Earth-Science Reviews 152 (2016) 88–105

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

The pre-Mesozoic rocks of northern Chile: U–Pb ages, and Hf and O isotopes

Robert J. Pankhurst [a,*], Francisco Hervé [b,c], C. Mark Fanning [d], Mauricio Calderón [b,c], Hans Niemeyer [e], Susanne Griem-Klee [f], Fernanda Soto [b]

[a] Visiting Research Associate, British Geological Survey, Keyworth, Nottingham NG12 5GG, United Kingdom
[b] Departamento de Geologìa, Universidad de Chile, Plaza Ercilla 803, Santiago, Chile
[c] Carrera de Geologìa, Facultad de Ingenierìa, Salvador Sanfuentes 2357, Universidad Andres Bello, Santiago, Chile
[d] Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia
[e] Departamento de Ciencias Geológicas, Universidad Católica del Norte, Av. Angamos 0610, Antofagasta, Chile
[f] Departamento de Geociencias, Universidad de Atacama, Copiapo, Chile

A R T I C L E I N F O

Article history:
Received 10 June 2015
Received in revised form 11 November 2015
Accepted 12 November 2015
Available online 19 November 2015

Keywords:
U–Pb
SHRIMP
Geochronology
Zircon
Pre-Andean basement
Provenance

A B S T R A C T

Supposed pre-Mesozoic igneous and metamorphic rocks from northern Chile are reviewed in the light of twenty-one new SHRIMP U–Pb zircon age determinations. Metamorphic rocks from the precordillera upthrust belt mostly show a wide spectrum of zircon ages, indicating derivation from sedimentary protoliths. Youngest detrital zircon ages (i.e., maximum depositional ages) range from *c.* 850 Ma at Belén to 1000–1100 Ma in Sierra de Moreno and Cordón de Lila. Late Proterozoic provenance throughout the region corresponds to a *c.* 1 Ga igneous and metamorphic event. The main source region could have been the Proterozoic MARA block or Laurentia to the west. Early Ordovician plutonic rocks (465–485 Ma) correlated with the Famatinian magmatism of NW Argentina are recognised in all three outcrop areas, and contemporaneous volcanic rocks in Cordón de Lila. Hf- and O-isotope data for Ordovician zircon in these rocks, and for *c.* 1450 detrital zircon in the metasedimentary rocks, are consistent with ultimate derivation from Early Mesoproterozoic to Paleoproterozoic lithosphere. A depositional age younger than 400 Ma is determined for the Quebrada Aroma metamorphic complex, indicating post-Early Silurian metamorphism and folding. Carboniferous igneous and deformational events occur in the Coast Range, where metasedimentary complexes are mostly related to Late Paleozoic subduction–accretion; deformation and metamorphism continued near the present Pacific shore line until Triassic and earliest Jurassic times. The underlying crust of much of Norte Grande is considered to be Proterozoic (Arequipa–Antofalla block or MARA), although there are no igneous rock outcrops of this age.

Contents

* Corresponding author.
E-mail addresses: rjpt@nigl.nerc.ac.uk (R.J. Pankhurst), fherve@ing.uchile.cl (F. Hervé), mark.fanning@anu.edu.au (C.M. Fanning), mccaldera@gmail.com (M. Calderón), hansn@ucn.cl (H. Niemeyer), susanne.griem@uda.cl (S. Griem-Klee), mf.soto@ug.uchile.cl (F. Soto).

http://dx.doi.org/10.1016/j.earscirev.2015.11.009

1. Introduction

The tectonic framework of South America (Cordani et al., 2000) comprises a long-lived stable platform in the north and east, and the Andean margin in the west. The stable platform is cored by Precambrian cratons assembled in Neoproterozoic to Early Cambrian times as part of the Gondwana supercontinent (e.g., Vaughan and Pankhurst, 2008). The Andean margin largely represents the subsequent accretion of terranes to this platform (Ramos, 1988, 2004) and modification due to (a) terrane collision and (b) volcanism, sedimentation and deformation associated with subduction of Pacific (and proto-Pacific) ocean floor. The pre-Mesozoic crustal structure of the Chilean margin is thought to include both truly exotic and autochthonous or para-autochthonous terranes and blocks with respect to Gondwana, some of which could be relics of an Early Paleozoic connection between Laurentia and Gondwana (Dalziel, 1997), but such distinctions have to be based on knowledge of the deep crust. A first step for discrimination is to define the age of the basement, i.e., crustal rocks underlying Mesozoic and later additions; U–Pb dating of zircon is now considered the most robust method for dating in reworked crust. Dating of the detrital zircon content of rocks that were originally sedimentary can also suggest the age of unexposed basement sources.

