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# Provenance variations in the Late Paleozoic accretionary complex of central Chile as indicated by detrital zircons

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## ABSTRACT

We present detrital zircon U–Pb SHRIMP age patterns for the central segment (34–42°S) of an extensive accretionary complex along coastal Chile together with ages for some relevant igneous rocks. The complex consists of a basally accreted high pressure/low temperature Western Series outboard of a frontally accreted Eastern Series that was overprinted by high temperature/low pressure metamorphism. Eleven new SHRIMP detrital zircon age patterns have been obtained for meta-turbidites from the central (34–42°S) segment of the accretionary complex, four from previously undated metamorphic complexes and associated intrusive rocks from the main Andean cordillera, and three from igneous rocks in Argentina that were considered as possible sediment source areas. There are no Mesozoic detrital zircons in the accretionary rocks. Early Paleozoic zircons are an essential component of the provenance, and Grenville-age zircons and isolated grains as old as 3 Ga occur in most rocks, although much less commonly in the Western Series of the southern sector. In the northernmost sector (34–38°30′S) Proterozoic zircon grains constitute more than 50% of the detrital spectra, in contrast with less than 10% in the southern sector (39–42°S). The youngest igneous detrital zircons in both the northern Western (307 Ma) and Eastern Series (345 Ma) are considered to closely date sedimentation of the protoliths. Both oxygen and Lu–Hf isotopic analyses of a selection of Permian to Neoproterozoic detrital zircon grains indicate that the respective igneous source rocks had significant crustal contributions. The results suggest that Early Paleozoic orogenic belts (Pampean and Famatinian) containing material recycled from cratonic areas of South America supplied detritus to this part of the paleo-Pacific coast. In contrast, in the southern exposures of the Western Series studied here, Permian detrital zircons (253–295 Ma) dominate, indicating much younger deposition. The northern sector has scarce Early to Middle Devonian detrital zircons, prominent south of 39°S. The sedimentary protolith of the northern sector was probably deposited in a passive margin setting starved of Devonian (Achalian) detritus by a topographic barrier formed by the Precordillera, and possibly Chilenia, terranes. Devonian subduction-related metamorphic and plutonic rocks developed south of 39°S, beyond the possible southern limit of Chilenia, where sedimentation of accretionary rocks continued until Permian times.

## 1. Introduction

A fossil Late Paleozoic subduction complex is exposed continuously along the Chilean margin south of 34°S. Willner (2005) quantified the metamorphic P–T conditions which affected the rocks near the northern end of the 34°–42°S sector considered here, and Glodny et al. (2005, 2008) suggested accretionary modes for different portions of the complex, mainly south of 36°S (see below). Dating of metamorphic processes has also been dealt with in a number of papers since Hervé et al. (1974b) with K–Ar, Hervé et al. (1984) with Rb–Sr whole rock methods and more recently by Willner et al. (2005) with Ar–Ar and Glodny et al. (2008) with Rb–Sr mineral whole rock isochrons. Detrital zircon age data, however, have remained very scarce or nonexistent for large tracts of the accretionary complex between 34 and 42°S. Willner et al. (2008) presented the results of two samples analyzed by ICP-MS and Duhart et al. (2001) presented data for individual detrital zircons for several samples of the southern (39°–42°S) sector, analyzed by TIMMS. In this contribution, 13 new metasedimentary samples were analyzed for their U–Pb detrital zircon age spectra with SHRIMP, and age determinations are presented for three samples from possible source igneous rocks in Argentina and two foliated granitoids from Liquiñe, east of the accretionary complex. The main purpose of this study is to examine the

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detrital zircon population present in the accretionary complex, detect their variations in space, if any, try to relate them to source areas, and interpret the tectonic setting of deposition. Additionally, isotopic studies of the detrital zircons were made to improve the possibilities of identifying the source areas, and to characterize some aspects of their geologic evolution. The results obtained indicate that previously unknown large variations in the areal distribution of the detrital populations of zircon are detectable in the accretionary prism. N–S variations in these populations are described and interpreted in terms of their geological significance for the Late Paleozoic development of the continental margin of Pangea in this portion of the Terra Australis orogen (Cawood, 2005), which represent the vestiges of tectonic activity within the paleo-Pacific Ocean (Murphy et al., 2009).

## 2. Geological setting

Two units with differing lithology and structure are recognized within the accretionary complex—the Western and Eastern series (Godoy, 1970; Aguirre et al., 1972). These have been recognized as paired metamorphic belts (*sensu* Miyashiro, 1961), now interpreted as representing the products of basal and frontal accretion respectively in an active continental margin (Willner et al., 2005; Richter et al., 2007; Glodny et al., 2006, 2008). The Eastern Series is intruded by the N–S elongated Coastal Batholith of Late Paleozoic age (see below).

In the study area (Fig. 1) the southern section is dominated by the Western Series (WS) whereas in the northern section it is confined to relatively small coastal outcrops. Although the limit between these sectors is not precisely determined, it must be close to the northwest trending Lanalhue lineament (Fig. 1), which has been interpreted as a suture zone (Ernst, 1973), a sharp transition between the two series (Hervé, 1977) and, more recently, as the Lanalhue Fault Zone (Glodny et al., 2008). The last authors state that “the Lanalhue Fault Zone juxtaposes Permo-Carboniferous magmatic arc granitoids and associated, frontally accreted metasediments (Eastern Series) in the northeast with a late Carboniferous to Triassic basal-accretionary forearc wedge complex (Western Series) in the southwest”. They further considered that an Early Permian period of subduction erosion to the north contrasted with ongoing accretion to the south, so that the coastal batholith appears to be displaced 100 km to the west north of the fault zone, with contrasting lithologies and metamorphic signatures across it.

The Eastern Series (ES) consists of alternating meta-sandstones and metapelites, with preserved bedding except in the easternmost, higher-grade areas; volumetrically small but ubiquitous calc-silicate pods are found throughout. The WS is composed of mica schists, greenschists, quartzites and scarce serpentinite bodies; rare primary sedimentary structures are observed, as well as occasional pillow structures in the greenschists.

The rocks of the two series differ in fabric and small-scale deformational features. The ES is mainly deformed into upright folds with subvertical $S_1$ foliation or cleavage in the metapelites, in which a less steep $S_2$ foliation is occasionally observed. In contrast, the main foliation in the WS rocks is generally $S_2$, accompanied by the main recrystallization and with transposition of earlier primary and tectonic fabrics. Peak metamorphic conditions also differ in the two series. Following Hervé (1977) it is clear that the ES represents low P/T (pressure/temperature) metamorphic gradients and the WS higher ones, the thermal gradient for the latter estimated by Willner et al. (2005) as about 10 to 12 °C/km.

Paleotectonic models of the evolution of the southwestern Gondwana margin include the hypothesis (Ramos et al., 1986) that between 28 and 39° S an exotic continental block called Chilenia collided with Gondwana during the Devonian, with the suture lying east of the present Andean Cordillera in Argentina. South of this latitude the Paleozoic development has also been interpreted as indicating collision of Patagonia with Gondwana (Ramos, 1984; Pankhurst et al., 2006; Ramos, 2008). The coastal accretionary complex studied here should contain a record that might help to confirm the occurrence of such collisional events.

## 3. Methods

Samples were collected from localities that displayed the typical outcrop characteristics of either the WS or the ES. Zircons were recovered from heavy mineral concentrates obtained by the standard method of crushing, grinding, Wilfley table, magnetic and heavy liquid separation at Universidad de Chile. Not all the samples yielded zircons, and from several only a few grains were obtained; the proportion of failed separates probably reflects a characteristic of the rocks, as this problem was unusual in previous work by the authors in the metasedimentary complexes in southern Chile. It is possible that the protolith of many of the WS schists was originally made up of distal fine-grained turbidites or mafic igneous rocks, relatively devoid of zircon crystals.

Zircon analyses were undertaken at RSES (Research School of Earth Sciences, The Australian National University, Canberra). The grains were mounted in epoxy, polished to about halfway through the grains, and CL (cathodo-luminescence) images were obtained for every zircon. U–Th–Pb analyses were then conducted using two sensitive high-resolution ion microprobes (SHRIMP II and SHRIMP RG) following the procedures described by Williams (1998). In some cases fewer than 70 individual zircon crystals were analyzed (see Electronic Supplement), which may lead to enhanced uncertainties in the identification of detrital zircon age populations, although the general consistency of the resulting age distributions suggests that this is not a significant problem.

Oxygen ($^{18}O/^{16}O$) and Lu–Hf ($^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$) isotope ratios were measured in a selection of detrital zircons from various samples with the aim of better defining possible source rocks. Following the U–Pb analyses, the SHRIMP 1–2 μm deep U–Pb pits were lightly polished away and oxygen isotope analyses made in exactly the same location using SHRIMP II fitted with a Cs ion source and electron gun for charge compensation as described by Ickert et al. (2008). Oxygen isotope ratios were determined in multiple collector mode using an axial continuous electron multiplier (CEM) triplet collector, and two floating heads with interchangeable CEM—Faraday Cups. The Temora 2, Temora 3 and FC1 reference zircons were analyzed to monitor and correct for isotope fractionation. The measured $^{18}O/^{16}O$ ratios and calculated $\delta^{18}O_{VSMOW}$ values have been normalized relative to an FC1 weighted mean $\delta^{18}O$ value of +5.4‰ (Ickert et al., 2008). Reproducibility in the Duluth Gabbro FC1 reference zircon $\delta^{18}O$ value ranged from ±0.23‰ to 0.47‰ (2σ uncertainty) for the analytical sessions, with most of the reference zircon analytical uncertainties in the range 0.21–0.42‰ (±2σ). As a secondary reference, zircons from the Temora 2 or Temora 3 zircons analyzed in the same analytical sessions gave $\delta^{18}O$ values of +8.2‰ and +7.59‰ respectively, in agreement with data reported by Ickert et al. (2008) and unpublished data for the Temora 3 reference zircon.

