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U–Pb SHRIMP detrital zircon dating of metamorphic rocks in north–central Chile (28°–33°S): Evidence for Carboniferous and Triassic metamorphism in a subduction setting

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ABSTRACT

U–Pb SHRIMP detrital zircon dating of ten samples of metamorphic "basement" rocks in north-central Chile and one granitic rock, improve knowledge of sedimentary, metamorphic and plutonic events in this segment of the Andean margin. The oldest possible sedimentation ages (Ordovician) come from a micaschist at Huentelauquén (477 Ma) and a granofels from a migmatite at Las Cruces (470 Ma) whose garnet-bearing granitic neosome (ca. 320 Ma) is essentially coetaneous with the extensive Coast Range Batholith. The rest of the samples show probable Carboniferous or Late Triassic maximum depositional ages. The late Paleozoic low-to-medium grade metasedimentary components of the basement, interpreted as forming part of a paleo-accretionary complex, have detrital zircon age patterns with prominent Famatinian and Grenville-age peaks; these are much less prominent in the Late Triassic rocks. The latter were deformed and metamorphosed shortly after their deposition, although some do not show visible evidence of metamorphism. Contemporaneous Triassic sedimentary, metamorphic and igneous events are recorded in Mejillones Peninsula (22°S) and in the Chonos archipelago (44°–47°S) but not in the 34°–42°S central Chile sector of the fossil accretionary complex. These events predate generalized Jurassic subduction beneath the western Gondwana continental margin that initiated the Andean orogenic cycle.

1. Introduction

The study region, locally known in Chile as Norte Chico, is spatially coincident with the present-day Pampean flat slab sector of the Andes (33°S to 28°S; Barazangui and Isacks, 1976; Becerra et al., 2016). Here the mainly Late Paleozoic metamorphic and plutonic complexes differ in some ways from those seen farther south (Fig. 1). In the 34°–42°S sector, the Coast Range is characterized by continuous outcrops of metamorphic rocks, which host the Pennsylvanian Coastal Batholith (Deckart et al., 2014). It was in this southern sector that the metamorphic rocks of the paleo-accretionary prism were sub-divided into a rather high P/T Western Series and a rather low P/T Eastern Series (Aguirre et al., 1972), now interpreted as basally and frontally accreted rocks respectively (Willner et al., 2005; Richter et al., 2007). In contrast, north of 33°S the outcrops of probably equivalent metamorphic rocks form dispersed outcrops along the Coast Range and have been given various local names. There is no Pennsylvanian batholith here the Elqui–Limarí batholith and the Paleozoic metamorphic rocks of the El Tránsito Metamorphic Complex crop out roughly 100 km further inland in the Main Andean Range (Figs. 1 and 2). The cause of this displacement is not known in detail.

This paper reports SHRIMP U–Pb ages of detrital zircon from ten samples as a tool to compare the coastal and cordilleran outcrops of Late Paleozoic metamorphic rocks and test for significant differences in their geological evolution (one related leucogranite is also dated by the same method). This technique has been widely used in the study of the Chile margin basement. South of 34°S Hervé et al. (2013) presented SHRIMP U–Pb detrital zircon ages on both the Western and the Eastern Series of the accretionary complex, and Hervé et al. (2016) gave a few data for some outcrops as far south as 43°S. Pankhurst et al. (2016) presented U–Pb dating of basement rocks north of 28°S (Norte Grande). Previous data for Norte Chico, considered below, have been provided by Willner

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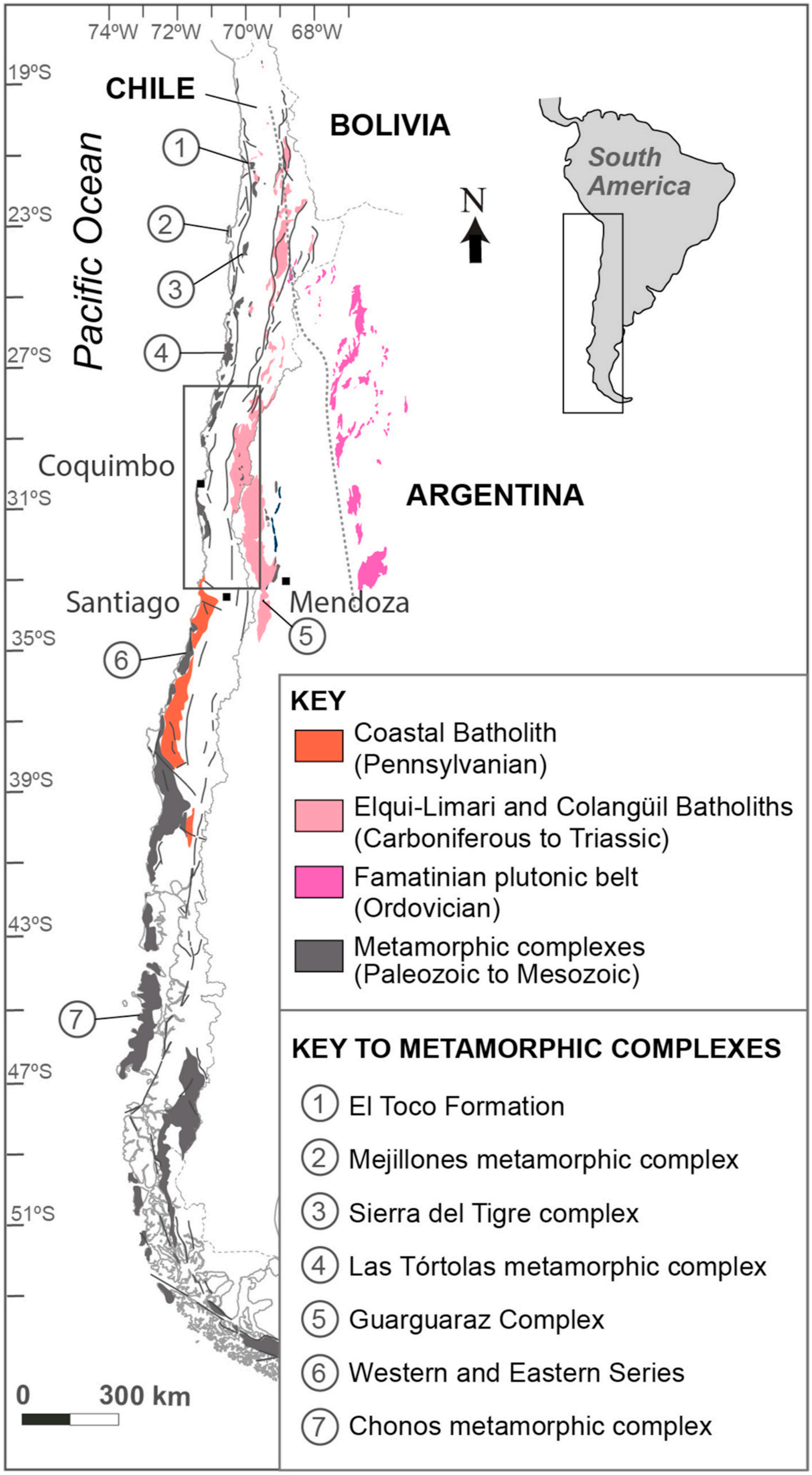

Fig. 1. General location map of the studied area in the Chilean continental margin.

