Resolving the paradigm of the late Paleozoic–Triassic Chilean magmatism: Isotopic approach

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A R T I C L E  I N F O

Article history:
Received 18 December 2015
Received in revised form 6 May 2016
Accepted 6 June 2016
Available online 16 July 2016

Handling Editor: J.C. Meert

Keywords:
Pangea assemblage
U–Pb geochronology
O–Hf isotopes
Zircon
Andean orogenic cycle

A B S T R A C T

The Andean orogenic cycle and its subduction-related magmatism along the southwestern margin of South America began during the early Jurassic after an accretionary history throughout Paleozoic times. The Chilean and Argentinian Frontal Andes batholiths, together with the Coastal Batholith, represent most of the pre-Andean orogenic cycle plutonism. However, how late Paleozoic–Triassic magmatism was related to these phenomena and its transition to the Andean orogenic cycle is still remains unclear. Here we present a geodynamic model using all the available published Lu–Hf and oxygen isotopic data ranging from latitudes 28° to 40°S, together with 5 new U–Pb zircon ages from the Chilean Frontal Andes. Data indicate that subduction began at least in the latest early Carboniferous and was continuous throughout the late Paleozoic–Triassic period. Isotopic and geochronological results show a continuous magmatic trend, from high δ18O values (continental) to mantle-like signatures, as the rocks get younger. Between latest early Carboniferous and earliest middle Permian, magmas formed in a subduction-related arc during the Gondwanide Orogeny. Later, throughout middle Permian to Triassic, magmatism occurred in a slab rollback extensional setting, triggered by low subducting plate velocities while Pangea was essentially in a static reference mode. There is no evidence for cessation of subduction during the Triassic and its renovation in the early Jurassic as previous work suggested. Therefore, we propose that Andean subduction has been a continuous tectonic process since Paleozoic times, whose initial geodynamic evolution was directly related to the Gondwanide Orogeny as part of the Pangea Assembly. Slab rollback, as well as shallowing and steepening of the subduction angle were among the triggers for the change in the type of magmatism observed among these rocks.

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1. Introduction

Although it is one of the Earth’s main plate boundaries, a complete comprehensive tectonic model for the paleo-South American southwestern margin in Chile does not exist. Specifically, the late Paleozoic–Triassic magmatism in Chile still has several important issues that remain unaddressed. First of all, how are these rocks related genetically along the Chilean margin (particularly from 28° to 40°S)? Second – and most important – in what tectonic setting did they originate? Traditionally, the geodynamic evolution has been explained through a collisional model (Ramos, 1988), which indicates that the southwestern part of South America registered a tectonic history dominated by the progressive accretion of allochthonous and/or para-autochthonous terranes. According to that model, the last stage of the Paleozoic collision involves the amalgamation of the Chilenia terrane at the western margin of Gondwana during Devonian times (Ramos et al., 1986; Álvarez et al., 2011) and the Patagonia terrane at the southwestern margin in the early Permian (Ramos, 2008). The eastward subduction of the paleo-Pacific oceanic plate under the Chilenia continental basement was responsible for the latest early Carboniferous–early Permian calc-alkaline I-type magmatism, now observed in the north-central Chilean and Argentinian Frontal Andes. Subsequently, during the Permian–Triassic period, calc-alkaline to transitional A-type granites were related to rifting (Mpodozis and Kay, 1992), which is associated with the Chojooyi province (23°S to 42°S in Chile and Argentina (Kay et al., 1989; Kleiman and Japas, 2009)). Based on these ideas, the change in the tectonic setting and thus its magmatism, has been interpreted as a consequence of a cessation in subduction after the accretion of an exotic, unidentified, ‘terrane X’ on the western side of Chilenia during the middle Permian (Mpodozis and Kay, 1992). This hypothetical collision was responsible for the cessation of subduction and therefore, formed the trigger for rifting conditions (extension due to slab collapse and lithospheric delamination). Re-establishment of subduction along the Chilean margin in the earliest Jurassic marked the initiation of the Andean orogenic cycle, which has continued without interruption to the present day (e.g. in Patagonia (Hervé et al., 2007)).
However, the tectonic process controlling the magmatism linking the Paleozoic accretionary history and the Jurassic Andean orogenic cycle is not clearly understood. Complete absence of geological evidence for the ‘terrane X’ and the remaining question whether subduction was renewed or intensified at the beginning of the Jurassic (Charrier et al., 2014) make the late Paleozoic–Triassic Chilean magmatism a crucial source of evidence. Moreover, there is no previous work relating all the intrusive units from that period of time (at least from 28° to 40°S). On the contrary, it has been suggested that units north and south of 33°S are genetically unrelated (Charrier et al., 2014; Hervé et al., 2014), arguing that the emplacement ages differ considerably between southern and northern plutons. Here we use all the available published Lu–Hf and oxygen isotopic data ranging from latitudes 28° to 40°S, together with 5 new Hf–O data and U–Pb zircon ages from the Montosa–El Potro Batholith (28°–28°30′S) in the Chilean Frontal Andes (Fig. 1) to propose a new tectonic scenario, and thus challenge previous models by