Lu–Hf isotopic measurements were conducted by laser ablation multi-collector inductively coupled plasma mass spectroscopy (LA-MC-ICPMS) using a Neptune MC-ICPMS coupled with a 193 nm ArF Excimer laser; similar to procedures described in Munizaga et al. (2008). Laser ablation analyses were centred on the same locations within single zircon grains used for both the U–Pb and oxygen isotope analyses described above. For all analyses of unknowns or secondary standards, the laser spot size was *c.* 47 μm in diameter. The mass spectrometer was first tuned to optimal sensitivity using a large grain of zircon from the Mud Tank carbonatite (see Woodhead and Hergt, 2005). Isotopic masses were measured simultaneously in static-collection mode.

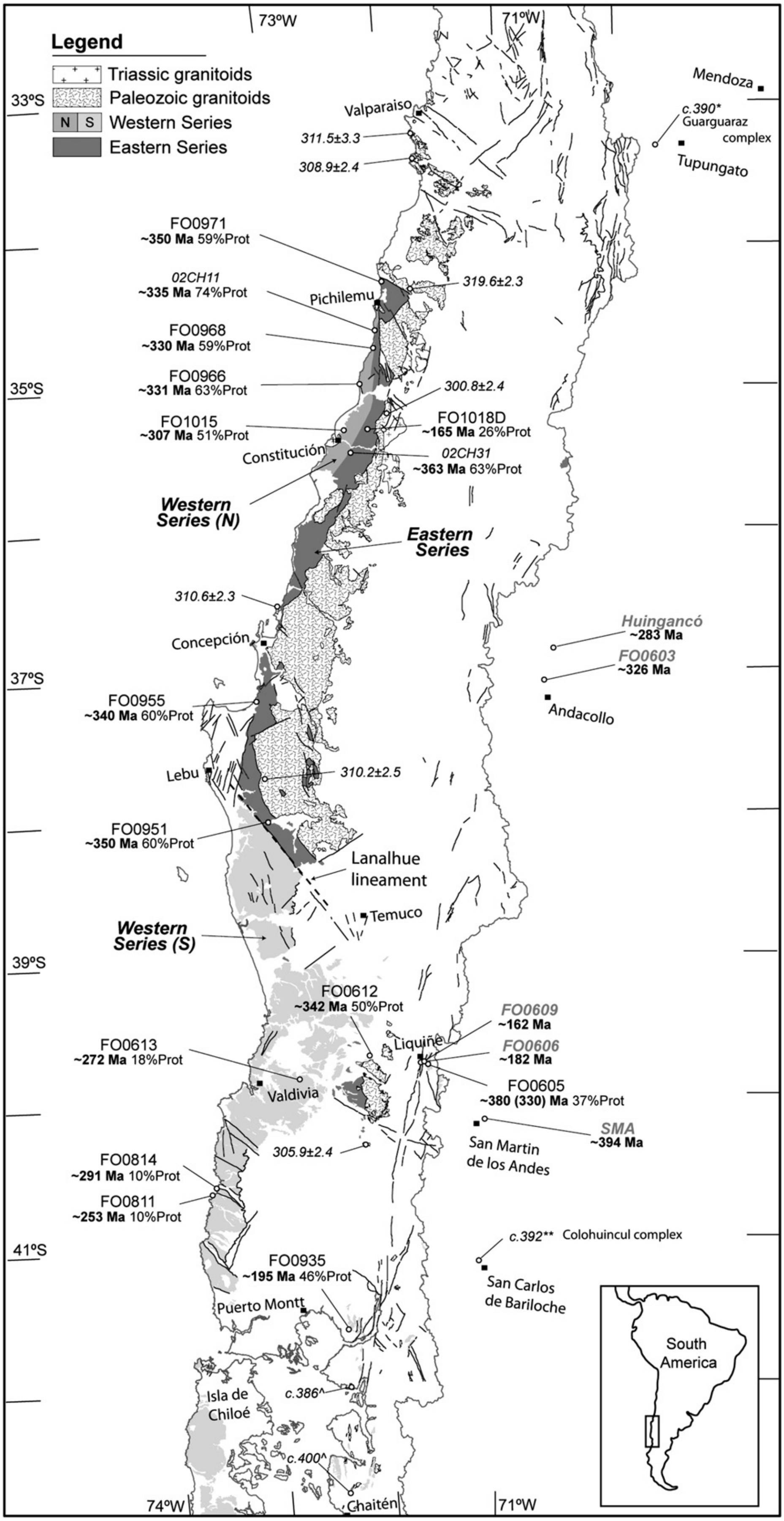
73ºW
71ºW
Legend
Triassic granitoids
Paleozoic granitoids
N S Western Series
Eastern Series
33ºS
35ºS
37ºS
39ºS
41ºS
Mendoza
c.390* Guarguaraz complex
Tupungato
Valparaiso
311.5±3.3
308.9±2.4
FO0971
~350 Ma 59%Prot
02CH11
~335 Ma 74%Prot
319.6±2.3
Pichilemu
FO0968
~330 Ma 59%Prot
FO0966
~331 Ma 63%Prot
300.8±2.4
FO1015
~307 Ma 51%Prot
FO1018D
~165 Ma 26%Prot
Constitución
02CH31
~363 Ma 63%Prot
Western Series (N)
Eastern Series
310.6±2.3
Concepción
Huingancó
~283 Ma
FO0603
~326 Ma
Andacollo
FO0955
~340 Ma 60%Prot
Lebu
310.2±2.5
FO0951
~350 Ma 60%Prot
Lanalhue lineament
Temuco
Western Series (S)
FO0612
~342 Ma 50%Prot
FO0609
~162 Ma
Liquiñe
FO0606
~182 Ma
FO0613
~272 Ma 18%Prot
Valdivia
FO0605
~380 (330) Ma 37%Prot
SMA
~394 Ma
San Martin de los Andes
305.9±2.4
FO0814
~291 Ma 10%Prot
FO0811
~253 Ma 10%Prot
c.392** Colohuincul complex
San Carlos de Bariloche
FO0935
~195 Ma 46%Prot
Puerto Montt
South America
c.386^
Isla de Chiloé
c.400^
74ºW
71ºW
Chaitén

**Table 1**
Sample localities and descriptions.

| | Lat °S | Long °W | Area | Lithology | Comments |
|---|---|---|---|---|---|
| *Western series* | | | | | |
| FO0968 | 34.6890 | 72.0598 | Boyeruca | Banded micaschist | Well developed $S_2$; $S_1$ preserved in microlithons, Qtz veins and symmetrical lenses parallel to $S_2$ |
| FO0613 | 39.8110 | 72.3039 | Antilhue | Micaschist | Qtz-albite composition, banded |
| FO0814 | | | Pucatrihue | Metapsammite | m-thick layer in micaschist with bands parallel to predominant subhorizontal planar $S_2$ |
| FO0811 | | | Maicolpue | Qtz micaschist | Predominant planar $s_2$ foliation, parallel to lithological banding and quartz veins |
| FO0966 | 34.9393 | 72.1846 | Iloca | Quartzite | Micaceous, interleaved with albite-bearing quartz micaschists |
| FO1015 | 35.2622 | 72.3313 | Putu | Psammopelitic schist | With quartz lenses parallel to the main flat-lying $s_2$ foliation |
| 02CH11 | 34.5700 | 72.0680 | | Metagreywacke | Qtz, Ab, white mica and Chl, recrystallized, with metamorphic banding formed by transposition foliation subparallel to former bedding. Willner et al. (2008) |
| *Eastern Series* | | | | | |
| FO0971 | 34.2280 | 71.9820 | Tanume | St metasandstone | Alternates with And-bearing metapelites with Qtz veins parallel to the axial planes of folds |
| FO0955 | 37.1520 | 73.1830 | Chivilingo | Bt-Ms metasandstone | m-thick beds interleaved with And-bearing metapelites that contain calc-silicate lenses |
| FO0951 | 38.0270 | 73.1230 | Puren | Bt-Ms metasandstone | Mildly foliated, alternating with metapelites |
| FO0612 | 39.6759 | 72.3039 | Playa Chauquen | Metasandstone | Alternating with pelite in beds 5–10 cm thick, subvertical stratification |
| FO1018D | 35.2630 | 72.1280 | Near Coipue | Metasandstone | Alternates with metapelites, well developed axial planar cleavage and parallel lamination. Mapped as ES (Gana and Hervé, 1983) but has Jurassic detrital zircons |
| 02CH31 | 35.4180 | 72.3250 | | Metagreywacke | Cf. 02CH11 except for Bt grown at the expense of Chl and Kfs due to high-T overprint. Willner et al. (2008) |
| *Liquiñe and Parque Alerce Andino paragneisses, mylonites and plutonic rocks* | | | | | |
| FO0605 | 39.7640 | 71.7810 | East of Liquiñe | Bt-Ms banded paragneiss | Tightly folded cm-scale qtz-rich veins |
| FO0606 | 39.7580 | 71.8310 | Furihuicul 4 bridge | Banded mylonite | Intruded by mafic dykes parallel to the mylonitic foliation, and cut by low-angle faults with a 5 cm-thick gouge. N5E/73 W foliation, with lineations plunging 23°N |
| FO0609 | 39.7560 | 71.8310 | Furihuicul 2 bridge | Bt-Hbl tonalite | Mylonitized, discrete anastomosing foliation planes separating m-long lenses of less deformed rock, cut by undeformed mafic dykes |
| FO0935 | 41.5937 | 72.5943 | Parque Alerce Andino | Bt-Ms paragneiss | Coarse-grained, well foliated with planar elongated qtz lenses |
| *Argentina* | | | | | |
| FO0603 | 37.0663 | 70.6489 | Cordillera del Viento | White rhyolite | Ore mineralization on fractures. Grupo Andacollo unit of Llambías et al. (2007) |
| Huingancó | | | Cordillera del Viento | Bt-perthite granodiorite | Coarse-grained, slightly altered. Huingancó volcano-plutonic complex of Llambías et al. (2007) |
| SMA | | | Lago Lacar, SE shore | Bt-Hbl tonalitic gneiss | Coarse-grained, faintly foliated |

