4</td>
<td>2.2 Range: 10.3/26.2</td>
<td>2.1 Range: 1.9/2.4</td>
<td>4.37 Range: 0.12/98.01</td>
</tr>
</tbody>
</table>

Structural formulae on the basis of 6 oxygens.

N = number of measurements per sample.
whole rock equation is only slightly lower and the pressure ranges calculated using the clinopyroxene/whole rock and clinopyroxene only equations are very similar. The consistency among the calculations using equilibrated and non-equilibrated samples suggests that the obtained P–T conditions probably represent a real stagnation level during magma ascent in the arc domain. Furthermore, the calculated pressure conditions are in agreement with the estimated depths of the lower-middle crust boundary in extensional convergent margins (Christensen and Mooney, 1995; Greene et al., 2006; Rudnick and Fountain, 1995) and similar to the emplacement depths for Jurassic plutonic bodies in Coastal Cordillera of northern Chile (González, 1999) that are commonly proposed as feeders of the Jurassic arc volcanism (Lucassen and Franz, 1994).

For the back-arc domain, the results using the different equations in equilibrated and non-equilibrated samples from the Quebrada Vicuña beds and Algarrobal Formation show narrow and overlapping ranges for crystallization temperatures and depths (~1150–1200 °C and 8 to 20 km) (Fig. 7d,e) which suggests that the data are valid. The Picudo Formation measurements show a wide range of equilibration conditions (Fig. 7f,g). Crystals in equilibrium with whole rock composition from the Picudo Formation basalt (PR-10-45) indicate equilibration temperatures higher than 1200 °C and depths of 35–36 km. The same results are obtained with clinopyroxene only equation. These conditions are somewhat higher than expected for mantle–lower crust boundary in the back arc region of extensional subduction systems. Thus, the calculated depth of crystallization of ~35–36 km of this sample could reflect another process.

Other samples from the Picudo Formation show no equilibration between predicted and measured clinopyroxene composition. They yielded lower temperatures than the equilibrated sample (PR-10-45), especially with the clinopyroxene/whole rock equation (Fig. 7f). The estimated crystallization depths are also lower than the equilibrated samples, whether using the clinopyroxene/whole rock or clinopyroxene only equation. These results are in agreement with the more evolved nature of the samples and overlap the calculated P–T conditions for other arc and back arc samples. However, given the lack of evidence for equilibration in the samples, with the exception of PR-09-05 (good match between measured and calculated REE, Fig. 10b), the data should be taken with caution.

The Lagunillas Formation alkaline basalts are equigranular, fine grained and have a restricted range of Mg#. Suggesting a history of fast cooling and very little fractionation for the magmas. However, they show a wide range of thermobarometric data, with no concordance between different equations. The calculations could then be geologically meaningless, even though a few pyroxenes show apparent equilibrium in measured versus predicted clinopyroxene composition (Fig. 10a).

Taking into account that the crystallization depths estimated from different geothermobarometers are similar for samples of the arc and back arc domains, it is possible to infer the existence of magma stagnation levels (or protracted P–T conditions for the crystallization of the phenocrysts) consistent with the existence of a thinned continental crust as result of the transtensional/extensional regime that dominated the Andean margin during the Jurassic (Creixell et al., 2011; Grocott and Taylor, 2002; Scheuber and
Furthermore, based on the obtained results we suggest that the architecture of the Jurassic arc crust had at least one main stagnation level between ~8 to 15 km, in both the arc and back arc domains, which probably corresponded to the lower-middle crust boundary. The existence of different reservoirs or stagnation levels has also been proposed for subduction-related middle Jurassic dyke swarms in central Chile (Creixell et al., 2009).

8.3. Petrogenesis of the Picudo Formation lavas and implications for the tectonics of the early Andean subduction

Conditions predicted for the Picudo Formation basalts seems difficult to be explained by a buoyancy driven stagnation level in a extensional back arc framework. In fact, the high diversity of geochemical compositions observed in this single unit over a restricted geographical area, which include typical arc related calc–alkaline andesites (PR-09-05), slightly Nb-enriched basalts (PR-10-45) and high-Sr basaltic andesites (PR-09-06 and PR-11-168), is surprising.
These heterogeneities were attributed to secondary alteration processes and remobilization of LILE by Rossel et al. (2013). However, the high Sr content in the fresh clinopyroxene phenocrysts is undoubtedly a magmatic feature. Furthermore, the high Sr lavas also have low contents of HREE and MgO, high Al2O3 concentrations and intermediate SiO2 contents (Rossel et al., 2013), that represent, with the exception of the low silica content, a typical adakitic signature (Defant and Drummond, 1990), as shown in the Sr/Y vs Y diagram (Fig. 11). In order to explain this geochemical signature, it is necessary to compare the geological setting proposed for the Jurassic and Lower Cretaceous in northern and central Chile.