2. Regional setting

Pre-Mesozoic basement rocks, mainly metamorphic and plutonic complexes, have been recognised throughout northern Chile and western Argentina, in what was part of the Terra Australis orogen, which developed along the southwestern margin of Gondwana from Early Paleozoic times (Cawood, 2005). The area studied here corresponds to the geographical region known as Norte Grande (*c.* 18°S to 27°S). A subsequent paper will deal with new data from Norte Chico (*c.* 27°S to 32°S). In central Chile (32–42°S) continuous basement outcrops in the Coast Range represent a mainly Carboniferous fossil accretionary prism and its associated magmatic arc — the Pennsylvanian coastal batholith, emplaced between 320 and 300 Ma (Deckart et al., 2014). Paleozoic basement rocks appear to be absent from the Main Range (Andean Cordillera) between 32 and 38°S, which is separated from the Coast Range by a well-developed central valley, but metamorphic studies of high-grade rocks on the eastern side of the Andes have lent support to the hypothesis of a buried basement terrane accreted in Devonian times (Chilenia: Ramos et al., 1986; Willner et al., 2010). In contrast, south of 38°S Cambrian magmatic rocks underlie the Magallanes basin of southern Chile, whereas most of the accretionary prism south of 38°S is composed of Permian and Triassic components (Duhart et al., 2001; Hervé et al., 2010, 2013).

Throughout the present-day fore-arc region of the Andes in northern Chile, small isolated outcrops of basement rocks occur beneath Mesozoic–Cenozoic cover. The exposures are mainly of metamorphic and igneous rocks, with very scarce fossil content, which has hindered the understanding of their ages and pre-Mesozoic geological development. We will follow the nomenclature of Hervé et al. (2007) who distinguished the precordillera upthrust belt in the east and the Coast Range in the west (Fig. 1).

Outcrops in the precordillera of Norte Grande are presumed to belong to the Arequipa–Antofalla block (AAB) a suspect terrane of Proterozoic rocks that is a key to interpretation of pre-Andean geological evolution of the Central Andes. The origin of the AAB basement on the western coast of southern Peru and northern Chile is debatable. The stable platform of South America to the northeast exhibits a simple pattern of crustal growth: a Paleoproterozoic core with progressively younger domains towards the southwest (e.g., Cordani et al., 2000). The AAB does not continue this pattern, which apparently exhibits a southward trend of crustal growth (Loewy et al., 2004; Wasteneys et al., 1995), with Paleoproterozoic (1.79–2.02 Ga) components metamorphosed at *c.* 1 Ga in the northern Peruvian outcrops, Mesoproterozoic rocks in the central segment (northernmost Chile), and a southern section in northern Chile and NW Argentina dominated by Ordovician rocks, largely igneous (Loewy et al., 2004). Although a para-autochthonous origin for the AAB has been postulated (e.g., Tosdal, 1996), most authors follow the idea that it is allochthonous to Amazonia (e.g., Ramos, 1988; Dalziel, 1994, 1997; Loewy et al., 2004). Ramos (1988) considered that it was accreted to Amazonia during the early Palaeozoic Pampean orogeny. Dalziel (1994, 1997) envisaged transfer of the AAB to Amazonia from the northeast corner of Laurentia during fragmentation of Rodinia, but this was refuted by Loewy et al. (2003, 2004) using whole-rock Pb isotopes and U–Pb geochronology. They suggested instead derivation from the Kalahari craton and probable collision with Amazonia at *c.* 1.0 Ga. Casquet et al. (2012) proposed that the AAB, including the southern outcrops in NW Argentina and the Río Apa block in Brazil, form a larger continental 'MARA' block underlain by Paleoproterozoic basement accreted to Amazonia, an idea substantiated by Rapela et al. (2015) who also proposed a Laurentian origin.

The main focus of this paper is the nature and extent of the AAB towards the south in northern Chile, where the disparity and variable quality of available geochronological data have always been a problem for tectonic analysis. We have studied (mostly) metamorphic rock outcrops extending from Belén in the north, through Quebrada Aroma, Quebrada Quipisca, Sierra de Moreno and Limón Verde to Cordón de Lila (Fig. 2). Some outcrops of metamorphic rocks in the Coast Range at Río Loa have also been analysed. Zircon concentrates from 21 rocks were analysed using SHRIMP U–Pb age determinations, thirteen for detrital zircon patterns in metamorphic rocks and eight for the crystallization ages of igneous rocks, with the aim of clarifying and better constraining the tectonic evolution of pre-Andean terranes in this part of the Central Andes.

3. Methodology

Samples were collected from localities displaying the typical outcrop characteristics of the different units, as detailed below. 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.