Mineral abbreviations are: And, andalusite; Bt, biotite; Chl, chlorite; Hbl, hornblende; Kfs, K-feldspar; Ms, muscovite; Qtz, quartz; St, staurolite; Ab, albite.

A gas blank was acquired at regular intervals throughout the analytical session (every 12 analyses). The laser was fired with typically 5–8 Hz repetition rate and 50–60 mJ energy. Data were acquired for 100 s, but in many cases we selected an interval over which the $^{176}$Hf/$^{177}$Hf ratios were consistent. Throughout the analytical session several widely used reference zircons (91500, FC-1, Mud Tank and Temora-2 or -3) were analyzed to monitor data quality and reproducibility. Signal intensity was typically ca.5–6 V for total Hf at the beginning of ablation, and decreased over the acquisition time to 2 V or less. Isobaric interferences of $^{176}$Lu and $^{176}$Yb on the $^{176}$Hf signal were corrected by monitoring signal intensities of $^{175}$Lu and $^{173}$Yb, $^{172}$Yb and $^{171}$Yb. The calculation of signal intensity for $^{176}$Hf also involved independent mass bias corrections for Lu and Yb.

## 4. Analyzed samples

The age spectra of detrital zircons from six samples of mica schist from the WS and four meta-sandstones from the ES were determined. Analyses were also made on samples whose relationships with the coastal accretionary complex are not well established. These are a white mica–biotite paragneiss, a biotite–hornblende tonalite and a mylonite from a hitherto undated igneous and metamorphic complex at Liquiñe and a biotite–muscovite paragneiss from the Parque Alerce Andino area. A felsic volcanic rock (FO0603), a biotite–perthite granodiorite (belonging to the Huingancó complex at Huaraco) and a biotite–hornblende tonalitic gneiss (SMA) from neighbouring parts of Argentina were also dated since they were considered potential source rocks for the detrital zircons of the coastal accretionary complex. The geographical location of all samples is listed in Table 1 and shown in Fig. 1, together with U – Pb ages for the mid-Carboniferous Coastal Batholith samples. Brief petrographic descriptions of analyzed samples are given in Table 1. The most important place names referred to in the text are partly shown in Fig. 1; for others please refer to the corresponding references.

## 5. Previous geochronological data

Existing detrital zircon age data from this great expanse of the Chilean metamorphic basement is very scarce. Two U – Pb LA-ICP-MS

**Fig. 1.** Geological sketch map of the studied area (34–42°S) (modified from SERNAGEOMIN 2003) with location of the analyzed samples. For each sample studied for provenance the minimum detrital zircon age and the percentage of Proterozoic zircons is shown. Ages of the Coastal Batholith are indicated in italics. Additional age data are U – Pb zircon crystallization ages (^: Duhart, 2008) and Lu – Hf mineral isochron ages (*: Willner et al., 2010) and electron microprobe Th – U – total Pb monazite ages (**: Martinez et al., 2011) for garnetiferous metamorphic rocks. Heavy line-work represents various generations of brittle and ductile faults.

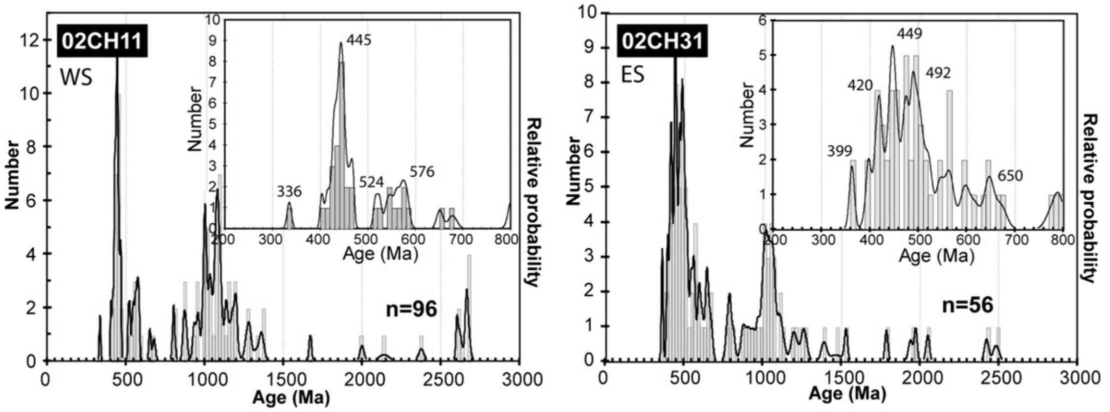

Fig. 2. Histogram and age vs. probability diagram for detrital zircons of the northern segments of the Western and Eastern Series from Willner et al. (2008).

detrital zircon patterns reported by Willner et al. (2008)—one each from WS and ES rocks, near the northern end of the study area—are shown in Fig. 2. The ES sample is in reasonable agreement with the data obtained here, but the WS sample shows significant differences, lacking any prominent Carboniferous zircon grains as reported herein (see below).

Duhart et al. (2001) report sparse detrital zircon TIMS U – Pb data for WS samples from the southern area. They obtained an upper intercept age of 266 ± 14 Ma based on analysis of 6 discordant zircon crystals from Hueyusca and suggested maximum depositional ages based on single concordant grains of 275 Ma and 305 Ma (Pucatrihue), 278 Ma (Isla Mancera) and 285 Ma (Punta Huezhui), as well as older limits of

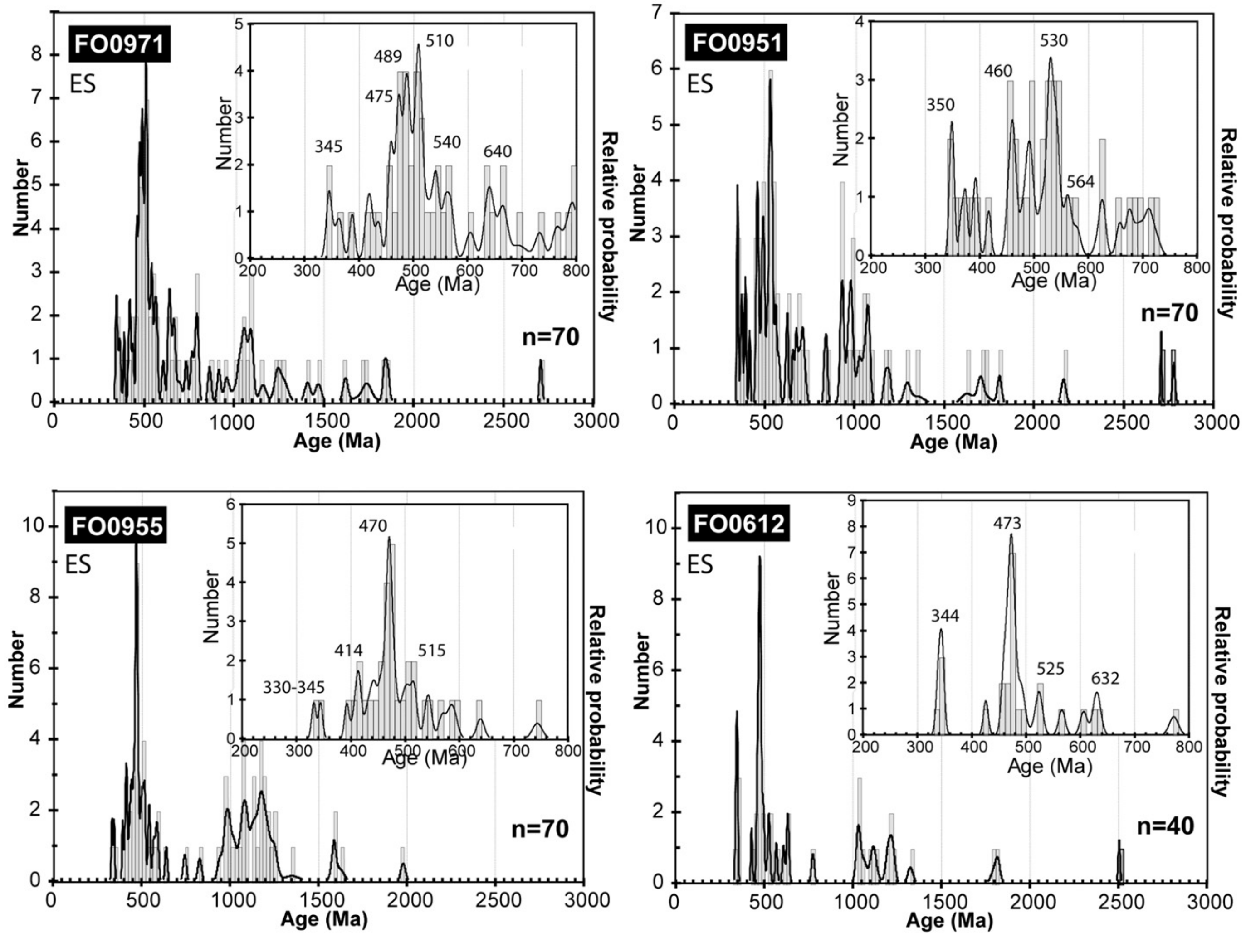

Fig. 3. Histogram and probability vs. age diagrams for detrital zircons of the Western Series of the accretionary complex of the coast ranges of Central Chile.