Fig. 1. Geographical distribution of the Chilean Frontal Andes late Paleozoic–Triassic batholiths and the Coastal Batholith (from ca. 20°S to 40°S). The location of the samples and their U–Pb crystallization ages are indicated (IC-17, IC-22, IC-58, IC-91, IC-93, this work; 1, Hervé et al. (2014); 2, Deckart et al. (2014); 3, Maksaev et al. (2014)). Tera Wasserburg concordia and age probability density plots of the analyzed samples are given in Fig. 2. Sample groups 1 and 2 have Hf–O isotopic data associated with the U–Pb ages (Fig. 3). Argentinian late Paleozoic–Triassic batholiths are also shown (4, Gregori and Benedini (2013); 5, SEGEMAR (2012)).
demonstrating a continuous magmatic evolution from the latest early Carboniferous to latest Triassic with a noticeable change in the middle Permian.

2. Materials and methods

The studied zircon grains are from 5 rock samples belonging to the Montosa–El Potro Batholith (28° to 28°30′S), which is part of the Chilean Frontal Andes (Fig. 1). Zircon grains were separated from 2 kg whole rock samples using standard techniques: grinding, Gemini table, heavy liquids and Frantz separation followed by final hand picking under a binocular microscope. Separating work was undertaken in the mineral separating facility of the Geology Department, University of Chile.

U–Th–Pb analyses were undertaken using a sensitive high-resolution ion microprobe (SHRIMP II) for defining the 206Pb/238U ages following standard procedures (Williams, 1998). Between 15 and 17 grains were analyzed in each sample to characterize the age variation present. Weighted mean 206Pb/238U ages were calculated and the uncertainties are reported as 95% confidence limits.

δ18O analyses were carried out using a sensitive high resolution ion microprobe (SHRIMP SI) and electron gun for charge compensation (Ickert et al., 2008) in the exact same spots were the U–Pb analyses were obtained with SHRIMP II. Calculated δ18O values were normalized relative to an FCI weighted mean δ18O value of +5.61‰.

Lu–Hf analyses were completed using laser ablation multi-collector inductively coupled plasma mass spectrometry (Neptune LA-MC-ICPMS) coupled with a HelEx 193 nm ArF Excimer laser ablation system (Eggen et al., 2005). Laser ablation analyses were done on the spots previously used for U–Pb and oxygen isotopes.

U–Pb, oxygen and Lu–Hf analytical labwork was undertaken at the Research School of Earth Sciences of the Australian National University in Canberra, Australia. Detailed analytical methods are found in Supplementary information.

3. Results and discussion

3.1. Chilean Frontal Andes (28°–28°30′S) results

Isotopic and geochronological analyses are summarized in Table 1. Full geochronological and isotopic data are provided in Supplementary data.