Melting of a subducted eclogitized slab, which produces senso stricto adakites (Defant and Drummond, 1990), is not a likely scenario given that (a) the subducted slab was probably old and cold during late Jurassic (Charrier et al., 2007) and (b) the depth of magma generation for the Picudo Formation volcanism was at least 100 km beneath the volcanic centers, if they were located in the back-arc, and for normal thermal conditions, melting of the slab is not possible at these depths (Mibe et al., 2011). Equally, melting of eclogitized rocks under a thickened continental margin, which produces sensu lato adakites, is unrealistic given the protracted extensional setting observed in the Andean margin since the Early Triassic (Charrier et al., 2007; Mpodozis and Ramos, 1989).

Recent works of Goss and Kay (2009) and Goss et al. (2013) have shown the existence of adakitic-like volcanics in the transition between the Chilean flat-slab and the Central Volcanic Zone, apparently related to the tectonic erosion and subsequent assimilation of fore-arc crust. Since no flat slab is observed in the area during Jurassic times this hypothesis could be hard to apply. MacPherson et al. (2006) have proposed another mechanism to produce adakite-like signature in subduction-related magmas that may apply to the samples of the Picudo Formation: high pressure fractionation of basaltic magmas beneath an island arc. Such a mechanism can explain the high variation in the La/Yb (HREE) ratios, without significant changes in the isotopic composition, of the Picudo Formation lavas, but fails to reproduce their high Sr contents.

Based on the available data published by Rossel et al. (2013) and Lucassen et al. (2001) we constructed isotope mixing curves between MORB and two other end members: the Paleozoic granitic rocks and depleted mantle MORB are from Workman and Hart (2005) and for subducted sediments are from Plank and Langmuir (1998). Mineral melt partition coefficients are 0.073 (Sr) and 1.63 for (Y) for clinopyroxene, 0.03 (Sr) and 0.0076 (Y) for rutile, 0.01 (Sr) and 0.036 (Y) for olivine and 0.03 (Sr) and 0.01 (Y) for orthopyroxene. Clinopyroxene, orthopyroxene and garnet coefficients are from Barth et al. (2002); rutile coefficients are from Foley et al. (2000) and olivine coefficients are from Philpotts and Schnetzler (1970) and Nielsen et al. (1992). BADR: “normal” arc basalt–andesite–dacite–rhyolite field.
the Lagunillas Formation average (Fig. A, Suppl. content). Our results show that the best way to achieve the isotopic composition for most of the Picudo Formation lavas is a mixture of 80% of MORB and 20% of Paleozoic rocks.

We consider unlikely that the upper plate Paleozoic rocks were introduced via crustal contamination of the magmas because there are no significant variations in the Sr isotopic composition of the Picudo Formation in spite of their range of silica concentrations (SiO₂ ~ 45 to 53%). Sediment subduction is thus a more plausible mechanism to achieve the composition of the Picudo Formation lavas, because it implies that the isotopic enrichment takes place before fractionation of the magmas.

Forward modeling was performed in order to explain the high Sr/Y and low Y contents of the Picudo Formation samples (Fig. 11). Based on the most likely magma sources for this unit derived from the isotopic composition of its volcanic rocks (see above and Fig. A of the suppl. content), two types of mixture were used in the modeling: MORB/sediments and Average Depleted Mantle/sediments. The best fit for the calculated curves is achieved using the composition of the present-day high Sr sediments from the Peru trench (Plank and Langmuir, 1998). Thus, the Sr and Y contents of the Picudo formation adakite-like lavas can be attained through 1) one stage melting (~3–5%) of a mixture of sediments and oceanic basalts or 2) a two stage process that starts with melting (~25%) of a mixture of depleted mantle and sediments to achieve the composition of the enriched basaltic sample PR-10–45, and subsequent high pressure fractionation of olivine, clinopyroxene and minor garnet.