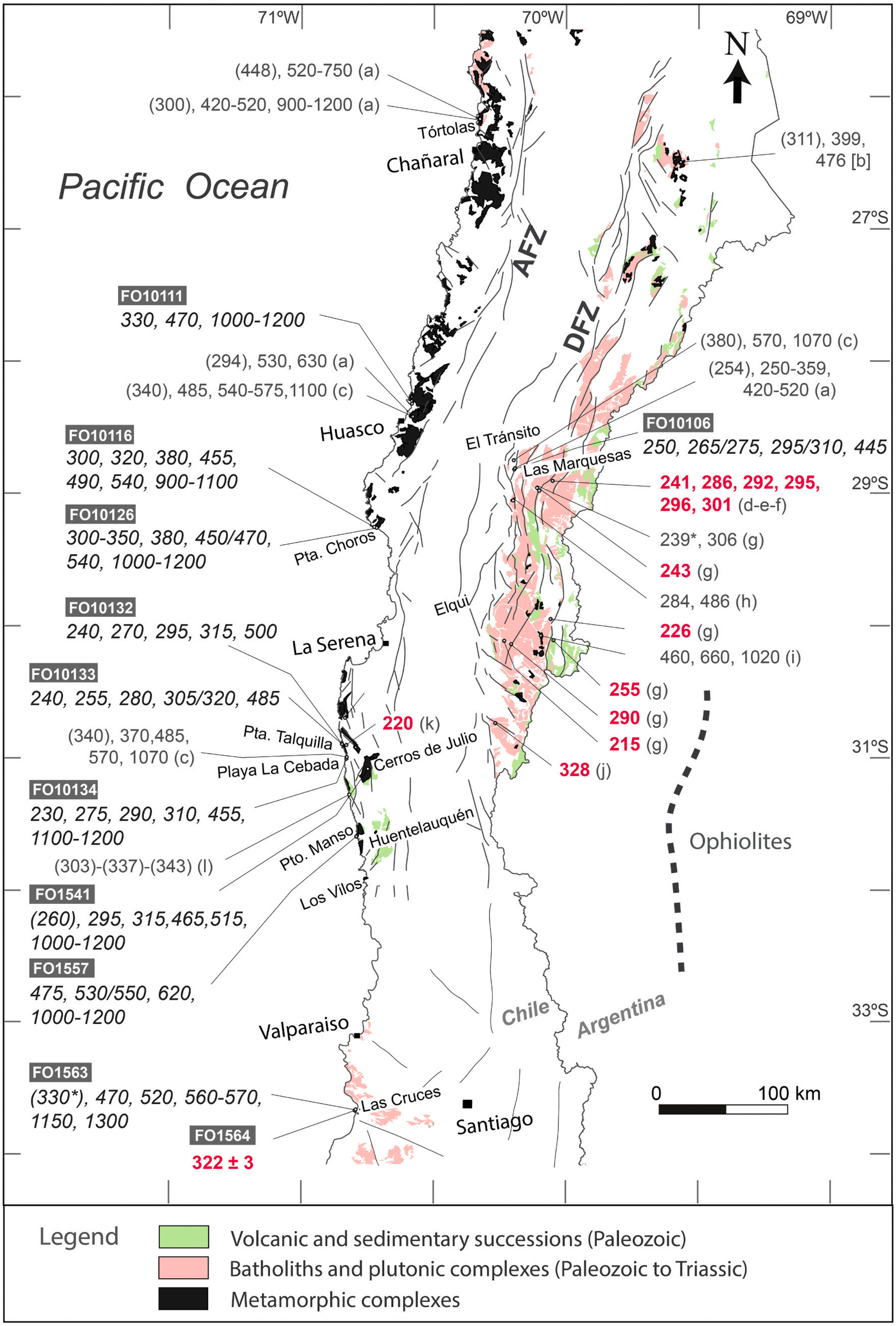

Fig. 2. SHRIMP U–Pb zircon ages for the 'basement rocks' of Norte Chico. Grey numbers indicate the dominant ages of detrital zircons in metasedimentary rocks: the youngest peak is in parentheses and an asterisk indicates metamorphic age. Red numbers indicate igneous rock crystallization ages. Data from **a)** Bahlburg et al. (2009); **b)** Maksaev et al. (2014); **c)** Alvarez et al. (2011); **d)** Coloma et al. (2012); **e)** Alvarez et al. (2013); **f)** Salazar et al. (2013); g) Hervé et al. (2014); **h)** Alvarez et al. (2013); **i)** Velasquez et al. (2015); **j)** Pineda and Calderón (2008); **k)** Firth et al. (2015); l) Willner et al. (2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al. (2008), Alvarez et al. (2011, 2013), and Creixell et al. (2016) for the coastal metamorphic rocks and, mainly by Alvarez and Mpodozis (2015) for the El Tránsito Metamorphic Complex and by Hervé et al. (2014) for the Elqui–Limarí batholith.

1.1. Geological context

Paleozoic geological development in the 27°–33°S present-day flat slab segment of the Andean margin was characterized by the collision of tectonostratigraphic terranes to the western margin of Gondwana (Ramos, 1988, 2008; Rapela et al., 1998). After the collision of the Cuyania terrane and development of the Famatinian magmatic arc, the Chilenia terrane is thought to have collided with Gondwana in the Late Devonian (Davis et al., 1999; Massonne and Calderón, 2008; Willner et al., 2010), and the hypothetical 'X' terrane (Mpodozis and Kay, 1992) in the Permian. These collisions were related to genesis of the Famatinian, Chanic and San Rafael orogenies (cf. García–Sansegundo et al., 2014).

Metamorphic complexes in this segment of the Andes (Norte Chico) crop out both in the high Andes in spatial association with the Elqui–Limarí batholith (which was emplaced in four main magmatic pulses, from the Early Permian to the Late Triassic, Hervé et al., 2014; Maksaev et al., 2014) and also in coastal complexes which have no associated contemporary plutonic belt. Coloma et al. (2017) have shown that the geochemistry of the batholith has a subduction zone signature, rather than one of an extensional tectonic regime. Del Rey et al. (2016) suggested that subduction was continuous through the Triassic, based on zircon isotope composition and a whole-rock geochemical compilation of plutonic rocks in the northern prolongation of the Elqui–Limarí batholith.

Díaz-Alvarado et al. (2019) present a revision of the diverse paleo-accretionary systems that have been exhumed in the Andean forearc along the Pacific coast of Chile. These systems experienced a common evolution, with the development of a magmatic arc and trench-vergent fold-thrust belts between Late Paleozoic and Triassic time. They relate deformation and metamorphism to the collision of oceanic terranes and the dynamics of the plate interaction at subduction zones.

Several units of metamorphic rocks are present in the study area. Alvarez et al. (2013) have dated the oldest ones in the high Andes of the El Tránsito river valley, with the maximum possible depositional age of metasedimentary rocks constrained by a protolith crystallization age of 486 Ma, in what they considered to be the only known outcrop of rocks belonging to the Chilenia terrane. Different youngest detrital zircon ages have been obtained from the El Tránsito Metamorphic Complex, varying from ca. 380 Ma (Alvarez et al., 2011) to ca. 255 Ma (Bahlburg et al., 2009). Velásquez et al. (2015) obtained Ordovician maximum possible depositional ages from El Cepo metamorphic rocks in the Elqui valley. Alvarez et al. (2011) determined an age of ca. 340 Ma for detrital zircons in the schists of the Choapa Metamorphic Complex at Playa La Cebada, where ca. 330 and 305 Ma detrital zircon ages were reported by Willner et al. (2008). Creixell et al. (2016) established that at 28°–29°30′S, three different units register Late Paleozoic events: the Punta Choros Metamorphic Complex interpreted as generated by basal accretion, the Chañaral Epimetamorphic Complex interpreted as generated by frontal accretion, and the Llanos de Chocolate Beds whose unmetamorphosed volcanic and sedimentary components were deposited in a forearc basin. Their data suggest that Late Paleozoic metamorphism, sedimentation and magmatism occurred contemporaneously in this forearc sector.