U–Pb zircon age determinations are summarized as follows (Fig. 2).

La Estancilla pluton sample (IC-17) yielded a weighted mean 206Pb/238U age of 286 ± 2 Ma (MSWD = 1.17); Montosa sample (IC-22), 253 ± 2 Ma (MSWD = 0.81); El León sample (IC-58), 257 ± 2 Ma (MSWD = 0.97); Chollay sample (IC-91), 259 ± 2 Ma (MSWD = 0.94); and El Colorado sample (IC-93), 248 ± 2 Ma (MSWD = 1.17).

Accordingly, La Estancilla pluton corresponds to Artinskian (early Permian) whilst the other 4 samples are very close to the Permian (middle Permian). High values of δ18O and δHf values do not show a considerable difference among the samples and range from −3.8 to +4.7, whereas δ18O indicates a considerable difference between the oldest sample (IC-17) and the rest of them (IC-22, IC-58, IC-91 and IC-93): values range between 6.6% and 7.5% for 4.4% and 6.7% respectively. The new data largely fill a previous apparent ‘gap’ in the trend of Fig. 3 (between the Coastal Batholith and the Frontal Andes Batholith) making it now continuous from latest early Carboniferous to Triassic.

Table 1

<table>
<thead>
<tr>
<th>Sample/unit</th>
<th>Geographical coordinates</th>
<th>Lithology</th>
<th>206Pb/238U age (Ma)</th>
<th>Initial εHf</th>
<th>δ18O (%)</th>
<th>TCMA Hf (Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC-17/Estancilla pluton</td>
<td>28°00′14″S 69°53′05″W</td>
<td>Hbl-bt tonalite</td>
<td>286 ± 2</td>
<td>−3.8 to +1.2</td>
<td>6.6-7.5/6.9</td>
<td>1.1-1.5</td>
</tr>
<tr>
<td>IC-22/Montosa</td>
<td>28°05′34″S 69°50′57″W</td>
<td>Hbl-bt tonalite</td>
<td>253 ± 2</td>
<td>−3.2 to +1.6</td>
<td>5.5-6.7/6.1</td>
<td>1.1-1.4</td>
</tr>
<tr>
<td>IC-58/El León</td>
<td>28°01′06″S 69°32′19″W</td>
<td>Bt-hbl monzogranite</td>
<td>257 ± 2</td>
<td>−2.5 to +2.0</td>
<td>5.5-6.4/6.1</td>
<td>1.1-1.3</td>
</tr>
<tr>
<td>IC-91/Chollay</td>
<td>28°28′17″S 69°43′25″W</td>
<td>Bt-hbl syenogranite</td>
<td>259 ± 2</td>
<td>−1.3 to +2.8</td>
<td>4.8-6.4/5.5</td>
<td>1.0-1.3</td>
</tr>
<tr>
<td>IC-93/El Colorado</td>
<td>28°24′38″S 69°47′11″W</td>
<td>Bt syenogranite</td>
<td>248 ± 2</td>
<td>−2.7 to +4.7</td>
<td>4.4-6.0/5.3</td>
<td>0.9-1.4</td>
</tr>
</tbody>
</table>

Note: TCMA: two-stage Depleted Mantle model age.
of the magmas from which the zircons crystallized had a significant residence time and therefore the magmatic arc formed on continental crust. Part or all of the continental crust–like material required for the high δ^{18}O values could correspond to sediments transported deep into the mantle wedge by the subducting slab (Gerya and Meiliick, 2011) or the isotopic signature could have been acquired through crustal contamination as the plutons were emplaced in the upper parts of the continental crust. Thus, the O–Hf compositions indicate a deep source of magmas, either affected by assimilation processes during magma ascent or with the influence of material acquired at depth, in the subcontinental mantle wedge.