369 Ma (El Mirador) and 388 Ma (Guabún). In addition, they reported a U–Pb zircon crystallization age of 396 ± 1 Ma for a trachyte at Zarao emplaced in mafic schists. Söllner et al. (2000) report a discordia line with a lower intercept of 293 ± 23 Ma interpreted as the crystallization age of a meta-ignimbrite, a rare constituent of the WS.

Metamorphic ages can also be used to place a limit on the time of deposition, but give no information with respect to provenance. Hervé et al. (1984) reported a Rb–Sr whole-rock isochron age of 310 ± 11 Ma (2σ) for blueschists/greenschists at Pichilemu (WS, northern area). Willner et al. (2005) used the Ar–Ar method on white mica to date the high P/T metamorphism of the WS to between 320 and 288 Ma and the high-temperature metamorphism of the ES to between 302 and 294 Ma, near the northern part of the study area. In the southern portion of the WS, Duhart et al. (2001)

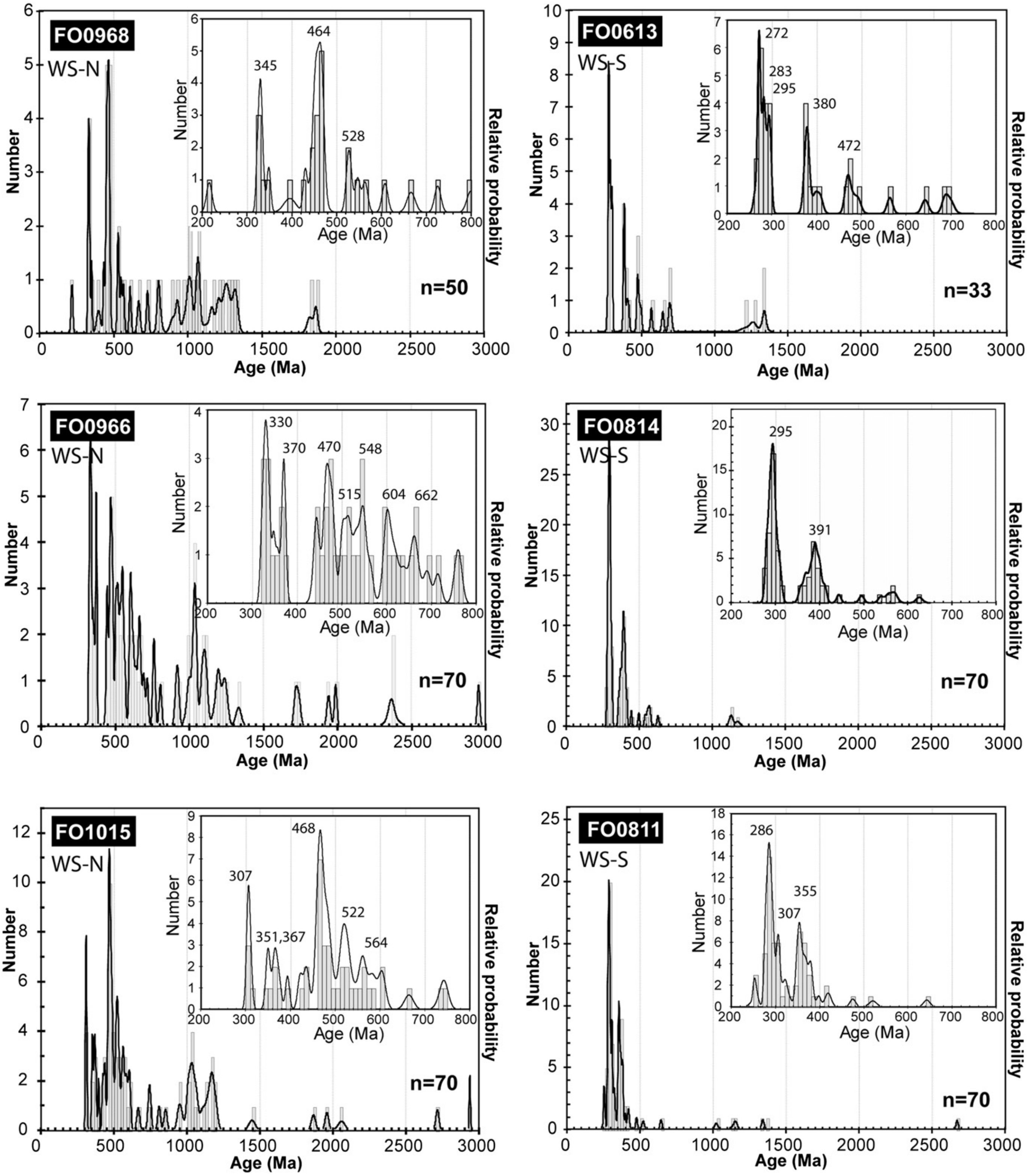

**Fig. 4.** Histogram and probability vs. age diagram for detrital zircons of the Eastern Series of the accretionary complex of Central Chile.

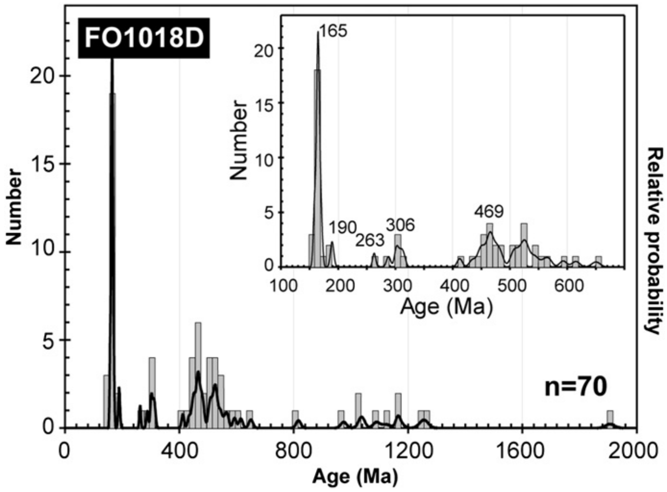

**Fig. 5.** Histogram and probability vs. age diagram for detrital zircons of a metasedimentary succession previously mapped as part of the Eastern Series (Gana and Hervé, 1983) but in fact corresponding to Jurassic deposits.

concluded, based on numerous Rb – Sr, K – Ar and Ar – Ar ages that the main metamorphism occurred at 260–220 Ma, and the high P/T blueschist metamorphism at 320–300 Ma. More recently, Glodny et al. (2008) obtained Rb – Sr mineral isochron ages (essentially white mica ages) between 307 and 272 Ma for the ES outcrops north of the Lanalhue Fault Zone and 295 to 255 Ma for the WS to the south. Kato and Godoy (1995) dated white micas (304 ± 9 Ma, K – Ar) in rare eclogite boulders in the WS at Los Pabilos; these rocks subsequently yielded Ar – Ar ages of 325 ± 1 Ma for white mica (Kato et al., 1997) and 361 ± 2 Ma for amphibole relict from the eclogite facies metamorphism (Kato et al., 2008). The overprinting event was dated at 305 ± 3 Ma from a Rb – Sr mineral isochron by Willner et al. (2004), who dispute the older age of Kato et al. (1997).

The Liquiñe gneisses have been poorly dated at 242 ± 42 Ma by the Rb – Sr isochron whole-rock method (Hervé and Munizaga, 1979).

Rocks dated as possible components of the source areas for the accretionary prism sediments include the deformed tonalitic intrusive body at San Martin de los Andes dated as Devonian by U – Pb methods on zircon by Varela et al. (2005) and Pankhurst et al. (2006). The latter authors also report a result of 401 ± 3 Ma, with a further age of 395 ± 3 Ma for a granite outcrop 10 km to the north. Also, the Huingancó granite and a rhyolite from the Arroyo del Torreón Formation of Cordillera del Viento have previous SHRIMP U – Pb zircon ages of 327.9 ± 2 Ma (Suárez et al., 2008) and 281.8 ± 2.1 Ma respectively (in Ramos et al., 2011), in close coincidence with our results (see below).