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 the grains, and CL (cathodo-luminescence) images were obtained for every zircon to select appropriate target 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). For igneous crystallization ages, and those detrital samples with metamorphic rims, SHRIMP II was used, whilst SHRIMP RG was used for the provenance samples. A selection of the dated zircons was

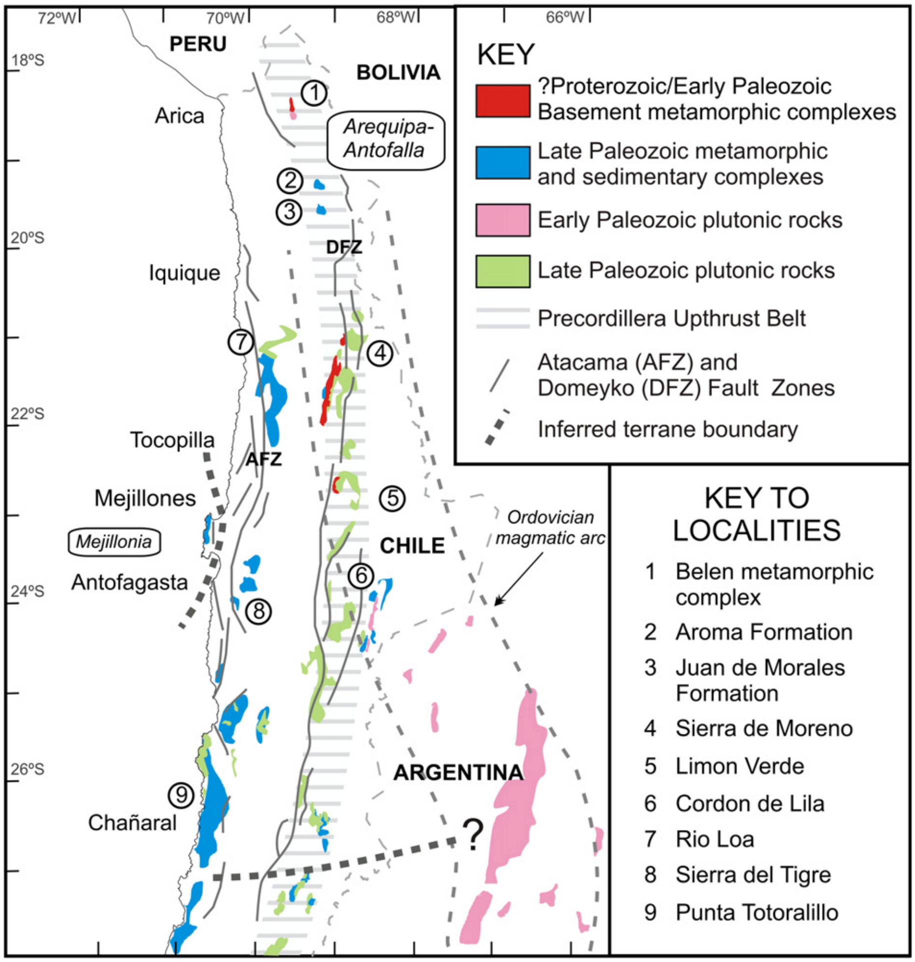

Fig. 1. Location map and geological sketch map of the igneous and metamorphic basement outcrops in Norte Grande, after Hervé et al. (2007). Significant later faults are shown. The heavy dotted lines represent possible terrane boundaries: that of the Mejillones terrane following Casquet et al. (2014) and the inferred southern limit of underlying Paleoproterozoic crust from the present work. The lighter dotted lines show the inferred eastern and western margins of the main Famatinian magmatic arc, which continues into coastal Peru.

then analysed for O-isotope composition using SHRIMP SI and for Lu–Hf isotope determinations using a Neptune LA-MC-ICPMS coupled with a HelEx 193 μm ArF Excimer laser ablation system, following procedures described in Fu et al. (2014). Analytical data and GPS readings for sample localities are given in the Supplementary data files (Tables DR1–3). Crystallization ages, where calculated, are reported here with a 2-sigma uncertainty.

4. Geochronology

Because this study covers a large region and a long period of geological evolution, for the sake of coherence previous geochronology is mostly summarized area by area along with our new results. A more complete account of older geochronological data for northern Chile can be found in Hervé et al. (2007), but more recent data that complement our investigation have been published by Munizaga et al. (2008), Bahlburg et al. (2009), Alvarez et al. (2011, 2013), Casquet et al. (2014) and Maksaev et al. (2014, 2015). More recently Augustsson et al. (2015) presented U–Pb analyses (Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry — LA-ICP-MS) of detrital zircon from Paleozoic samples, mainly in a transect across the Andes between 23°S and 25°S; 8 of these are in the southern part of Norte Grande. In addition, relevant University of Chile theses have been lodged by Soto (2013), Arancibia (2014), Morandé (2014) and Mellado (2015). Our study does not include detailed discussion of the Late Paleozoic batholiths in Norte Grande (Carboniferous to Permian, even Triassic), for which the reader is referred to an overview and new study by Maksaev et al. (2014). A synthesis of our new results is presented in Table 1, and they are shown together with the most relevant recently published data in Fig. 2. The various basement areas are considered in turn, from north to south. The IUGS chronostratigraphic chart is used throughout (Cohen et al., 2013; updated).