The younger rocks of this study (≤270 Ma) show markedly different δ^{18}O compositions to the rocks described above. They show δ^{18}O < 6.5‰ (Fig. 3), along with a wider range of εHf, values (mostly from −3 to +3). The δ^{18}O data (4.9 to 6.5‰) indicate mantle source magmas from which the zircons crystallized with no ingestion of continental crust or supracrustal material (units fall completely within the mantle zircon range; taken from Valley et al. (1998)) or minor participation of the latter (δ^{18}O slightly above the mantle zircon limit). In the case of εHf values, although they are very concordant, they tend to decrease from less to more radiogenic as the rocks get younger. Positive εHf values indicate a more mantle-derived influence (Valley et al. 1998; Pietranik et al., 2013) (Fig. 3), which could reflect the addition of juvenile material in a foreland region (Dahlquist et al., 2013). Nevertheless, the overlap of isotopic data and ages does not allow a more specific differentiation among these samples and thus the differences can be attributed to variations in the magma source and/or in the magmatic differentiation processes. On the other hand, low δ^{18}O values (between 3.5 and 5.5‰) with positive εHf ratios (ca. +3 to +7) could be related to a subcontinental mantle source of magmas with assimilation of high temperature altered continental rocks or oceanic crust (Bindeman and Valley, 2001; Monani and Valley, 2001; Bolhar et al., 2008).

Some zircons, although showing mantle-like δ^{18}O values and εHf, between +2 and −2, are from highly differentiated rocks (i.e. granites). This signature is normally a characteristic of mafic igneous rocks and can be observed in arc magmas contaminated by sediments, since the O-isotope signature is relatively insensitive to mixing with arc-subducted sediments (Nebel et al., 2011). Melting of old mafic crust, even with limited proportions of sediments, can produce mantle-like δ^{18}O signatures without a real involvement of mantle material (Clemens et al., 2011; Villaros et al., 2012; Pietranik et al., 2013). This means that the rocks emplaced during the middle Permian–Triassic could have involved melting of an old, thinned, mafic crust (e.g., IC-93, IC-91, Fig. 3) with more or less continental crust material involvement (e.g., IC-22, IC-58, Fig. 3). The newly formed magmas inherited mantle-like δ^{18}O values from the mafic crust (lower continental crust) and some of them were slightly contaminated with a continental crust component. The resulting rocks were more differentiated but preserved mantle-like δ^{18}O signatures. It can be postulated that this occurred in a thinned continental crust context — possibly due to an extensional setting.

Higher δ^{18}O samples could have resulted from subduction-related magmatism in a normal-to-thickened continental crust, with involvement of continental crust to supracrustal material. Such a tectonic setting has been proposed for the Coastal Batholith (Deckart et al., 2014), which in consequence could define a single magmatic belt together with the Frontal Cordillera batholiths. U–Pb zircon ages from previous works (e.g., Maksaev et al., 2014) (Fig. 1) allow us to identify continuous plutonism from 328 to 300 Ma along the entire belt between 21°S and 40°S. There was protracted plutonism from 328 to ca. 270 Ma north of 33°S in Chile, but subduction-related granitoids younger than 300 Ma are absent to the south. Furthermore, a single inherited zircon core from a 257 Ma sample (at around 28°S with mantle-like δ^{18}O) yielded ca. 336 Ma and δ^{18}O and εHf values of 8.7‰ and −2.88 respectively, showing the same isotopic signatures as the rocks from the older units here analyzed. Despite that it may be arguable that it is only one zircon core, it still shows the same isotopic composition as the coeval zircon grains and therefore, it can give a glimpse of older rocks forming under the same tectonic conditions.

Although previous work (Charrier et al., 2014; Hervé et al., 2014) defined four magmatic groups ranging from latest early Carboniferous to late Triassic based on age clusters, their geochemical and isotopic characteristics are coherent with the two groups described here and also coincide with major episodes of volcanism (Maksaev et al., 2014). Rocks younger than middle Permian (≤270 Ma) show a more juvenile isotopic composition whereas the older ones (i.e. latest early Carboniferous–early Permian), represent rocks syntectonically emplaced into thickened crust.