In the 33°–42°S segment, the Eastern Series and the coastal batholith are covered unconformably at different localities by Late Triassic (Carnian–Rhaetian) sedimentary units (Hervé et al., 1987) that are weakly folded, rarely develop a slaty cleavage, and are essentially unmetamorphosed. On the basis of preservation of organic matter, Askin et al. (1981) suggested that these rocks may have reached only meta-anthracite grade. This shows that the regional imprint of Triassic dynamo-thermal metamorphism is barely visible in this segment.

2. Methodology

Samples were collected from localities displaying the typical outcrop characteristics of the different units, as detailed below in the Results section. Zircons were recovered from heavy mineral concentrates obtained by standard methods of crushing, grinding, Wilfley table separation, magnetic and heavy liquid separation at Universidad de Chile, Santiago. Zircons from the Las Cruces samples were separated in the mineral separation laboratory of Universidad Andres Bello by German Huaiquifil under the guidance of Dr. Cristobal Ramirez de Arellano.

Zircon analyses were undertaken at the Research School of Earth Sciences, The Australian National University, Canberra. The grains were mounted in epoxy, polished to about half-way through, and cathodoluminescence (CL) images were obtained for every zircon to select appropriate targets areas. U–Th–Pb analyses were then conducted using either of two sensitive high-resolution ion microprobes (SHRIMP II and SHRIMP RG) following the procedures described by Williams (1998). 60 or more grains were analyzed as provenance was the target, to allow a reasonable statistic dataset. The data are provided in the accompanying supplementary repository files; crystallization ages, where calculated, are reported in the following text with a 2σ uncertainty. The IUGS chronostratigraphic chart is used throughout (Cohen et al., 2013; updated). In assessing the maximum age of sedimentation for each sample we have generally taken the youngest age represented by at least three coherent results and ignored individual outliers that may have suffered open system behaviour.

3. Results

A synthesis of the results is presented in Table 1 and in Fig. 2. Previous U–Pb zircon ages are also shown in Fig. 2. Detailed results for each sample are presented in Figs. 3–6. Sample localities are given in Table 1. The various coastal basement study areas are considered from north to south.

3.1. High Andes

3.1.1. El Tránsito Metamorphic Complex

Sample FO10106 from near Las Marquesas is a crystalline white-mica schist with abundant albite porphyroblasts organized in bands, and a complexly folded foliation. Rare garnet porphyroblasts are also found. It is interbedded with greenschists. The detrital zircon U–Pb data (Fig. 3) indicate an Early Triassic maximum possible sedimentation age of ca. 240–250 Ma. There are significant but scattered older late Paleozoic ages with peaks at ca. 265–275, ca. 295–305 and ca. 445 Ma and few scattered older ages.

The age of this unit has been a matter of controversy since whole-rock Rb–Sr isochrons (Ribba et al., 1988) were interpreted as indicating Carboniferous metamorphism. Bahlburg et al. (2009) obtained late Permian ages on detrital zircons, which were not reproduced in a different sample analyzed by Alvarez et al. (2011) that gave much older maximum possible sedimentation ages. Recently, Alvarez et al. (2013) and Hervé et al. (2014) have presented evidence that the Pampa gneiss, at some time considered to be representative of the old crust of Chilenia terrane, is in fact a Permian metamorphic rock that underwent Middle Triassic high-grade metamorphism, with metamorphic zircon overgrowths of ca. 240 Ma.

3.2. Coast Range

Metasedimentary rocks were sampled from four coastal localities between 29°S and 33°S.

Table 1
Detrital zircon ages from this study. The last column indicates maximum possible sedimentation age, and other peaks in the zircon population. One sample of a leucogranite intruding the Las Cruces Metamorphic Complex is also presented. For location of samples see Fig. 2.

Sample nº	Lithology	Geographical Coordinates		Geological Unit	Ages
		South	West		(Ma)
FO10106	Micaschist	28° 49′ 56.8″	70° 26′ 18.4″	El Tránsito Metamorphic Complex at Las Marquesas	250, 265/275, 295/310, 445
FO10111	Metasandstone	28° 19′ 09.9″	71° 09′ 01.3″	Chañaral Epimetamorphic Complex at north of Huasco	330, 470, 1000-1200
FO10116	Micaschist	29° 14′ 56.3″	71° 27′ 51.1″	Punta Choros Metamorphic Complex	300, 320, 380, 455, 490, 540, 900-1100
FO10126	Metagraywacke	29° 15′ 06.2″	71° 27′ 32.0″	Punta Choros Metamorphic Complex	300-350, 380, 450/470, 540, 1000-1200
FO10132	Gneiss	30° 52′ 53.6″	71° 41′ 14.0″	Choapa Metamorphic Complex at Punta Talquilla	240, 275, 295, 315, 500
FO10133	Metaconglomerate	30° 52′ 38.8″	71° 40′ 42.5″	Choapa Metamorphic Complex at Punta Talquilla	240, 255, 280, 305/320, 485
FO10134	Metasandstone	30° 58′ 39.4″	71° 38′ 52.0″	La Corvina Strata at Playa La Cebada	230, 275, 290, 310, 455, 1100-1200
FO1541	Phyllite	31° 04′ 35.1″	71° 30′ 46.4″	Choapa Metamorphic Complex at Cerros de Julio	(260), 295, 315, 465, 515, 1000-1200
FO1557	Micaschist	31° 34′ 19.6″	71° 36′ 09.2″	Choapa Metamorphic Complex at Huentelauquén	475, 530/550, 620, 1000-1200
FO1563	Granofels	33° 30′ 05.1″	71° 37′ 15.0″	Las Cruces Metamorphic Complex	(330*), 470, 520, 560–760,1150, 1300
FO1564	Leucogranite	33° 30′ 05.1″	71° 37′ 15.0″	Coastal Batholith at Las Cruces	321.6 ± 2.5

* metamorphic zircon crystallization age.

3.2.1. *Huasco*

FO10111 is from a metasandstone layer in the Chañaral Epimetamorphic Complex, cropping out on a coastal road north of Huasco, where 1–2 m thick massive metasandstone beds are interbedded with laminated metapelites exhibiting folds and quartz segregations and veins. Cleavage and stratification are parallel to N15E/75E. There is a major zircon age grouping at ca. 470 Ma, with a significant younger one at ca. 330 Ma, with a minor grouping at ca. 540 Ma. The rest of the zircon ages are scattered, with some dispersed clusters between ca. 1000 to 1200 Ma (Fig. 4a). A Middle Mississippian or younger depositional age is indicated. Bahlburg et al. (2009) presented a youngest age of ca. 295 Ma for detrital zircons in this unit.

The maximum possible sedimentation age is comparable with that proposed by Creixell et al. (2016) for the Llanos de Chocolate unit, which they interpreted as having been deposited in a forearc basin.

3.2.2. *Punta Choros*

The Punta Choros Metamorphic Complex is composed of micaschist, amphibole schist and metaturbidite. They bear evidence of at least three deformational events during metamorphism and exhumation from an accretionary prism (Navarro, 2013). Metamorphic conditions for a rare garnet-bearing lithology indicate a counterclockwise P-T trajectory culminating at ca. 1 GPa and 700 °C. These conditions are comparable to those of rocks in the Western Series of Central Chile at Punta Sirena (Willner et al., 2005; Hyppolito et al., 2014). The metaturbidites are rocks of much lower metamorphic grade and can be compared to the Eastern Series of Central Chile; here they are finely interleaved with higher-grade rocks, probably as the result of late stage tectonism.