4.1. Precordillera upthrust belt

This sector contains the largest and most widespread outcrops regarded as pre-Late Palaeozoic basement, and also contains rocks that have previously often been considered to be the oldest in Chile. We concentrate here on such rocks. It should be noted that Carboniferous, Permian and Triassic plutonic and volcanic outcrops are common throughout the belt from *c.* 21°S to 26°S (see study and compilation by Maksaev et al., 2014); only a representative selection of their U–Pb ages can be shown in Fig. 2.

4.1.1. Belén metamorphic complex

Pacci et al. (1980) reported Rb–Sr whole-rock data for micaceous schist and gneiss from around Belén, a selection of which fell around a 1000 Ma reference line. This result was apparently supported by Grenville-age basement ages (multi-grain zircon U–Pb upper intercepts) and Pb isotope composition data from Bolivia and Argentina (e.g., Tosdal, 1996) and influenced subsequent ideas until challenged by U–Pb zircon data. Basei et al. (1996) presented a U–Pb discordia with upper intercepts of 509 ± 46 and 482 ± 32 Ma for multi-grain zircon fractions from orthogneiss and a granite vein, respectively.

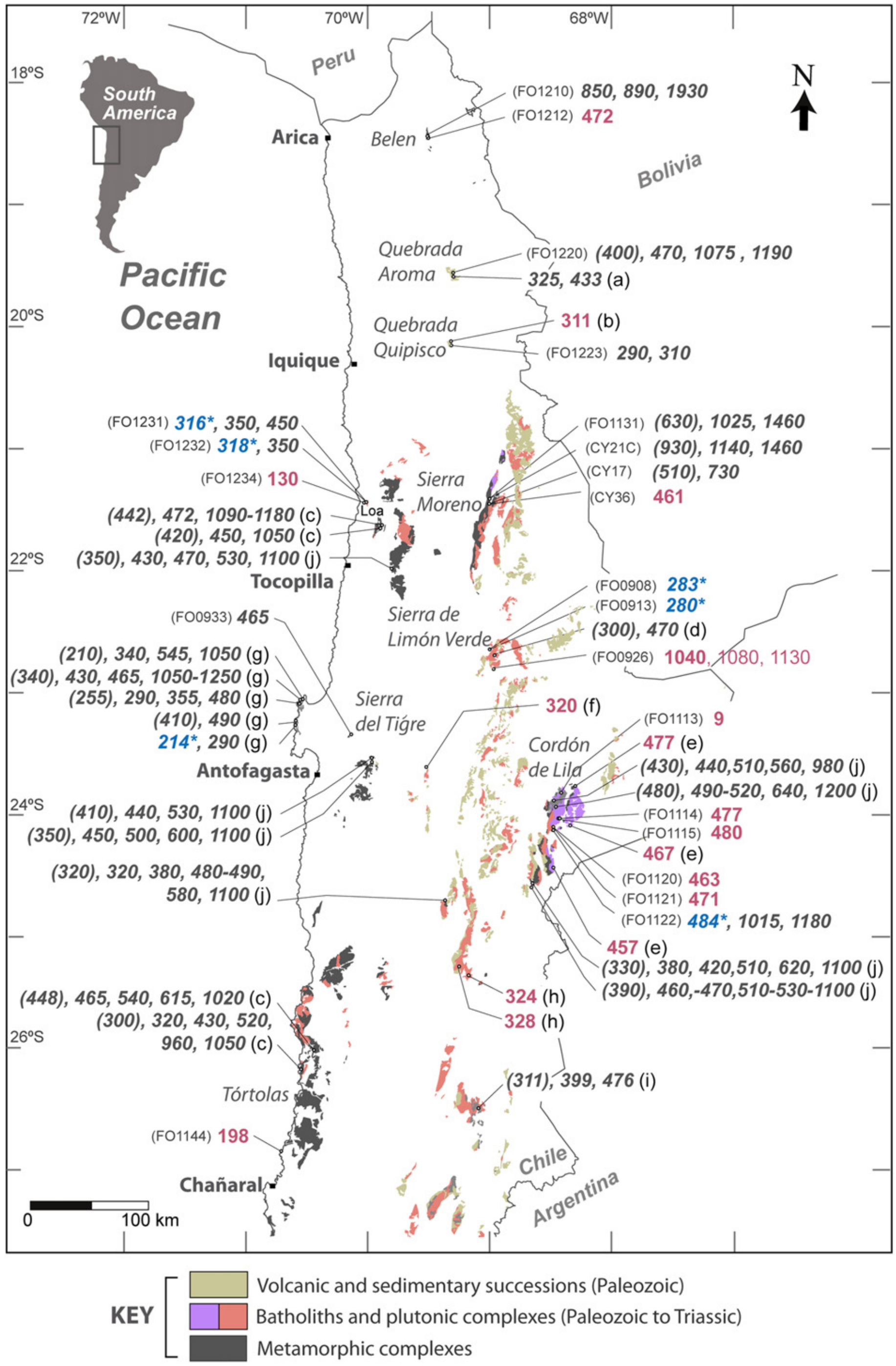

Fig. 2. New SHRIMP U–Pb zircon ages (Ma) from Norte Grande, with sample numbers as in Table 1. The published U–Pb zircon ages referred to are either SHRIMP or LA-ICP-MS analyses. In-situ crystallization ages are indicated in red. Asterisks signify metamorphic ages. Other ages are the youngest obtained detrital age, i.e., maximum sedimentation ages (those in parentheses may not be significant due to insufficient data or possible Pb-loss), older ages indicate principal provenance but reference should be made to Table 1 for more complete analysis. References to published data (selective in the case of Late Paleozoic igneous rocks): (a) Mellado (2015), (b) Blanco et al. (2012), (c) Bahlburg et al. (2009), (d) Morandé (2014), (e) Niemeyer et al. (2014), (f) Maksaev et al. (2014), (g) Casquet et al. (2014), (h) Venegas et al. (2013), (i) Arancibia (2014) — see Maksaev et al. (2015) for further data, and (j) Augustsson et al. (2015).

Wörner et al. (2000) reported further multi-grain U–Pb data: four out of five fractions from amphibole gneiss gave a discordia with a lower intercept of 366 ± 3 Ma and a long extrapolation to an upper intercept of 1877 + 139/− 131 Ma, the fifth fraction being concordant at 380 Ma; $^{207}Pb/^{235}U$ ages were claimed to indicate metamorphism at 380 and 400–420 Ma. For a garnet–biotite gneiss sample, four of five fractions defined a discordia with intercepts at 456 ± 4 Ma and 1745 ± 27 Ma, with the fifth point discordant at *c.