### 3.3. Magma genesis and geodynamic evolution

#### 3.3.1. Pre-middle Permian

The Andean margin of Gondwana can be considered as an accretionary orogeny (Vaughan and Pankhurst, 2008). Between Silurian and Devonian periods, the Chilenia terrane accreted onto the western Pangean margin of Gondwana (Ramos et al., 1986; Bahlburg and Hervé, 1997) (Fig. 4A). Convergence in this segment may have started between ca. 343 and 310 Ma (Willner et al., 2012). Orogenic deformation due to changes in the intensity of plate convergence during that period marks the commencement of a major subduction cycle (Ramos and Alemán, 2000). Subsequently, from latest early Carboniferous to earliest middle Permian, high δ^{18}O isotopic signature plutons were emplaced in a subduction-related compressional setting, possibly as the roots of the magmatic arc beneath the Chilenia basement (Fig. 4B). This orogenic deformation corresponds to the Gondwanide Orogeny, which is also part of the end of the Terra Australis Orogen, starting with Rodinia break-up at ca. 630–530 Ma (Cawood, 2005). It includes the San Rafael event (ca. 284 Ma to 276 Ma), a compressional episode marked by intense folding and thrusting (Llambias and Sato, 1990) observed in the Argentinian Frontal Cordillera. In this tectonic configuration, isotopic data suggest a crustal to supracrustal component in the magmas and/or the influence of mature sediments transported through the subducted slab, given the increased δ^{18}O values and negative εHf, the latter indicating the input of less radiogenic, continental-like material.

This orogenic event was the result of a major global plate reorganization: the assembly of Pangea (Cawood, 2005), which occurred between ca. 320 and 280 Ma (Li and Powell, 2001) and was contemporaneous with the high δ^{18}O magmatism described above. In other words, all the magmatism from latest early Carboniferous to earliest middle Permian was emplaced in a subduction setting under orogenic conditions during the Gondwanide Orogeny as a consequence of the subduction of the Pantalassa Oceanic Plate under the southwestern margin of the assembling Pangea (Fig. 4B).

#### 3.3.2. Post-middle Permian

After ca. 270 Ma and once Pangea was fully assembled, a new post-orogenetic extensional setting was configured. Due to Pangea being in a static reference mode (Vilas and Valencio, 1978) or with arrested continental drift (Charrier et al., 2014) and in consequence, with ceasing or very low subduction velocities (Charrier et al., 2014), a new geodynamic scenario was configured. A low subducting plate velocity promotes a relatively steady hinge retreat (Schellart, 2005) resulting in backarc extension. Additionally, a plate rollback velocity greater than the movement of the continent towards the trench – which in the case of Pangea can be considered arrested – can also trigger backarc extension (Grocott and Taylor, 2002). This tectonic setting can be seen in two active continental margins today: East Asia and the Mediterranean (Schellart, 2005). Generalized extension at the southwestern margin of Pangea affected pre-existing zones of weakness (Charrier et al., 2014), particularly the hanging walls of sutures between the Paleozoic accreted terranes (Mpodozis and Ramos, 2008; Ramos, 2009). This resulted in the development of several NW–SE basins whose deposits...
are generally marine to continental from the coast to their inland prolongations (Charrier et al., 2014), including the rift-related bimodal sequences of the Choiyoi province (Kay et al., 1989). Moreover, considering at around 40°S the southernmost limit of the accreted Chilenia terrane (Ramos, 2009) and thus the area of the lateral slab edge, rapid rollback can be expected there (Schellart et al., 2007; Schellart, 2008). This results in significant upper plate extension within 1800 km of the lateral slab edge (Schellart et al., 2007) that can explain the increasing extensional-related magmatism and depocentres of the Triassic-earliest Jurassic rift systems towards 40°S (between 22° and 40°S ≈ 2000 km).