Sample FO10116 is from a white-mica schist with abundant albite porphyroblasts and bands rich in small biotite crystals. It has prominent, but dispersed clustering of detrital zircon ages between ca. 300 and 455 Ma, and intermediate groupings at ca. 490 and 540 Ma (Fig. 4b). Ignoring two isolated ages <270 Ma, these data suggest a Pennsylvanian maximum possible depositional age. There is also abundant, but variably discordant, Proterozoic detrital zircon around 900–1100 Ma, and some even older.

FO10126 is from a 2 m long tectonic lens of metagreywacke in a N10E/30E shear zone, surrounded by the white-mica schists. The two principal detrital zircon age groupings are at 450–475 Ma and 1000–1200 Ma (Fig. 4c). Importantly, there are scattered younger ages which more conservatively indicate a maximum possible sedimentation age of ca. 295 Ma.

3.2.3. *Punta Talquilla*

The rocks at this locality were included in the Choapa Metamorphic Complex by Irwin et al. (1988). FO10132 is a sample of well-banded (N13E/90) gneiss. It has ca. 40% of quartz–feldspar laminae up to 1 mm thick, quartz augen 3–5 mm long and abundant disseminated pyrite, and it bears folded amphibolite bands (probably originally mafic dykes). The detrital zircon age spectrum (Fig. 5a) has a major grouping at ca. 295 Ma but with significant younger peaks at ca. 275 and 240 Ma, the latter indicating that the protolith, probably an arkose, had a Middle Triassic maximum possible sedimentation age. There is a poorly-defined minor cluster at 465–500 Ma and the sparse, scattered, older detrital zircon ages remarkably extend back into the Archean.

FO10133 is a mylonitic conglomerate or diamictite, with quartz and granitic clasts in a well-foliated matrix with orientated biotite crystals. These rocks are regionally intruded by Late Triassic pink granites (Calderón, M., personal communication; Firth et al., 2015). This sample also has a Middle Triassic maximum possible sedimentation age of ca. 240 Ma (ignoring two grains with ages of ca. 205 Ma). The major detrital provenance is at ca. 255–280 Ma (Fig. 5b). There is a small, minor grouping at ca. 485 Ma, but very few Proterozoic zircons are represented in the pattern.

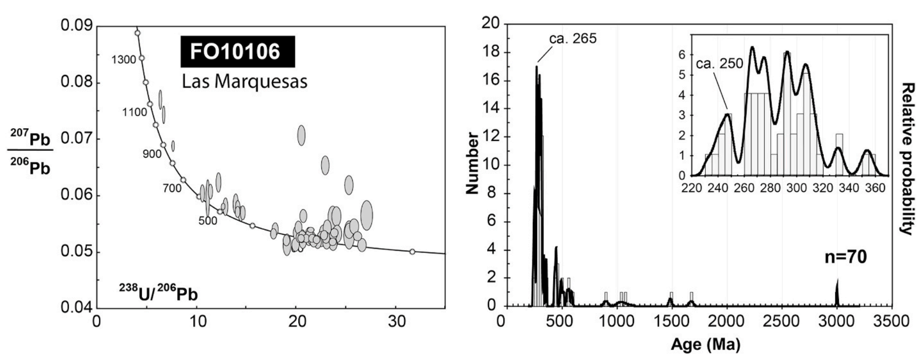

Fig. 3. a) Tera-Wasserburg and age vs probability diagrams for sample FO10106, El Tránsito Metamorphic Complex at Las Marquesas.

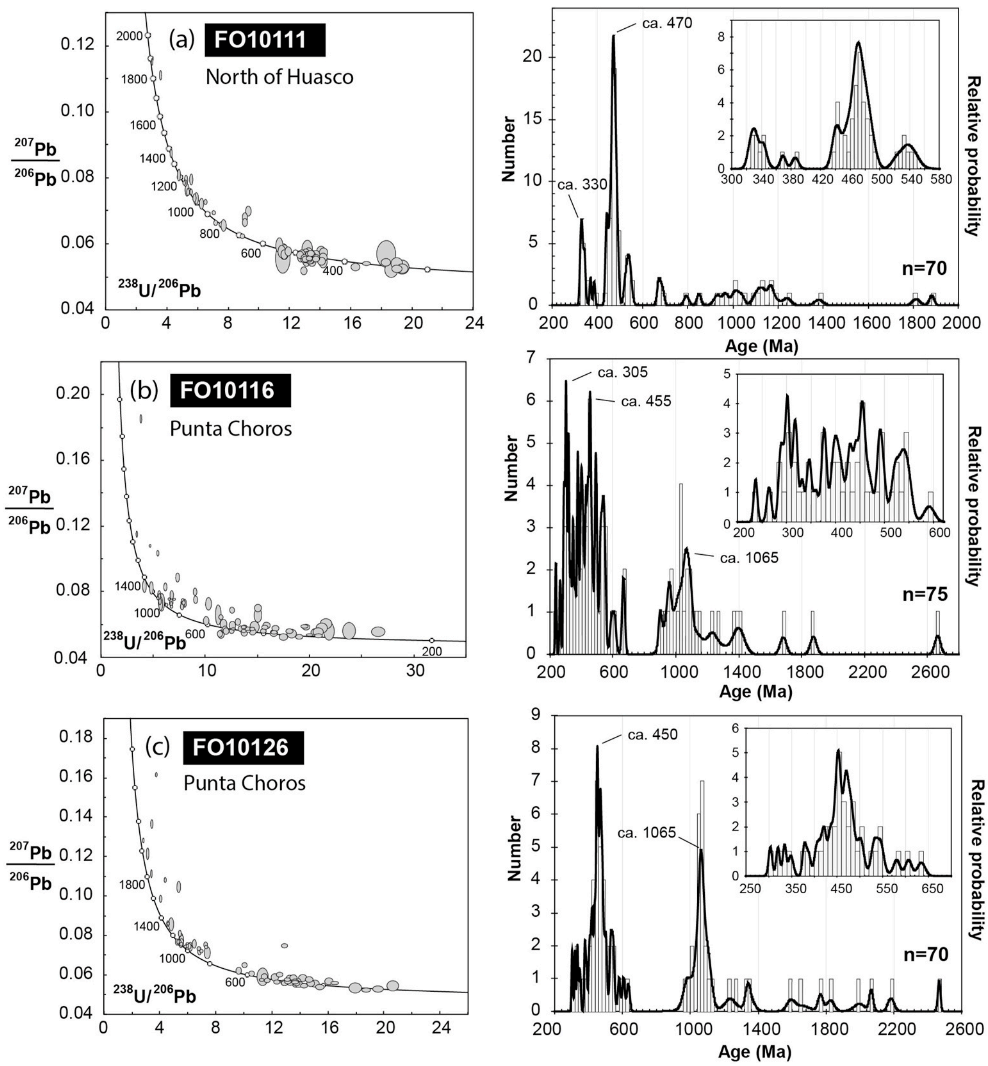

Fig. 4. Tera-Wasserburg and age vs probability diagrams for: a) sample FO10111, north of Huasco, Chañaral Epimetamorphic complex; b) sample FO10116 and c) sample FO10126, both from Punta Choros, Choapa Metamorphic Complex.