* 620 Ma. These results were interpreted as showing recycling from a Paleoproterozoic protolith such as the Arequipa massif of Peru. The lack of evidence for Grenville-age events in these U–Pb results is notable. Loewy et al. (2004) undertook a more extensive multi-grain U–Pb zircon study of Peru and northern Chile basement rocks, their main conclusion being the threefold domain structure mentioned above. Two samples of foliated granodiorite cutting the schists at Belén gave clear evidence of Ordovician emplacement: one with four almost concordant fractions at 473 ± 2 Ma had an upper intercept of 1559 ± 21 Ma, the other had two concordant fractions at 473 ± 3 Ma, one showing slight Pb loss

Table 1
Summary of U–Pb zircon SHRIMP results from Norte Grande.

Sample	Rock Type	Locality	Age (Ma)†
Precordillera Upthrust Belt			
1. Belén metamorphic complex			
FO1210	Micaschist	Chapiquiña	850, **885**, 1000, 1780, **1860**, **1930**, **2015**, ~2250
FO1212	Amphibole orthogneiss	Pachama	**472 ± 3**
2. Aroma Formation			
FO1220	Metasandstone	Quebrada Aroma	400, 470, 530, 735, 1030, **1075**, **1190**, 1380, 2280
3. Quebrada Quipisca: Juan de Morales Formation			
FO1223	Sandstone	Quebrada Quipisco	**290**, **310**, 470, 630, 1065, 1230
4. Sierra de Moreno			
CY36	Quartz diorite	Quebrada del Burro	**461 ± 4**, 477 ± 5
CY21C	Garnet gneiss	Quebrada del Burro	935, 1140, **1460**, 2660
FO1131	Metasandstone	Quebrada del Burro	1025, 1170, **1460**, 1780, 2520
5. Limón Verde			
FO0926	Clast in diamictite	Sierra Limon Verde	1030, **1080**, **1130**
FO0908	Micaschist	Sierra Limon Verde	***283 ± 2***
FO0913	Micaschist	Sierra Limon Verde	***280 ± 2*** (320, 470, 625)
6. Cordón de Lila			
FO1122	Biotite gneiss	Quebrada El Leon	***485***, **1015**, 1080, **1180**, 1385, 1445
FO1120	Biotite monzogranite	Quebrada El Leon	**463 ± 4**
FO1121	Biotite-hornblende granodiorite	Quebrada El Leon	**471 ± 4**
FO1114	Rhyolite	Quebrada del Viento	**477 ± 3**
FO1115	Dacite	Quebrada del Viento	**480 ± 4**
FO1113	Perlite dyke	Quebrada Almohadillas	6.0, **9.2** (270)
Coast range			
7. Río Loa			
FO1231	Biotite gneiss	Rio Loa	***316 ± 3*** (**350**, **450**, **530**, 580, 1000, ~2200+)
FO1232	Migmatitic gneiss	Rio Loa	***318 ± 4*** (**350**, 390, 465, 510, 565, 640, ~1000, 2780)
FO1234	Red granite	Rio Loa	**130 ± 1** (145)
8. Sierra del Tigre			
FO0933	Banded micaschist	Sierra del Tigre	**465**, 540, 625, 1000, 1100–1200, 1340, 2150
9. Punta Totoralillo			
FO1144	Tonalite	Punta Totoralillo	**198 ± 2**

Crystallization ages calculated with 2-sigma uncertainties; italics indicate metamorphism.
† Significant peaks in detrital zircon age patterns (most abundant in bold type).

and one reversely discordant. Selected data (three out of four fractions) for a felsic dyke cutting the schists yielded an even younger lower intercept of 227 ± 17 Ma ascribed to radiogenic-Pb loss and a tightly defined upper intercept of 1866 ± 2 Ma. The latter was thought to reflect a detrital contribution from the northern domain basement of the AAB.