Slab rollback extension promoted the conditions for the mantle-like δ18O and progressively higher εHf magmatism. As the continental crust thinned (orogenic collapse), decompression triggered melting in the mantle. Large amounts of juvenile basaltic magmas accumulated below the continental crust (underplating) providing sufficient heat for melting of the old thinned mafic crust and thus, new melts inherited mantle-like δ18O signatures but relatively low εHf. This configuration lasted at least from 270 Ma to 210 Ma according to δ18O and εHf signatures (Fig. 4C). However, the presence of bimodal magmatism (from 20°S to 40°S) until the late Triassic (ca. 205 Ma (Maksaev et al., 2014)) suggests that the slab rollback extensional setting was continuous throughout middle Permian and Triassic times. This scenario is coherent with slab rollback during early Carboniferous in the Eastern Sierras Pampeanas, Argentina (Alasino et al., 2012), thus making it a relatively continuous process (except for the San Rafael compressional event) which progressed westwards to the Chilean Frontal Andes, and ultimately defined the tectonic configuration during middle Permian–Triassic. εHf values reported here are within the range of previous results (Dahlquist et al., 2013, 2016), supporting the idea of addition of variable amounts of juvenile material in a foreland extensional region.

South of 31°S, progressive slab shallowing from ca. 300 to 290 Ma displaced the magmatism eastwards. Permian–Triassic plutonism was not developed in the Chilean margin but is present in Argentina. The shallower slab setting was not uniform from 31°S to 40°S; it was gradually shallower from 31°S to 36°S, completely flat between 36°S and 39°S and again shallower from 39°S to 40°S (Kleiman and Japas, 2009).
Fig. 4. Tectonic model. A. Latest early Carboniferous to earliest middle Permian (325 - 270 Ma)

North present-day 31°S

GONDWANIDE OROGENY

Accretionary Prism

Supracrustal contamination

Sediments transported through the subducted slab

Devonian Suture

Chilean Frontal Andes

Compression-related units

Low values of \( \varepsilon \) values (ca. +1 to −4) with high \( \delta^{18}O \) (ca. +6.5‰) indicate an elevated supracrustal component and the addition of less radiogenic continental-like material; magmas formed in a subduction-related continental arc during the Gondwanide Orogeny. B. Middle Permian to Triassic (270 - 210 Ma)

Middle Permian - Triassic (270 - 210 Ma)

North present-day 31°S

EXTENSIONAL COLLAPSE OF OROGEN

Devonian Suture

Chilean Frontal Andes

Melting of an old thinned mafic crust

Juvenile material (Underplating)

Low subduction velocity triggered backarc extension due to hinge retreat

Accretionary Prism

South present-day 31°S

EXTENSIONAL COLLAPSE OF OROGEN

Devonian Suture

Scarce anorogenic Triassic granites in Chile

Proper Slab Shallowing Southwards in Rollback Conditions

Extension-related magmatism displaced eastwards

AA, Arequipa–Antofalla; CP, Cuyania–Precordillera; Ch, Chilenia; Pa, Patagonia; AP, the Antarctic Peninsula. Global reconstruction based on previous work (Keppie and Ramos, 1999; Torsvik and Cocks, 2013).
This segmentation explains the presence of subduction-related magmatism (ca. 276 Ma), which later changed into a transitional, post-orogenic crust-derived middle Permian (273–262 Ma) to Triassic bimodal magmatism in Argentina (Gregori and Benedini, 2013) (Fig. 5), in agreement with the isotopic interpretations presented here. Notwithstanding a shallower oceanic plate, arrested continental drift and slow subduction velocity prevailed. Thus, slab rollback extension was still present south of 31°S during middle Permian–Triassic times. In addition, scarce late Triassic anorogenic extensional-related A-type granites within the Coastal Batholith Range (Vásquez and Franz, 2008) can be linked to this tectonic setting as magmatism produced by crustal melting due to orogenic collapse (decompression) during the extensional period (middle Permian–Triassic). In sections: orange units represent latest early Carboniferous–middle Permian subduction-related magmatism; purple units, slab rollback middle Permian–Triassic extensional-related magmatism. Permian–Triassic units in Argentina (SEGEMAR, 2012; Gregori and Benedini, 2013) (gray on map) correspond to both subduction- and extension-related magmatism, in agreement with the timing of the tectonic evolution proposed here.