3.2.4. *Playa La Cebada*

Sample FO10134 is a 5 cm thick metasandstone from a slate–metasandstone alternation in the La Corvina Strata (García, 1991; Irwin et al., 1988). It shows a cleavage (N55W/20N) oblique to the subhorizontal (N45E/7E) stratification planes. These rocks, which are intruded by basic dykes, are separated from the schists of the Choapa Metamorphic Complex by a tabular silicified body, probably resulting from hydrothermal processes on a fault zone. The main peaks in the zircon age provenance pattern are at ca. 275, 290 and 310 Ma, together with ca. 455 Ma (Fig. 5c). A Late Triassic maximum possible depositional age can be taken from the youngest definable peak at ca. 230 Ma (3 grains).

According to Irwin et al. (1988), brachiopod fossils thar occur as detrital allochems in this unit are “no older than Late Paleozoic and probably Permian”, which he interpreted as a maximum possible sedimentation age.

3.2.5. *Cerros de Julio*

The rocks analyzed at this locality are banded phyllites (FO1541) with detrital white mica and boudinaged quartz veins. There are sinistral shear kinematic indicators along N25W/60W foliation planes with lineations in N5E direction. The most pronounced peak in the detrital age pattern is at ca. 315 Ma (Middle Pennsylvanian), with lesser ones at ca. 295, 465, 515 Ma, and the usual late Mesoproterozoic spread between ca. 1000 and 1200 Ma (Fig. 6a). The three youngest ages scattered between 245 and 270 Ma have no clear definition and are discounted.

3.2.6. *Huentelauquén*

Micaschists from this locality have a strong penetrative S2 crenulation foliation, with quartz veins folded at small scale. Mineral association is quartz-white mica-biotite-chlorite-apatite. Discounting two single discrepant ages of ca. 300 and ca. 355 Ma, sample FO1557 has a youngest and predominant peak in the detrital age pattern at ca. 475 Ma (Early Ordovician), with scattered minor peaks near ca. 540, 620, and 1000–1200 Ma (Fig. 6b).

3.2.7. *Las Cruces*

Sample FO1563 is of a complexly folded, banded, quartzo-feldspathic granofels with patches and folded bands of coarse-grained, isotropic biotite. The metasedimentary nature of the granofels protolith is supported by the dispersion of individual detrital zircon ages (many discordant) from ca. 330 to 1340 Ma (Fig. 7a). The older provenance includes minor peaks at ca. 520, 560–760, 1150 and 1300 Ma. Importantly, several of the areas analyzed, including the youngest, have very low Th/U ratios (<0.1), probably representing metamorphic zircon overgrowths (see Fig. 8). The youngest well-defined group of igneous detrital zircons are ca. 470 Ma (early Middle Ordovician).

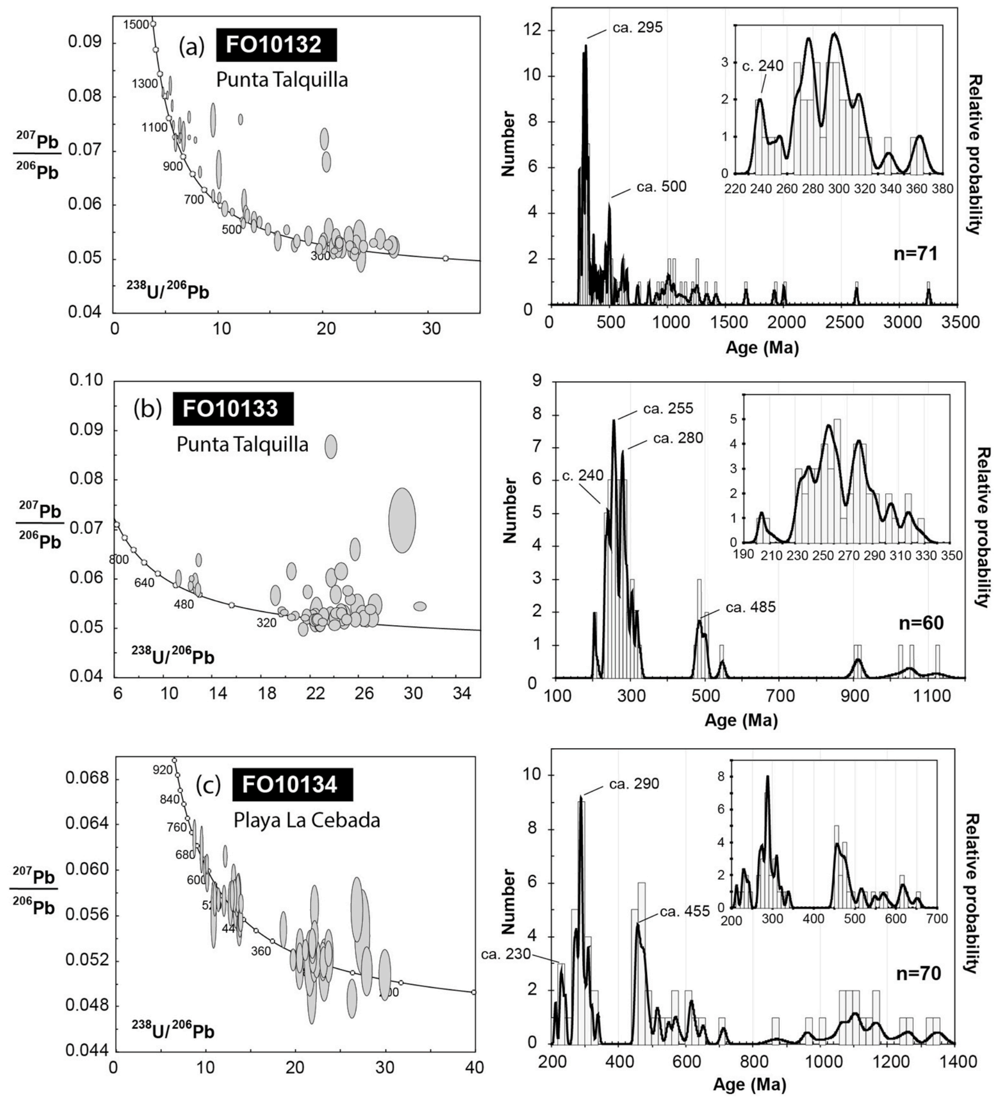

Fig. 5. Tera-Wasserburg and age vs probability diagrams for: a) sample FO10132 and b) FO10133 from Punta Talquilla, Choapa Metamorphic Complex; and c) FO10134 from Playa La Cebada, La Corvina Beds.

The outcrop at Las Cruces also contains garnet-bearing leucogranite such as sample FO1564, a granitic vein (Fig. 7b). Ignoring 3 slightly older ages that may reflect inheritance, there is a well-defined peak with a weighted mean age of 322 ± 3 Ma interpreted as the age of crystallization (latest Mississippian or earliest Pennsylvanian), essentially comparable with the age of the youngest metamorphic zircon in the granofels.

4. Discussion

The studied metamorphic rocks are quite varied in their probable ages, potential correlations, likely protoliths and tectonic significance.

In assessing the age of sedimentation it has to be remembered that the age of detrital zircon can only be treated as a maximum age for deposition. Close to an active volcanic arc entrained igneous zircon should be penecontemporaneous, but this would not necessarily be the case in passive margins (Cawood et al., 2012).

Group 1, Mid Paleozoic? The oldest potential depositional ages are recorded by the Huentelauquén schist, and the Las Cruces granofels, both in the southernmost part of Norte Chico. Their best-defined youngest detrital igneous zircon ages are Early/Middle Ordovician (Table 1, Fig. 9), which would be compatible with mid-to-late Paleozoic deposition. This is also consistent with the ca. 486 Ma age from Alvarez and Mpodozis (2015) for the paleosomes of the Quebarda Seca migmatities and the youngest detrital zircon ages of ca. 437 to 490 Ma obtained by Velasquez et al. (2015) for the El Cepo Metamorphic Complex. The rocks of this latter complex crop out sporadically in the Frontal Andes between 29° and 31°S as roof pendants or mega-xenoliths in Permian intrusive bodies, confirming pre-Mesozoic deposition. They show a contact metamorphic overprint including andalusite, sillimanite and staurolite which is not seen in the lower-grade Huentelauquén sample.