Sample *FO1210* is from a highly sheared outcrop 7 km due north of Belén: it is a mylonitic biotite–garnet schist, with S–C texture. The S bands are biotite-rich seams parallel to ribbon-quartz bands which contain stretched poikilitic garnet porphyroblasts wrapped around by the foliation. Some bands are twinned plagioclase rich, altered to fine grained sericite. Opaque minerals and zircon are accessories. The zircons are relatively small (*c*. 50–100 μm), round to sub-round in shape and heterogeneous under CL imaging (Fig. 3). Many grains are comprised of at least two components and there are homogeneous grains and rims that are interpreted as metamorphic. Apparent ages range almost continuously from around 800 Ma to 2600 Ma (Table 1), but the Wetherill concordia plot shows that most are discordant (Fig. 4) forming a discordia trend between *c*. 1950 Ma and *c*. 950 Ma. At the lower intercept there is a series of concordant groupings (Fig. 5) with possibly two main early Neoproterozoic events, one at 850–885 Ma and a lesser one at *c*. 1000 Ma. A number of these areas are in zircon interpreted as metamorphic, whilst others have an igneous CL structure. A group of five apparent $^{207}Pb/^{206}Pb$ ages at *c*. 1400 Ma are 10–20% discordant and are therefore not considered to reflect a meaningful geological event. The lack of zircon younger than 850 Ma suggests early Neoproterozoic deposition. The Paleoproterozoic provenance is very significant, with $^{207}Pb/^{206}Pb$ age peaks of *c*. 1780, 1860, 1930, and 2015 Ma, and a few ages back to ~2500 Ma; three analysed areas with essentially no Th, and therefore almost certainly formed during high-grade metamorphism, as confirmed by the CL images, have a mean $^{207}Pb/^{206}Pb$ age of 2000 Ma.

FO1212 is an amphibole gneiss with visible plagioclase phenocrysts, 8 km north of Belén. The plagioclase phenocrysts are embedded in a blue-green hornblende aggregate, with interstitial quartz, biotite and lesser white mica and opaque minerals, the whole with a mild preferred orientation. The separated zircons are coarse, elongate (200–400 μm long), sub-round to subhedral grains. The CL images (Fig. 3) show dominantly oscillatory internal zoning, though many have likely inherited central areas, whilst others have little to unzoned areas that may reflect metamorphic developments. Twenty-three of the areas analysed are dominated by radiogenic Pb and give a weighted mean $^{206}Pb/^{238}U$ age of 472 ± 3 Ma (MSWD = 0.7, Fig. 6), which is interpreted as the igneous crystallization age. Two analyses of inherited cores have Paleoproterozoic ages, one of which is concordant at *c*. 1850 Ma.

4.1.2. Quebrada Aroma

This thick low-grade metaturbidite sequence shows large-scale folds and has previously been considered to be of Devonian or Silurian age. No previous U–Pb data have been published but very recently Mellado (2015) reports LA-ICP-MS results for four samples. These consistently show major input of Ordovician (*c*. 465 Ma) and late Mesoproterozoic (1000–1200 Ma) detrital zircon with other peaks in some cases at *c*. 540, 680, and 1800 Ma. The youngest population identified varied from one sample to another (*c*. 435, 395, 345 and 325 Ma) and was claimed to indicate post-Mississippian deposition.

Sample *FO1220* is a fine-grained foliated metasandstone or schist from the thick folded sequence in Quebrada Aroma. It is composed of quartz, albite, biotite and white mica, and exhibits a tight crenulation foliation superimposed on a first fold foliation. Tourmaline, zircon and opaque minerals are accessory. Late quartz–carbonate veins are present. The separated zircons are relatively small (*c*. 50–100 μm), and range from round to sub-round grains to euhedral crystals or prismatic