## 6. Results

### 6.1. U – Pb zircon data

Analytical data for the studied samples are presented in Supplementary Tables S1 to S18, available from the journal website. Age versus probability density diagrams for all the samples are presented in Figs. 3–7. The most striking difference in the age distributions recorded is between the southern segment of the WS and the other samples.

All samples of the ES (Fig. 3) and the northern area WS samples (Fig. 4) show major input from Ordovician (*c.* 470 Ma = Famatinian) sources. In addition peaks at 530–510 Ma (Pampean), and 950–1250 Ma ('Grenvillian') are present in many, albeit in variable proportions, and sparse 'Brasiliano' (640–590 Ma) and Paleoproterozoic to Archaean ages are sometimes observed. These constitute the main features of a typical western 'Gondwana' margin provenance signature (Ireland et al., 1998; Cawood et al., 1999; Hervé et al., 2003; Goodge et al., 2004). In the northern segment, ES and WS samples have similar detrital zircon age spectra but the maximum possible sedimentation ages determined by the youngest reliable detrital zircons are significantly younger in the latter (mostly *c.* 330 Ma as opposed to mostly *c.* 345 Ma). This difference is also apparent in the two samples analyzed by Willner et al. (2008), albeit with older limits of 335 Ma (WS) and 365 Ma (ES). All zircons are older than the mid-Carboniferous Coastal Batholith, with the exception of some as young as 305 Ma in the sample from Putu (FO1015). There is a high proportion of Proterozoic zircon grains (Table 2), although this is significantly lower in the younger Putu sample. With the exception of FO0966 and the two samples analyzed by Willner et al. (2008), there are few zircons in the age range of 350–450 Ma, a robust peak occurs at 465–470 Ma, and a significant proportion lie in the range of 500–530 Ma.

FO1018D (Fig. 5) is an exception, as it was previously mapped as part of the ES, but the well cleaved meta-sandstone/metapelite alternation gives a Jurassic sedimentation age and thus belong to the units deposited in the Hualañé-Gualleco extensional basin (Belmar and Morata, 2005), lying unconformably over the accretionary rocks. Its zircon age pattern indicates derivation from the erosion of the accretionary prism together with zircons from the Coastal Batholith (see below) and Jurassic igneous rocks.

In the southern segment, the ES provenance patterns (Fig. 3) are similar to those in the north, but the WS samples (Fig. 4) have very different detrital zircon age spectra. All of the latter have a predominant population of zircons in the range of 250–300 Ma (with a peak at *c.* 290 Ma). As in all the ES samples, the youngest Carboniferous zircons are around 345 Ma, but there is a significant Devonian input with ages between 350 and 420 Ma (peaking at around 380 Ma). The Ordovician peak at 470 Ma is essentially absent from the southern WS spectra and the proportion of Neoproterozoic ages is much smaller (<20%); zircons older than 'Grenvillian' are completely absent.

The Coastal Batholith yielded very consistent mid-Carboniferous U – Pb zircon ages of 300 to 320 Ma (late Mississippian to early Pennsylvanian) along its 700 km extent (see Fig. 1). The significance of the results from the Coastal Batholith, including O and Lu – Hf isotope determinations on zircons, will be presented in a separate paper (Deckart et al., 2012).

The Liquiñe gneisses are considered to form part of the Colohuincul complex, whose main outcrops are on the eastern slope of the Andes in Argentina (Hervé et al., 1974a). Sample FO0605 (Fig. 6) has a relatively low yield of complex zircon grains and only 30 grains have been analyzed. A number of the grains have a zoned core and homogeneous rim structure as seen under CL imaging (Fig. 6), or show a mottled texture consistent with alteration of mostly primary igneous zircon. The resultant age spectrum is quite varied, suggesting a polygenetic provenance. Three metamorphic rims, with low Th/U ratios (≤0.01) record Triassic ages; one of these grains has a Devonian core (grain 25 at *c.* 400 Ma). Four other grains record ages ≤380 Ma and three of these have low Th/U ratios ≤0.01; namely, analyses of mottled areas in grains 4 and 9, and an interpreted metamorphic rim to grain 14. Note that grain 14 also has a Devonian core (*c.* 380 Ma). The zoned igneous core to grain 21 is *c.* 330 Ma and has a normal Th/U ratio for igneous zircon (*c.* 0.36). While a single analysis does not constrain the maximum time of deposition for the protolith to this Liquiñe gneiss it is either at *c.* 330 Ma, or the grouping at *c.* 380 Ma indicating a possible Devonian depositional age (Fig. 6).

In the Parque Alerce Andino sample (FO0935; Fig. 6), many of the zircon grains have thin, ragged homogeneous CL overgrowths that are less than 10 μm in width. The main components of these grains range in CL structure from oscillatory (grain 55) and sector zoning (grain 67) to more homogeneous, interpreted metamorphic CL features (grain 61). Core and rim areas were analyzed on 4 grains, mostly recording Devonian or older ages. Grain 8 however has a Triassic

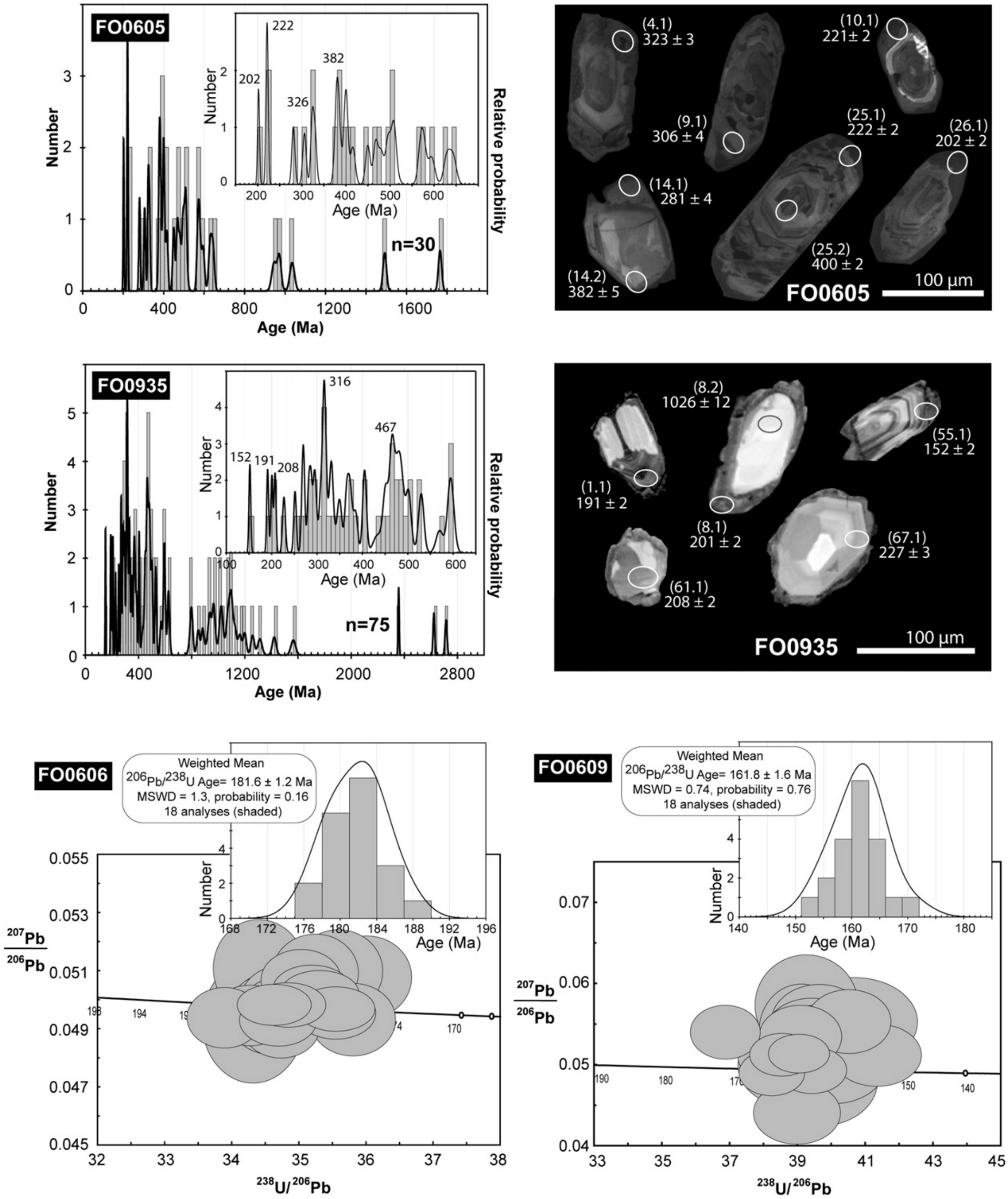

**Fig. 6.** Histogram and age vs. probability diagrams for detrital zircons of the Liquiñe (FO0605) and Parque Alerce Andino (FO0935) gneisses. CL images of selected grains in both samples with the location of analyzed spots also shown. Banded mylonite (FO0606) and mylonitized hornblende–biotite tonalite (FO0609) spatially associated to the Liquiñe gneiss give Jurassic crystallisation ages.

rim with a Grenville-age core. Four other grains record relatively young ages ≤230 Ma (grains 1, 55, 61 and 67) demonstrating that this rock has a protolith as young as Late Triassic or Early Jurassic. The prominent, but thin metamorphic rims probably formed in response to the Jurassic 182 and 162 Ma intrusive event indicated by the mylonite (FO0606) and mylonitic granodiorite (FO0609) of the Liquiñe area, which has not up to now been detected in the poorly studied Alerce Andino area.