Both our samples have one or two scattered younger grains down to 300 or 330 Ma, respectively. Although single grain ages are not considered reliable, low Th/U ratios suggest that some are of metamorphic origin. Such metamorphism could be related to the migmatization that generated the Pennsylvanian garnet-bearing granite at Las Cruces (FO1664), suggesting activity coetaneous with emplacement of the Coastal Batholith (300–320 Ma, Deckart et al., 2014). Moreover, $^{40}Ar/^{39}Ar$ ages on minerals of metamorphic and igneous rocks at Las Cruces (Webb and Klepeis, 2019) indicate a long history of igneous and deformational events extending from Late Pennsylvanian (ca. 300 Ma) to Triassic and Jurassic (ca. 160 Ma) times.

In addition to the pronounced Ordovician provenance, this group

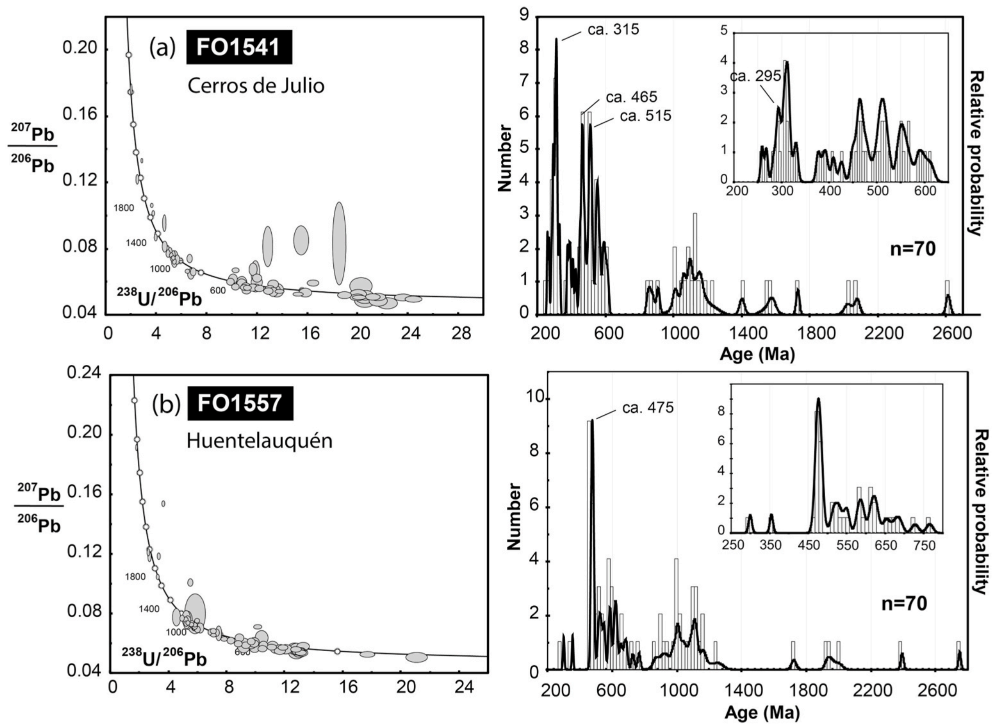

Fig. 6. a) Tera-Wasserburg and age vs probability diagram for: a) for sample FO1541, Cerros de Julio, Choapa Metamorphic complex; b) sample FO1557, Huentelauquén.

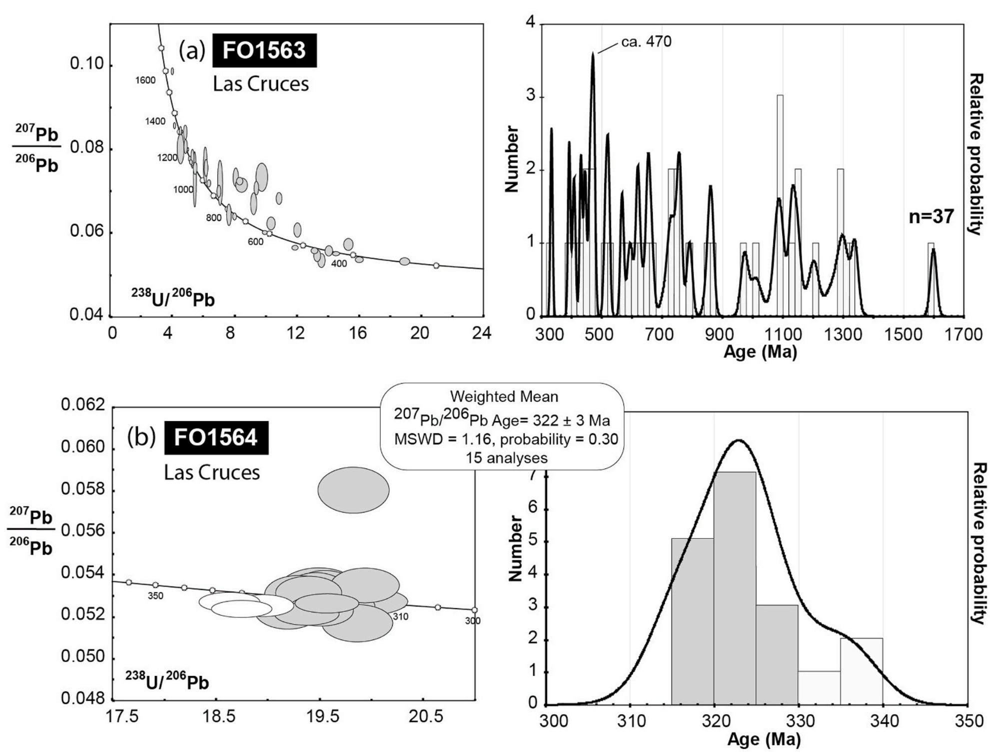

Fig. 7. a) Tera-Wasserburg and age vs probability diagram for sample FO1563, Las Cruces Metamorphic complex; b) for leucogranite sample FO1564 from Las Cruces.

records the presence of minor Cambrian detrital zircon, a range of Neoproterozoic and a broad span of Mesoproterozoic zircon. Collectively these are typical of the Famatinian, Pampean and 'Grenville-age' rocks found in the Western and eastern Sierras Pampeanas (Rapela et al., 2018). The evidence of the leucogranite FO1564 at Las Cruces might suggest that the Coastal Batholith contained anatectic melts of Ordovician (or younger) sedimentary rocks derived from a foreland backstop for a late Carboniferous accretionary prism. Uplift, erosion and sedimentation of this material might be related to the tectonic accretion of Chilenia or Terrane X.