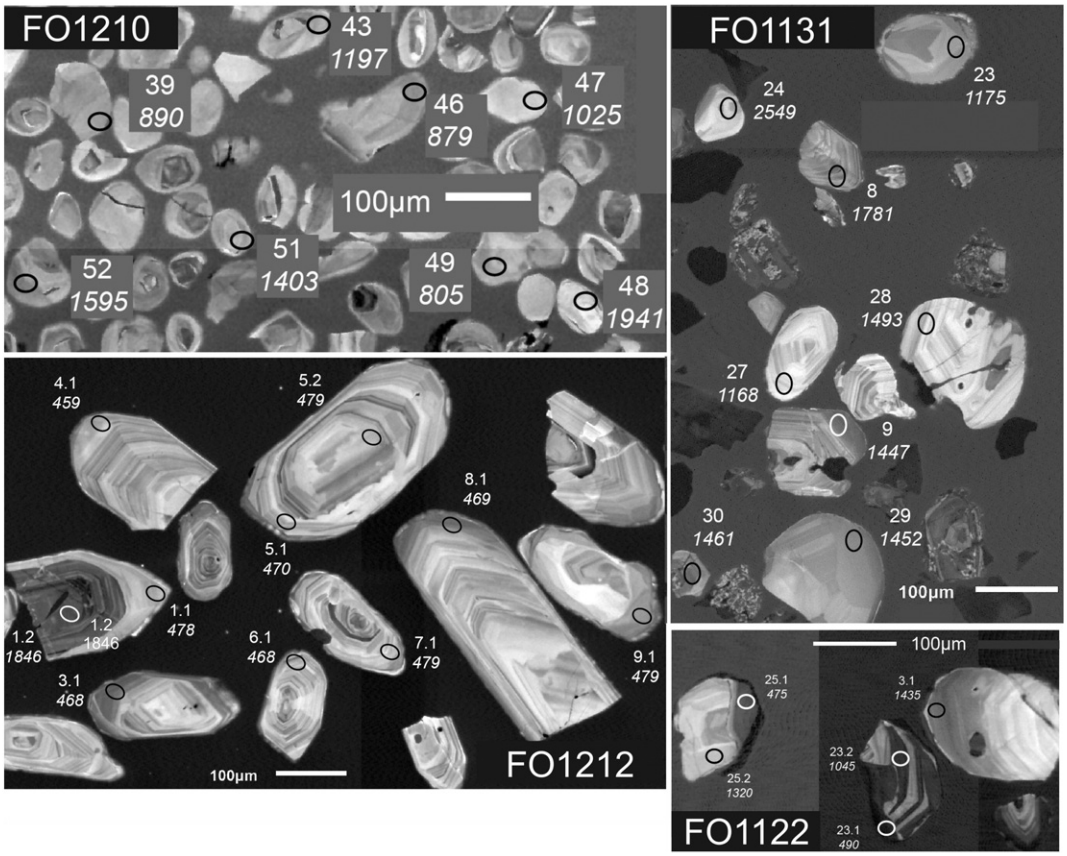

Fig. 3. Illustrative cathodoluminescence images of dated zircon grains (U–Pb ages in italic type) from samples of Belén schist (FO1210), Belén amphibole gneiss (FO1212), Sierra de Moreno quartzite (FO1131) and Cordón de Lila biotite gneiss (FO1122).

fragments. The zircon age distribution differs somewhat from those obtained by Mellado (2015) in that there is a wide range of apparent ages, from *c.* 400 to 2300 Ma, but principally between *c.* 980 and 1400 Ma, with peaks at 1030, 1075 and 1190 Ma, and a minor one at *c.* 1380 Ma (Fig. 5). The younger ^{206}Pb/^{238}U ages are scattered in the range 400–750 Ma and although there are suggestions of 470 Ma (Famatinian) and 530 Ma (Pampean) provenance, the only significant cluster is at 735–750 Ma. The youngest individual grain ages are *c.* 398 and 418 Ma, and whilst no geological significance can be based on such single grain analyses in view of the data of Mellado (2015) deposition of the sequence was possibly post-Devonian.

4.1.3. Quebrada Quipisca

The Lower Permian (Artinskian–Kungurian) paleontological age of the Juan de Morales Formation is based on a coquina (shell) bed stratigraphically *c.* 100 m above the dated sample (Diaz-Martínez et al., 2000). Sample *FO1223* is a sandstone from near the base of the sedimentary succession, overlying 311 Ma rhyolitic rocks (Blanco et al., 2012). The sandstone is a well-sorted reddish litharenite, with quartz (40%), siliceous volcanic rock (25%) and detrital white mica fragments. The matrix (15%) is composed of interstitial carbonate, phyllosilicate and opaque minerals. Zircons are a heterogeneous mixture of euhedral crystals with pyramidal terminations, broken fragments and round to sub-round grains. The CL images show the presence of many oscillatory zoned crystals, with some clearly metamorphic zircon grains and some with metamorphic rims. The detrital zircon age distribution (Fig. 5) has a prominent peak at 303 ± 3 Ma (14 analyses; MSWD = 1.19), with minor peaks at 460–480, 630 and 1050–*c.* 1300 Ma. The maximum possible sedimentation ages are slightly older than the biostratigraphical age (285–270 Ma), although there are three grains with ^{206}Pb/^{238}U ages between *c.* 275 Ma and *c.* 285 Ma.