The orthogneiss from San Martin de los Andes in Argentina records a well-defined magmatic zircon crystallization age of 393 ± 3 Ma in good agreement with the 401 ± 3 Ma result of Pankhurst et al. (2006). Crystallization ages of 283 ± 2 Ma (Huingancó granite) and 326 ± 3 Ma for a rhyolite of the Arroyo del Torreón Formation (Llambías et al. (2007) were obtained from Cordillera del Viento in Argentina. These results, mentioned by Godoy et al. (2008), are shown in Fig. 7.

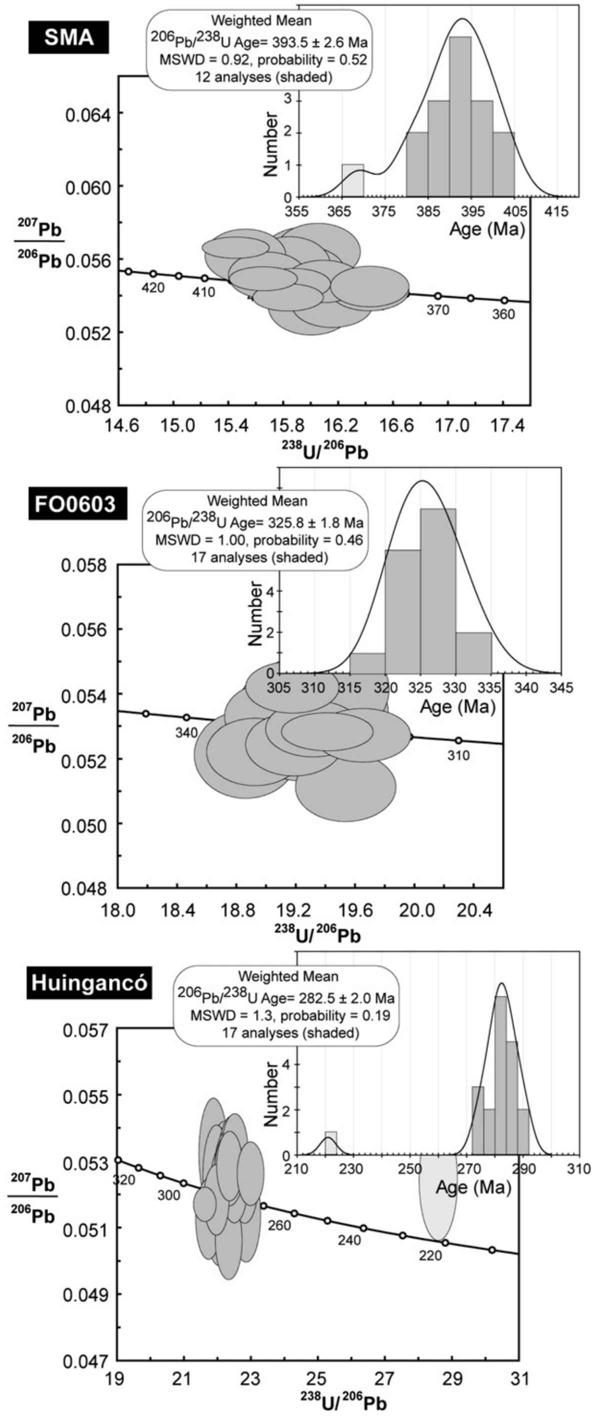

**Fig. 7.** Age vs. probability diagrams of the San Martin de los Andes orthogneiss, Huingancó granite and Andacollo rhyolite on the eastern flank of the Andes, Argentina. These samples were analyzed on the premise that they could be part of the source area for detrital zircons in the coastal range accretionary complex.

### *6.2. Oxygen and Lu–Hf isotope data in zircons*

In order to characterize and trace potential source(s) of the detrital zircon grains oxygen and Lu–Hf isotope ratios were determined on a selection of the zoned igneous zircon components discussed above, mostly in the age range of 250–580 Ma, with some random older grains (Supplementary Table S19). While some Hf data are available from both detrital zircons and source rocks of geological units related to the ones studied here, there are few or no published oxygen isotope data. Hf studies have thus far concentrated on detrital zircon and in general the aim in such studies has been to cover the full gambit of the age spectra recorded; see for example Willner et al. (2008), Bahlburg et al. (2009), Rapela et al. (2008). More focused studies on specific age ranges are less common, but likely to be of

**Table 2**
Summary of the geochronological results on detrital zircons obtained in this study.

| Sample number/ points analyzed | Locality | Geological Unit | Youngest significant detrital age | Proterozoic zircons (%) |
|---|---|---|---|---|
| FO0966/70 | Iloca | WS-N | 330 | 64 |
| FO0968/50 | Boyeruca | WS-N | 330 | 59 |
| FO1015/70 | Putu | WS-N | 307 | 40 |
| 02CH11*/96 | | WS-N | 335 | 74 |
| FO0613/33 | Antilhue | WS-S | 272 | 18 |
| FO0814/70 | Maicolpue | WS-S | 291 | 10 |
| FO0811/69 | Pucatrihue | WS-S | 253 | 10 |
| FO0971/70 | Tanume | ES-N | 350 | 59 |
| 02CH31[a]/94 | | ES-N | 363 | 63 |
| FO0955/70 | Chivilingo | ES-N | 340 | 60 |
| FO0951/70 | Puren | ES-S | 350 | 60 |
| FO0612/40 | Playa Chauquen | ES-S | 342 | 50 |
| FO1018D/70 | Coipue | Hualañé–Gualleco basin | 165 | 26 |
| FO0605/30 | Liquiñe | | 330 or 380 | 37 |
| FO0935/54 | Parque Alerce Andino | | 195 or 206 | 46 |

Western and Eastern Series rocks are differentiated into northern segment (N) and southern segment (S) relative to the Lanalhue fault zone. Ages in Ma.

[a] Indicates samples from Willner et al. (2008).

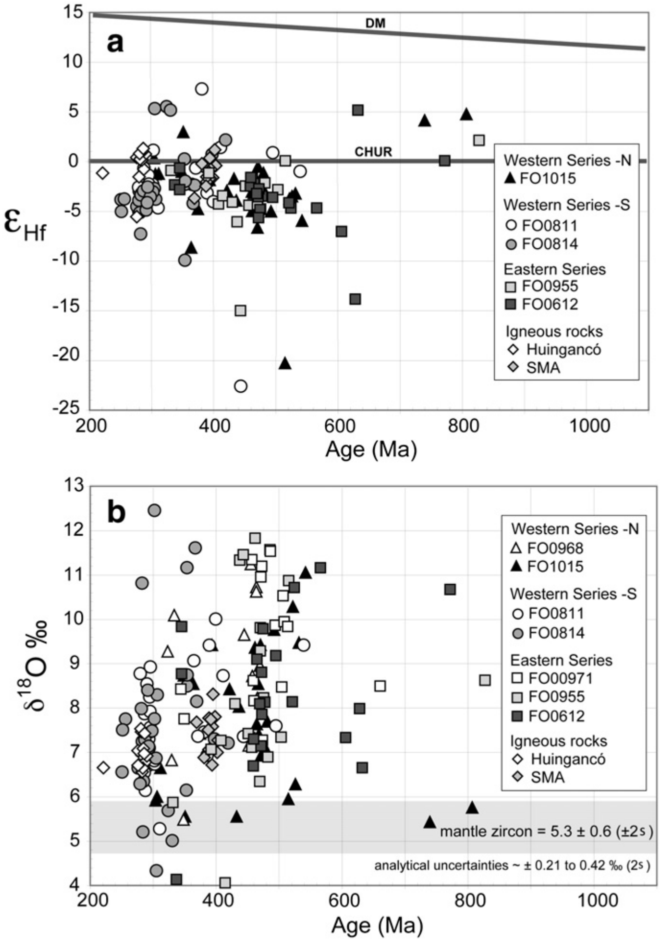

**Fig. 8.** (a) Age vs. εHft diagram for detrital zircons of the accretionary complex of Central Chile, (b) Age vs $\delta^{18}$O‰ diagram for detrital zircons of the accretionary complex of Southern Chile.

greater value in unravelling specific detrital zircon sources (see Fanning et al., 2011). Further, by combining Lu – Hf with oxygen isotope analyses an extra dimension in characterisation and source identification is likely.

The Lu – Hf data on detrital zircons are presented in Fig. 8a. Most of the analyzed grains are typical magmatic zircons, with well developed oscillatory or sector zoning. In the samples from the WS, all the Permian zircons have negative initial εHf values (−1 to −8) similar to those shown by detrital zircons of similar age on the basement units of southern Chile and Antarctic Peninsula (Fanning et al., 2011). This indicates that the magmatic sources are evolved and have resided in the continental lithosphere for some time; i.e., there is a strong crustal contribution. The Early Paleozoic zircons include some with slightly positive εHf values (up to +2), suggesting that the source of these zircons has been influenced by the addition of mantle-derived components within predominantly crustal magmas. The main exception, however, is for zircons that crystallized during the period *c.* 330 to 305 Ma, which have uniformly positive initial εHf values (+4 to +5) indicating a pulse of relatively juvenile magma overlapping emplacement of the Coastal Batholith. The Permian Huingancó granite in the Cordillera del Viento of Argentina is more juvenile than the rest of the predominant coeval detrital grains, with εHf values mostly in the range of 0 to −2.