The one-stage model fails to explain the low SiO₂ and Mg contents (~52% and ~3% respectively) of the adakite-like lavas, and it is not realistic considering the expected thermal conditions of the slab below the back-arc domain (Mibe et al., 2011). The basaltic sample (PR-10–45) follows the melting curve of MORB and sediments but the contents of Ni and Cr are higher whereas SiO₂ is significantly lower than the average MORB, which make a genetic relationship with this raw endmember questionable. The two stage modeling on the other hand, can explain both the elemental heterogeneity and the isotopic homogeneity of the Picudo Formation lavas. Moreover, the crystallization conditions calculated in clinopyroxenes of Picudo Basalt (PR-10–45) are in agreement with the high pressure fractionation model proposed by MacPherson et al. (2006).

Otherwise, if no sediments are involved, it is possible to infer the subduction erosion of the Jurassic fore-arc as the source of the high-Sr component, as proposed by Goss and Kay (2009) and Goss et al. (2013) for Miocene adakites in the flat slab region at 27°–30°S. If this is the case, a contractional pulse during late Jurassic is needed in order to trigger subduction erosion. Scheubert and González (1999), Creixell et al. (2011) and Ring et al. (2012), propose the existence of a transpressional event, recorded in the Middle to Upper Jurassic arc units from northern and central Chile. The transpression could have caused a minor event of subduction erosion that fed the magmatic system and mixed with mantle melts beneath the back-arc area, producing the adakite-like lavas of the Picudo Formation lavas.

9. Conclusions

Major and trace element chemistry of clinopyroxene phenocrysts from altered Jurassic volcanic rocks cropping out in northern Chile were studied in order to gain petrogenetic information otherwise difficult to obtain via a conventional whole-rock study. Clinopyroxenes are classified in two groups: the first are augite phenocrysts in rocks of the main Jurassic arc, Algarrobal Formation and Quebrada Vicuñita Beds. These pyroxenes are depleted in Ti, trace elements such as Zr, Hf and have flat REE patterns, suggesting that the parental melts originated from depleted mantle sources typical for the supra subduction asthenosphere. The second group comprises aluminous diopsides from the Picudo Formation and aluminous-subsilic-titanian diopsides from the Lagunillas Formation. These pyroxenes, especially those from the Lagunillas Formation, have enrichments in Ti, Zr, Hf, and Nb, and steeper RREE patterns compared to the former group. The compositional features observed in the Picudo Formation clinopyroxenes are indicative of complex petrogenetic processes that involve subduction erosion of enriched sediments or forearc rocks and subsequent high pressure fractionation that led to the formation of adakitic melts, whereas the compositional features observed in clinopyroxenes of Lagunillas Formation suggest anhydrous melting of an enriched source such as the subcontinental mantle.

Trace element variations in the studied samples suggest that clinopyroxene and olivine extraction are responsible for the fractionation patterns observed in the back-arc units Quebrada Vicuñita Beds and Algarrobal Formation, whereas in the Picudo Formation magmas, garnet is fractionated.

The petrographic analysis and the thermobarometric calculations suggest that plagioclase was the first Ca phase to crystallize in most of the studied samples. Clinopyroxene crystallization conditions indicate slightly lower but overlapping temperatures and pressures for the crystals belonging to arc units, relative to the back-arc ones. The results suggest the presence of at least one main stagnation level for the magmas, both in the arc and back arc domains, located at ~8–15 km (and 1100 °C) below the surface. This depth could represent the lower-middle crust boundary. A sub-group of analysis from the Picudo Formation pyroxenes suggest deeper crystallization levels at ~35–36 km (and ~1200 °C) below the back arc area, which could be related to high pressure fractionation and resulted in the adakite-like signature observed in two samples. The interpretation of the thermobarometric results in Lagunillas Formation lavas is not straightforward, but the equigranular textures and limited range of Mg# suggest rapid ascent of the magmas to the surface through the lithosphere and very little fractionation.

The obtained geochemical and thermobarometric results are consistent with the main extensional–transitional framework proposed for the Andean margin during Jurassic and Early Cretaceous.

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