### 3.3.3. Overall geodynamic evolution

The latest early Carboniferous–middle Permian high δ¹⁸O granitoids, as well as the middle Permian–Triassic extension-related plutonic complexes, formed a continuous magmatic belt at least between 20°S and 40°S. The magmatism progressively and almost uninterrupted evolved from a continental-derived source towards mantle-like signatures from latest early Carboniferous to late Triassic as a response to the tectonic changes before, during and after Pangea Assembly (Fig. 4). First, subduction of the paleo-Pacific ocean plate (Panthalassa Ocean) under the western margin of paleo-South America (southwestern margin of Gondwana) was the cause of the crust-derived magmatism, which was syntectonic with compressional deformation of the San Rafael Tectonic Event during the Gondwanide Orogeny. Subsequently, and throughout the existence of Pangea as a supercontinent (after ca. 270 Ma), low subduction velocity triggered steady backarc extension and related magmatism due to hinge retreat. Progressive slab shallowing from 31°S southward (starting ca. 300–290 Ma), shifted magmatism inland. This tectonic configuration remained continuous until the latest Triassic, when the initial break-up of the Pangea Supercontinent took place (ca. 200 Ma (Deckart et al., 1998; Veevers, 2005; Torsvik and Cocks, 2013)). Changes of the plate dynamics from the static mode of Pangea towards an increased convergence rate of the newly re-established Gondwana (with higher subduction velocity) concluded slab rollback extension and thus, its magmatism in the backarc region. Because of the new conditions, and possibly in association with steepening of the oceanic subducting plate, magmatism was displaced westwards (i.e. trenchward), occurring primarily within the mantle wedge overlying the subducted slab (Pankhurst et al., 1988). This tectonic evolution is coherent with the presence of the early–late Jurassic magmatic arc in the Coastal Range (Charrier et al., 2014), stretching from southern Peru to central Chile (Mpodozis and Ramos, 2008). The locus of plutonism jumped to the Coastal Range from the east by the beginning of the Jurassic in an almost non-magmatic episode (scarce presence of latest Triassic–earliest Jurassic plutons: ca. 205–200 Ma), which is comparable to the jump of the magmatism from the Coastal Range to the High Andes (west to
east) during Cenozoic times (Parada et al., 2007). The magmatism (between 195 and 155 Ma) occurred in an extensional intra-arc basin due to sinistral movement in a high-stress regime with oblique convergence (Parada et al., 2007).

Finally, the continuous north to south latest early Carboniferous–Triassic magmatic belt was displaced from east to west by Mesozoic extension and basin development (Parada et al., 2007), while the corresponding South American continent was essentially static in a mantle reference framework (Brown, 1991). The displacement of the magmatic belt can be seen at ca. 31°–32°S (Fig. 1), corresponding to the Coastal Batholith and the Frontal Andes batholiths, as well as by the occurrence of late Paleozoic–Triassic plutonic rocks in the Coastal Range and Frontal Andes at 26°S (Brown, 1991) (Fig. 1).