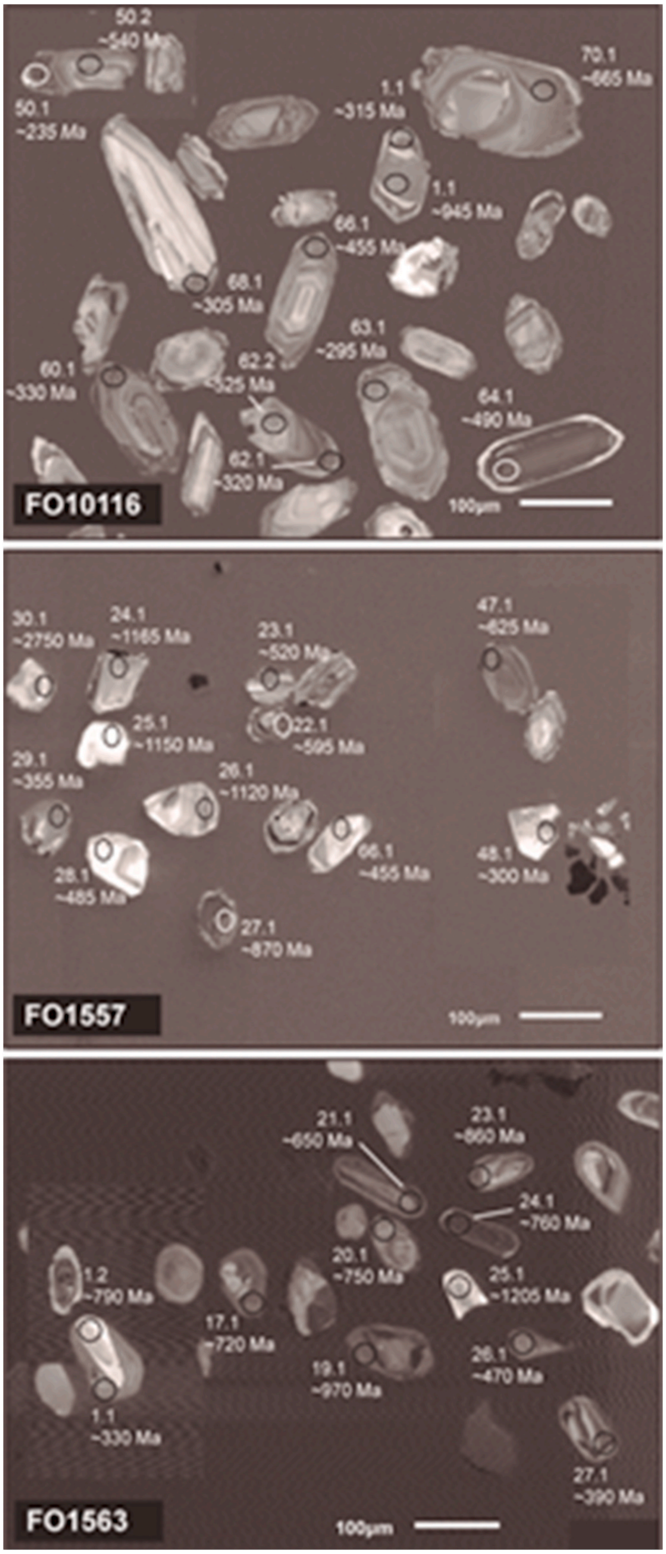

Fig. 8. Representative CL images of analyzed zircons from 3 samples.

Group 2 Permo-Carboniferous The Cerros de Julio schist, the Punta Choros Metamorphic Complex and the Chañaral Epimetamorphic Complex all have Carboniferous maximum possible depositional ages (Table 1). The Choapa Metamorphic Complex at Playa La Cebada shares this characteristic, according to the data of Alvarez et al. (2011).

The maximum possible sedimentation age of these metasedimentary rocks is considerably younger than the Early Devonian (400 Ma) to Late

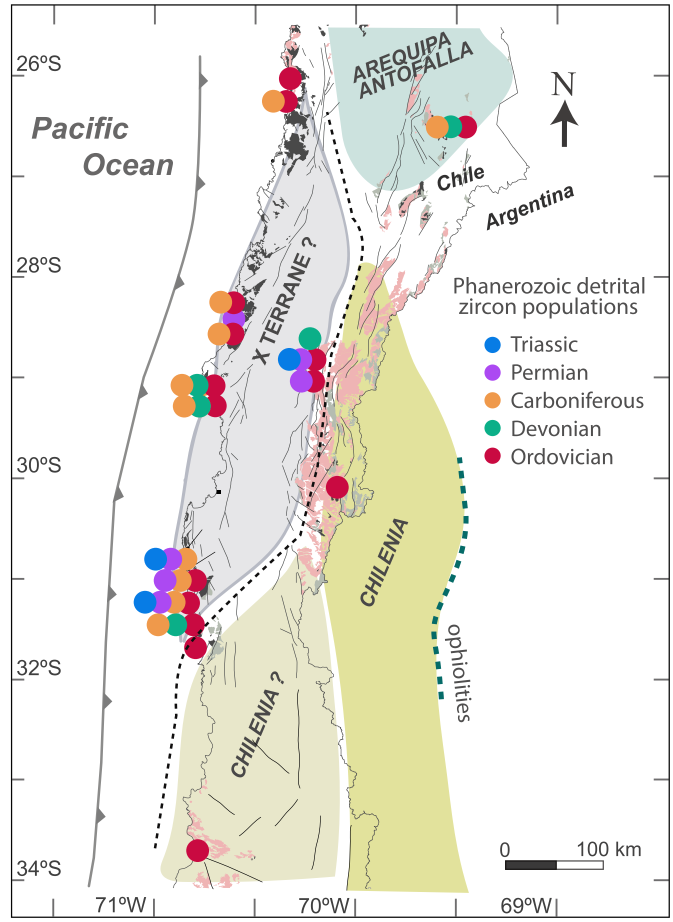

Fig. 9. Sketch map showing the different Late Paleozoic and Triassic domains of the accretionary margin between 26° and 34°S. Coloured circles indicate the age of detrital zircon peaks in the considered samples (1–3 peaks are shown for each sample). The dotted line represents the western limit of samples with Ordovician maximum depositional age.

Ordovician (450 Ma) maximum possible sedimentation ages of the Las Tórtolas, El Toco and Sierra del Tigre units further north along the Coast Range (Bahlburg et al., 2009; Pankhurst et al., 2016). Nevertheless, all show a prominent component of Famatinian and Grenville-age zircons. Carboniferous A-type intrusive rocks that crop out in western Argentina (Dahlquist et al., 2015) could have been the source of the Mississippian zircons observed. The Pennsylvanian zircons could have been derived from the Llanos de Chocolate unit (Creixell et al., 2016) or directly from the Coastal Batholith. Carboniferous metamorphism in the accretionary wedge of the Punta Choros Metamorphic Complex has been well established by $^{40}Ar/^{39}Ar$ dating by Creixell et al. (2016).

The provenance patterns of the samples in this group also present the same evidence for ultimate derivation from the Sierras Pampeanas to the east, although the Punta Choros rocks have a notably higher proportion of Proterozoic zircon, perhaps indicating more proximal detritus from the Western Sierras Pampeanas where direct potential sources of this age are found (Casquet et al., 2006, 2008).

Group 3 Middle to Late Triassic. The El Tránsito Metamorphic Complex at Las Marquesas, the Choapa Metamorphic Complex rocks at Punta Talquilla, and the La Corvina Strata at Playa La Cebada, were probably deposited during Late Triassic times since all have minimum zircon ages of 230–240 Ma. The rocks at Punta Talquilla, with maximum possible deposition ages of Anisian to Carnian, underwent deformational metamorphism, which apparently did not significantly affect the neighbouring and possibly slightly younger La Corvina Strata; Irwin et al. (1988) had suggested a significantly younger age for this last unit.

These rocks have a much subdued component of Famatinian zircons. This could reflect a profound morphological change in the continental margin environment where their deposition was taking place as a consequence of the San Rafael orogenic phase (García-Sansegundo et al., 2014). An angular unconformity is observed 2 km south of Los Vilos (Charrier et al., 2007), where the Late Triassic El Quereo Formation was deposited over both the low-grade Choapa Metamorphic Complex and the Arrayan Formation which bears Devonian fossil plants (Bernardes de Oliveira and Rösler, 1980). It might be suggested that this orogenic phase isolated Famatinian sources from the coastal depositional basins.