O isotope data on the same detrital zircons are presented in Fig. 8b. The $\delta^{18}$O values are mostly more positive than +6.5‰, well above the range recorded by zircons with a mantle oxygen isotope signature. This data confirms the strong crustal influence, especially in the pre-Carboniferous zircons, with a general trend to more primitive compositions, lower $\delta^{18}$O, from the older to the younger grains. Again, the only typical mantle values are shown by some of the grains in the age range of the Coastal Batholith and slightly older, i.e., 305–330 Ma.

## 7. Discussion

### *7.1. Provenance indications*

The older components in the provenance patterns of all samples show a range of Early Paleozoic, Neoproterozoic and scarce older detrital zircons typical of the Early Paleozoic tectonomagmatic belts of southern South America, notably the Pampean (Cambrian) and Famatinian (Ordovician) belts of western Argentina (e.g., Rapela et al., 2007; Verdecchio et al., 2011). These belts formed on the paleo-Pacific margin of the continent and are the most obvious sources for the older zircons in the basement complexes west of the Andes. The scarce Paleoproterozoic and Archaean content is similarly attributable, having been reworked from cratonic sources that are not specifically identifiable. The samples analyzed in this study are more remarkable for the variations in their Late Paleozoic provenance, which are more diagnostic of tectonic influences in the sedimentary environment.

The prominent Early Permian provenance in the southern sector WS, which is absent from the remaining basement areas studied here, is traceable to the voluminous Permian igneous rocks of the Choyoi province and/or the presumably related subvolcanic granites of the North Patagonian Massif, the latter occurring directly to the present east of the coastal basement outcrops at 40°–41°S. Although the major Choiyoi rhyolite volcanism occurred rather later (250–260 Ma), recently published U – Pb zircon ages confirm an early phase at *c.* 280 Ma (Rocha-Campos et al., 2011) and many of the Patagonian granites were emplaced at this time (Pankhurst et al., 2006), as was the Huingancó granite. Such a correlation would be compatible with the broadly crustal Hf isotope signature noted above for the Permian zircons (Fanning et al., 2011). The Choyoi province exhibits its major development north of about 34°S, but the absence of similar detritus from the ES and the northern sector of the WS is explained by the fact that these rocks were deposited earlier, in Carboniferous times.

The Carboniferous provenance of the basement samples studied here indicated by the major peaks in their detrital zircon patterns are *c.* 345 Ma in the ES and *c.* 330 Ma in the northern sector WS. These are maximum ages for deposition, which as discussed above was pre-Permian. The fact that the ES is intruded by the 300–320 Ma Coastal Batholith and the absence of zircons derived therefrom means that these peak ages are probably very close estimates of sedimentation age, which is thus constrained to the Mississippian (Early Carboniferous). Early Carboniferous subduction-related granitoids of predominantly A-type geochemistry, many with U – Pb zircon ages of *c.* 340–350 Ma, occur in the Eastern Sierras Pampeanas of Argentina at 27–30°S (see Alasino et al., 2012, and references therein). It seems quite possible that similar magmatism extended farther south than the Sierras Pampeanas, which are only exposed as a result of uplift and exhumation above the 'flat-slab' portion of the Andean subduction system, and that this is the source of the detrital zircons in the ES. Carboniferous subduction-related magmatism migrated or jumped towards the Pacific during the mid-Carboniferous and arc-derived I-type granitoids of 310–330 Ma are known in the Frontal Cordillera itself (albeit so far without U – Pb zircon ages). This event is also registered in the western border of the North Patagonian Massif (Pankhurst et al., 2006) and there is no doubt that subduction was active at this time along the whole of the Chilean proto-Pacific margin. This is the obvious source of the younger Carboniferous detrital zircon peaks seen in the northern sector WS. The virtual absence of zircons of Carboniferous age from the post-Early Permian southern WS probably indicates that the Coastal Batholith was not exhumed in this area during the Permian. The remaining difference between the northern and southern sectors is the significant proportion of Devonian detrital zircon in the latter, which is largely absent from the former (although a few grains are seen in the northern WS samples). Bahlburg et al. (2009) also noted the scarcity or absence of Devonian detrital zircons in late Paleozoic metasedimentary rocks in northern Chile (31°–22°S). This is discussed further below.

### *7.2. Provenance of Devonian detrital zircons*

There is abundant evidence for Devonian magmatism and deformation in the eastern flank of the main Andean cordillera between 39° and 42°S that can be considered the most likely source of Devonian detrital zircons in the southern part of the Western Series. This is represented around San Martin de los Andes (*c.* 40°S, 71°W; see Fig. 1) by small outcrops of variably deformed igneous, orthogneissic and migmatitic rocks, consistently dated at *c.* 385–405 Ma by Varela et al. (2005), Pankhurst et al. (2006), Godoy et al. (2008) and the present paper (sample SMA, 393.5 ± 2.6 Ma). Such a belt could even extend southeastwards to Colan Conhué at 43°S, 70°W (see fig. 3 of Pankhurst et al., 2006). Lucassen et al. (2004) published a Rb – Sr mineral isochron age of 368 ± 9 Ma for a migmatite from San Martín de Los Andes, and a $^{206}$Pb – $^{238}$U age of 380 ± 2 Ma for titanite from a gneiss–migmatite association 100 km further southeast near Piedra del Aguila, interpreted as approximating the time of the metamorphic peak. In the Alumine area at c. 39°S, approximately 150 km north of San Martin, the oldest K – Ar age on fine fractions of metamorphic schists (*c.* 370 Ma; Franzese, 1995) indicates Late Devonian deformation or cooling of these rocks, and the overall range (*c.* 300–370 Ma) is consistent with partial resetting of the K-Ar system by contact metamorphism in the late Paleozoic. Devonian Rb-Sr whole-rock isochron ages have been obtained from metasedimentary rocks of the Cushamen Formation in the North Patagonian Massif close to Colan Conhué (Ostera et al., 2001). Recently, Martinez et al. (2011) have published single electron microprobe Th – U – total Pb monazite ages of 392 ± 4 Ma and 350 ± 6 Ma (interpreted as indicating collision metamorphism and a later retrograde event, respectively) in schists belonging to the Colohuincul complex on the eastern slope of the Andes near San Carlos de Bariloche (41°S). Ramos et al. (2010) have shown that Colohuincul complex rocks include Devonian detrital zircon grains. Even farther south at 42°–43°S in the western flank of the Andes, albeit on the coast, Duhart (2008) reports the existence of foliated granitoids of similar Devonian ages: the Chaitén metatonalite (c. 400 Ma) and the Pichicolo microdiorite (c. 386 Ma).

In one respect, the absence of Devonian detrital zircon in the northern region of the Central Chile basement is notable. Devonian granite magmatism and shearing in the sierras of Córdoba and San Luis of northwest Argentina have been dated by U–Pb and Ar–Ar methods and interpreted as constituting the Achalian orogeny (see Sims et al., 1998; Stuart-Smith et al., 1999). Dorais et al. (1997) and Rapela et al. (2008) have dated the major intrusive representative, the Achala granite batholith, with U–Pb zircon ages of 368 ± 2 to 379 ± 4 Ma. From *c.* 200 km to the southwest, in the Frontal Cordillera, Willner et al. (2010) published Lu–Hf mineral isochrons for garnetiferous pelitic schists and amphibolites of the Guarguaraz complex, obtaining consistent ages of 390 ± 2 Ma. Additionally, Heredia et al. (2012) report the presence of clasts of plutonic rocks of western provenance in the Devonian Vallecito Formation on the eastern slope of the Andes at 34°S, which they relate to magmatism in Chilenia during pre-collisional west-directed subduction of the intervening ocean between Chilenia and Gondwana. Thus, although genetically different from the Devonian belt 600 km away in the southern region, there is clear expression of a contemporaneous mid-Devonian igneous and metamorphic belt to the east of the northern part of our study area, at latitudes 31–34° S.