4. Conclusions

We propose that tectonic conditions from the latest early Carboniferous to late Triassic and the continuity of magmatism, strongly supported by the geological records, are the results of the subduction-related convergent evolution of the paleo-Pacific border of Pangea since the Terra Australis Orogen until its break-up (i.e. 200 Ma (Deckart et al., 1998), among others). Furthermore, the progressive evolution from an orogenic compressional setting with expansion of magmatism to later slab shallowing (with flat slab in the southern region), extension, orogenic collapse and slab steepening, allows us to re-define the Andean orogenic cycle (at least between latitudes 20°S and 40°S), as a continuous subduction-related process since the latest early Carboniferous to the present day. Consequently, its roots are linked to the Terra Australis Orogen. The sequence of events is in agreement with the idealized tectonic evolution of an Andean orogenic cycle (Ramos, 2009) where the angle of subduction is the key factor controlling magma-mixing processes (Pankhurst et al., 1988). In addition to that, the expected westward retreat of the arc at the beginning of the Jurassic due to the end of slab rollback also fits the idealized model. There is no reason to consider cessation of subduction during the late Permian/Triassic and its renovation in the early Jurassic (Mpodozis and Kay, 1992; Franzese and Spalletti, 2001), and therefore the existence of the hypothetical ‘terran e X’ (Mpodozis and Kay, 1992). The Andean orogenic cycle due to the subduction of the Pacific/paleo-Pacific ocean plate underneath South America/paleo-South America has been a continuous process since the late Paleozoic. The major differences observed since that period are the prevailing global geodynamic conditions. While Pangea was being assembled, those conditions were different enough (compared to the traditionally defined Andean orogenic cycle; e.g. Charrier et al. (2014)) to produce noticeable changes in the magmatism (i.e. extreme extensional conditions due to low subducting plate velocities and slab rollback). Analogue models (Schellart, 2008) demonstrate that low subduction velocities trigger backarc extension due to hinge retreat. Also, Jurassic intrusions are located in a belt from 20°S to 36°S, ending at the beginning of the flat-slab segment (also present in the eastern margin of the Southern Patagonian batholith south of 48°S; Hervé et al. (2007)). The Paleozoic accretionary history of the south-western margin of Gondwana (up to 40°S) was completely finished by latest early Carboniferous and was followed by the Andean subduction, a continuous process since Paleozoic times and not from the early Jurassic as previously thought (e.g. Mpodozis and Kay, 1992; Charrier et al., 2014). Distinctive magmatism during the mid Permian–Triassic was due to Pangea Assembly, a unique and global event that conditioned geodynamic processes worldwide. Moreover, the presence of a rift-related belt of magmatism in Peru and Bolivia from the late Permian–middle Jurassic (Sempere et al., 2002) allows us to speculate the idea of the continuity of the Andean orogenic cycle northward to 8°S–20°S. Nevertheless, more evidence is required to confirm this hypothesis. The new tectonic model proposed here, unravels the paradigm of the latest early Carboniferous–Triassic magmatism in Chile and Argentina. This model also shows how global geodynamics (i.e. assembly and break-up of supercontinents) are a key factor in the occurrence of certain type of magmatism (rifting-related A-type granites; e.g. Mpodozis and Kay (1992)) which otherwise can be considered ‘odd’ if analyzed only from a local point of view.

Acknowledgements

We thank Juan Vargas and Roberto Valles (Universidad de Chile) for the zircon separation; Dr. Mark Fanning (ANU) for the Lu–Hf, O and U–Pb analytical work at the ANU; and Drs. Jacobus Le Roux and Gregory De Pascale (Universidad de Chile) for the English language corrections. The authors would like to acknowledge the constructive comments and discussions by Dr. Robert Pankhurst during revision of the manuscript. This research was funded by the Servicio Nacional de Geología y Minería (SERNAGEOMIN) project Plan Nacional de Geología (Geological Map Iglesia Colorado — Cerro El Potro) and the Masters fellowship of the Comisión Nacional de Investigación Científica y Tecnológica – CONICYT (grant no. 221320626). Additional funding was provided by the Departamento de Postgrado y Postítulo, Universidad de Chile. This work is part of the M.Sc. thesis of the principal author.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gjrz.2016.06.008.

References