4.1. Triassic arc sedimentation and tectonics on the Chilean margin

Based on U–Pb zircon dating, Creixell et al. (2016) have shown that the Llanos de Chocolate unit near Punta Choros represents active volcanism between 290 and 320 Ma. These rocks, and the associated sedimentary ones, are neither deformed nor metamorphosed, apparently indicating a rapid waning of locally intense deformation and metamorphism over a short distance. Irwin et al. (1988) concluded that the Choapa Metamorphic Complex was assembled before 220 Ma, when it was affected by metamorphic and igneous activity observable at latitude 31°S and revealed by Rb–Sr and K–Ar dating of the metamorphic and plutonic minerals and rocks of that area. Such a Late Triassic metamorphic age is comparable with the depositional ages determined in this study. U–Pb zircon dating of intrusive bodies near Punta Talquilla (Firth et al., 2015) have yielded crystallization ages of ca. 220 Ma, thus confining deformation in the area to Late Triassic times, and probably indicating increased geothermal gradients during this period resulting in thermal metamorphism.

Triassic evolution contemporaneous with that of the Punta Talquilla gneisses has been established for the metamorphic rocks of the Mejillones Peninsula further north (22°S) by Casquet et al. (2014), discounting a previously assigned Early Paleozoic age. SHRIMP U–Pb zircon data indicate that deposition, metamorphism and igneous intrusion occurred there in rapid succession during Late Triassic times. Calderón et al. (2017) show that metamorphism followed a clockwise trajectory suggesting that the Morro Jorgino block of the Mejillones Metamorphic Complex was buried to ~25 km depth in a subduction setting. The Elqui–Limarí batholith in the High Andes has been dated using the U–Pb zircon method by Coloma et al. (2012). Hervé et al. (2014), Maksaev et al. (2014) and Del Rey et al. (2016), yielding a range of ages from scarce Mississippian to predominant early Permian, late Permian and Middle-to-Late Triassic, suggesting that the Triassic period was one of active subduction.

Late Triassic deposition of sediments considered to belong to the Gondwana margin fossil accretionary prism is also known far to the south in the Chonos Metamorphic Complex (latitudes 44° to 47°S). Metaturbidites there have 220 Ma detrital zircons (Hervé and Fanning, 2001) and sparse Late Triassic fossil fauna (Fang et al., 1998), and were metamorphosed during a Late Triassic–Early Jurassic event ascribed to the Chonide orogeny (Thomson and Hervé, 2002).

However, evidence for Late Triassic tectono-metamorphism has not been found in the 34°–43°S sector of the fossil accretionary prism, where Carboniferous depositional ages predominate. Late Triassic sedimentary successions there are mainly unmetamorphosed (Hervé, 1977; Askin et al., 1981). Localized post-tectonic A-type granites of similar age have been dated in this area (Vasquez and Franz, 2008). It is possible that outside the southern and northern limits of this sector subduction erosion has largely removed the Late Paleozoic accretionary prism, as has been proposed on a smaller scale for the 37°–40°S area by Glodny et al. (2008).

It is also evident that in the 33°–42°S segment, the exposed metamorphic rocks represent deeper levels of the crust, in contact with the Pennsylvanian Coastal Batholith, while north of 33°S the data on the Carboniferous volcanic and low-grade Llanos de Chocolate Beds indicate that they were not deeply buried. Additionally, Pennsylvanian U–Pb zircon ages have been obtained in a granitic inclusion in a mafic dyke crosscutting the Choapa Metamorphic Complex at Puerto Manso (ca. 10 km north of Huentelauquén, Sigoña, 2016), suggesting the presence of a plutonic body coeval with the Coastal Batholith below the present erosional surface.

Kato and Godoy (2015) suggested that a transpressive fault zone parallel to the present-day coast and comparable to the San Andreas fault system was active during the Triassic. They considered that this brought deeply metamorphosed blocks of the accretionary prism into contact with shallower components along the continental margin, from the latitudes investigated here (28°–33°S) to as far as 42°S. Although the structural pattern of the rocks deformed during this event are not known in detail, the results obtained here are not inconsistent with this model. However, the argument of Kato and Godoy (2015) that higher-pressure metamorphic rocks at Bahia Mansa (40°S) and at Infiernillo (34°S) represent piercing points indicating up to 600 km of latitudinal displacement must be considered with caution: similar high–pressure metamorphic rocks are also known from Punta Choros (30°S) as indicated above, suggesting that the sparse distribution of these rocks might be controlled by other tectonic factors.

The southwestern margin of Gondwana in the Triassic period has been traditionally considered as characterized by extensional tectonics that resulted in a series of NW-orientated rifts (Charrier et al., 2007; Franzese et al., 2003). Late Triassic sedimentation, metamorphism and igneous intrusion in the studied area, with similar evidence from Mejillones to the north and the Chonos archipelago to the south, suggest that Late Triassic–Early Jurassic subduction was also important. Rocks deposited and metamorphosed during this time, including pillow basalts of supposed oceanic origin, form discontinuous outcrops along the margin. The varying metamorphic grade and tectonic configuration of the forearc, as envisaged by Thiele and Hervé (1984), means that it is difficult to present a detailed reconstruction. A recent study of the Triassic depositional basins by Salazar et al. (2020) in a region slightly north of the area considered here, indicates the presence of volcanic and plutonic units, and recurrent unconformities, which may broadly relate to continuing subduction at the continental margin during the Triassic. A similar conclusion was suggested by Del Rey et al. (2016) based on the crystallization ages of plutons in this same area.

5. Conclusions

Middle to Late Triassic sedimentary rocks of the Choapa and El Tránsito metamorphic complexes, were probably metamorphosed and deformed prior to the deposition of the Late Triassic Quereo Formation, in the coastal areas and Precordillera of Norte Chico (28°–33°S) in Chile. These metamorphic complexes appear to be composed of rocks of differing ages and their redefinition may be necessary. Their depositional basins were fed by detrital zircons mainly from the younger components of the Elqui–Limarí Batholith. In this they are distinguished from the Huentelauquén micaschists and the Las Cruces granofels, which contain Ordovician zircons indicating Famatinian or older sources and possible Carboniferous sedimentation. This implies that the sedimentary protoliths may have formed part of the Chilenia terrane, which collided with Gondwana during the Late Devonian, or perhaps the 'X' terrane, as suggested by by Sigoña (2016).

Late Triassic metasedimentary rocks are not known from the southern (34°–42°S) sector of the Coast Range fossil accretionary prism, where contemporaneous rocks are unmetamorphosed. However, metamorphosed Late Triassic rocks are known from the Chonos and Mejillones archipelagos, suggesting that during this time there was tectonic segmentation in the margin of Gondwana with limits at around 34° and 43°S (present coordinates). This could be causally related to initiation of the present-day flat-subduction zone of the Nazca plate.

Declaration of competing interest

The authors are not aware of any perceived conflicts of interest. They do not envisage any conflicts of interest arising.

CRediT authorship contribution statement

F. Hervé: Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition, Project administration. **M. Calderón:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **C.M. Fanning:** Investigation, Data curation, Methodology, Writing - original draft, Writing - review & editing. **R.J. Pankhurst:** Conceptualization, Investigation, Data curation, Writing - original draft, Writing - review & editing. **J. Navarro:** Investigation, Writing - original draft.

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