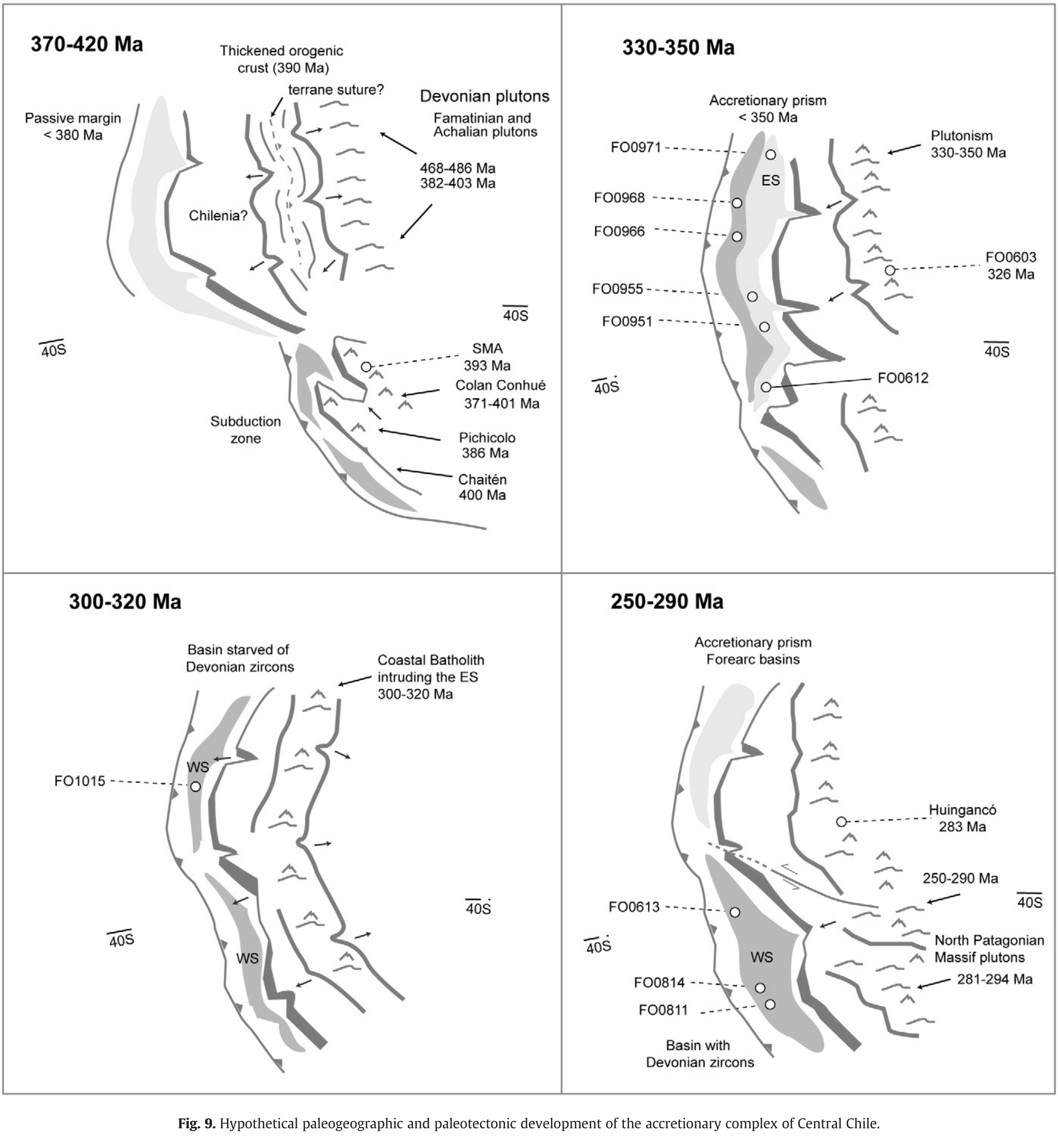

**Fig. 9.** Hypothetical paleogeographic and paleotectonic development of the accretionary complex of Central Chile.

### 7.3. Tectonic considerations

Thus contemporaneous Mid-to-Late Devonian granitoids and metasedimentary rocks, variously affected by tectonism, and metamorphic/thermal events, developed within the western margin of this segment of Gondwana from *c.* 28° to 42° or even 43°S (Fig. 9). Regardless of their varied petrogeneses, these Devonian rocks constituted an eroding area while sediments of the southern portion of the WS were being deposited during the Permian, as Devonian zircons are found therein. The fact that few detrital zircons of this age reached the Early Carboniferous proto-Pacific margin deposits in the north may mean that they were still unexhumed at that time, but more probably indicate the presence of a topographical barrier. The Precordillera terrane could have formed such a barrier, having been accreted to the margin during the Ordovician Famatinian orogeny. Additionally, Stuart-Smith et al. (1999) ascribed the Achalian magmatic and tectonic cycle to the Devonian collision of a further terrane to the west, i.e., Chilenia (Ramos et al., 1986). Massonne and Calderón (2008) and Willner et al. (2010) also argued that the P-T path determined for the metasedimentary rocks indicated crustal thickening, consistent with a Devonian terrane collision. A similar explanation for the metamorphism of the Colohuincul complex at 41°S was given by Martinez et al. (2011). A problem with the latter interpretation is that, according to current models, the southern limit of the Chilenia terrane is the E–W Huincul lineament, located near the latitude of the Lanalhue Fault Zone (37°–38°30′S). Extension of Chilenia to 41°S to explain the Devonian metamorphism is problematic since at that latitude the coastal accretionary complex extends eastwards as far as the western flank of the present-day Andes, leaving little space for an intervening continental sliver. As suggested by Kato et al. (2008), subduction was already active here in the Devonian, a view that is supported by data presented here and by McDonough et al. (as cited by Duhart et al., 2001). Thus the proposed Devonian metamorphism of the Colohuincul complex could be related to the subduction episode that gave rise to the Devonian arc plutons, probably in a back-arc position. Another possible alternative is that the rocks studied by Martinez et al. (2011) were tectonically "extruded" to the south of the Chilenia terrane limit during and/or after the Chilenia–Gondwana collision. Also, as already pointed out by Duhart et al. (2001), sedimentation of the southern portion of the WS took place during the Permian, well after the peak metamorphism of the eclogites and blueschists.

Further difficulties for the Chilenia hypothesis are that no Devonian I-type plutons are known from the northern area and Rapela et al. (2008) showed the Achala granites to be geochemically peraluminous A-type rather than collision-related S-type. Alasino et al. (2012) have argued that the Devonian and Early Carboniferous A-type granites were generated above a zone of flat-slab subduction followed by rapid roll-back and renewed subduction with increasingly I-type magmatism at the Late Carboniferous margin outboard of an extensive retro-arc.

Thus the mid-Carboniferous metasedimentary basement of the northern sector should have involved a wide Late Paleozoic depositional basin prior to the establishment of the Coastal Batholith. This basin developed either on the trailing edge of an exotic terrane accreted in the Devonian (Chilenia) or a long-lived accretionary platform west of the Precordillera terrane accreted in the Ordovician. Sedimentary detritus could have been received from contemporaneous Early Carboniferous I-type and A-type igneous activity far to the east but apparently did not include material from the Devonian complexes, which may have been buried at the time. It is also notable that there is a scarcity of zircons of *c.* 570 Ma, which Álvarez et al. (2011) suggested as possibly indicating the basement of Chilenia.

In northern Patagonia, Carboniferous I-type magmatism represents east-to-northeastward subduction at 330 Ma (Pankhurst et al., 2006). The northernmost proven outcrop of these rocks near Bariloche is less than 100 km south of the Devonian magmatic and metamorphic rocks around San Martin de los Andes (Pankhurst et al., 2006, their Fig. 2) and thus appear to be slightly inboard of the Devonian margin. It is often considered that northern Patagonia collided with the rest of South America in the Carboniferous as in the model of Ramos (2008 for the latest version), and paleomagentic data would allow a separation of up to about 1500 km across the intervening 'Colorado Ocean' (Rapalini et al., 2010). If this were so we should expect a major discontinuity in the Devonian and Early Carboniferous record at the latitude of the Huincul Ridge at 39°S, which is not apparent. The collision suture suggested by Pankhurst et al. (2006) was south of the North Patagonian Massif and the Carboniferous outcrops, and so might still be viable, but if the Devonian granite at Colan Conhue is considered to be a continuation of the Devonian belt at San Martin de los Andes, this model also would be doubtful.

## 8. Conclusions

The metasedimentary basement rocks of Central Chile north of the Lanalhue lineament (*c.* 37°–38°30′S) form a penecontemporaneous paired metamorphic belt. Our data show that the Eastern Series was deposited in Early Carboniferous times, shortly before the Western Series but both prior to emplacement of the 305–320 Ma subduction-related Coastal Batholith, which intrudes the former. The provenance for both series was older Gondwana margin basement of the Pampean and Famatinian belts, including reworked cratonic material, and Carboniferous magmatism east of the present-day Andes. Metamorphism of the accretionary wedge seems to have overlapped with the late plutonic phase, but may have continued later in the high P/T Western Series.

The Eastern Series is of limited extent south of about 39°S, but is similar to the low P/T metasedimentary series in the north. However the predominant Western Series in the southern sector is much younger, with abundant Permian detritus derived from the Choiyoi province or subvolcanic plutonic rocks in the North Patagonian Massif. There is also a secondary provenance of Devonian age, which is absent from its northern counterpart and the entire Eastern Series. O and Lu – Hf data indicate a mature crustal source for all zircons except those that crystallized during Carboniferous subduction.

Analysis of igneous and metamorphic rocks from farther east show that inboard of the southern sector there is a Devonian igneous and metamorphic block or belt of more significant extent than has been previously noted, which is the presumed source of the detritus of this age in the southern Western Series. The relative paucity of Devonian provenance in the north is explained by a wide crustal zone separating the Devonian igneous rocks of the Sierras Pampeanas in Argentina from the site of the Carboniferous accretionary deposits, including the Precordillera terrane and possibly Chilenia, when subduction jumped to the west in the Early Carboniferous.

The apparent continuity of the Devonian–Early Carboniferous magmatic and metamorphic rocks as far as 43°S or more does not support the idea that the North Patagonian Massif was separated from the rest of southern South America by a significant ocean at this time.

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