4.1.4. Sierra de Moreno–Chojas

A Proterozoic age was proposed for the high-grade Chojas metamorphic complex by Damm et al. (1990) on the basis of poorly constrained upper intercepts for multi-grain zircon fractions of *c.* 1250–1200 Ma; lower intercepts ages of 466 ± 8 and *c.* 415 Ma were interpreted as due to metamorphic resetting. Better-defined upper intercept ages of 1067 ± 4 and 1024 ± 5 Ma were obtained for orthogneiss and megacrystic granite respectively by Loewy et al. (2004) but the lower intercepts at 497 ± 16 and 444 ± 8 Ma were thought to reflect igneous crystallization. Analyses from a dacite dyke gave intercepts at 1697 ± 48 and 635 ± 5 Ma. Previous Rb–Sr whole rock data and mineral ages using K–Ar and Sm–Nd methods (Skarmeta, 1983; Lucassen et al., 2000) range from *c.* 500 Ma to <300 Ma. At Quebrada Mani-Choja, Wilke et al. (1997) reported a Sm–Nd mineral isochron of *c.* 506 Ma, and K–Ar ages of *c.* 406 and *c.* 478 Ma (hornblende) and *c.* 296 Ma (biotite).

We have analysed three samples from basement rocks cropping out in the southern flank of the E–W striking Quebrada Sama, Sierra de Moreno, at the confluence of N–S striking Quebrada del Burro, and in Quebrada Amarilla a few hundred metres further east.

CY36 is a quartz diorite exposed in the eastern flank of the basement block. The outcrop is slightly S-shaped, *c.* 2 km wide and more than 6 km long, striking NNE–SSW. It is in contact with metamorphic basement rocks to the west and the Carboniferous Pinchal pluton to the east (Niemeyer et al., 2006). The texture is typically plutonic, phaneritic, fine-to-medium grained with respect to the essential minerals, which are green hornblende, plagioclase, quartz, biotite and chlorite; the minor components include sericite, zircon, apatite, calcium carbonate, Fe-oxides and a small amount of titanite. The larger hornblende grains are characterised by plagioclase, quartz and zircon inclusions, which produced pleochroic haloes in the host mineral. The quartz content

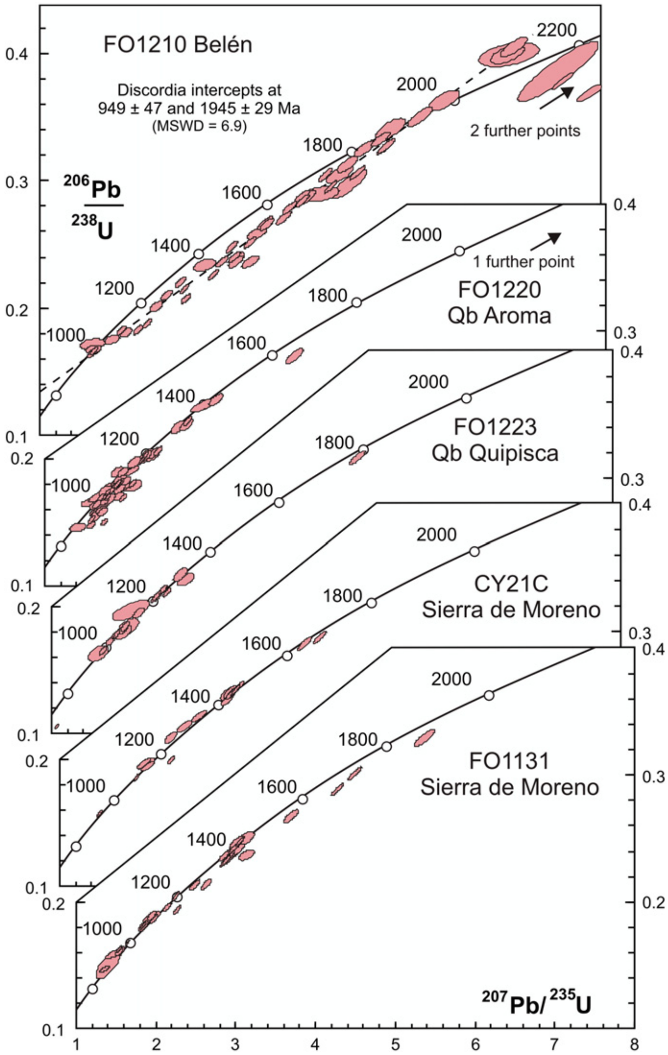

Fig. 4. Wetherill concordia plots of ^{204}Pb-corrrected U–Pb data for the older detrital zircons from Norte Grande basement rocks (Belén, Quebrada Aroma, Quebrada Quipisca and Sierra de Morena). The younger part of the age spectrum is included in Fig. 5.

does not exceed 10% and the quartz/plagioclase ratio varies from *c.* 0.175 to 0.25. The separated zircons are generally elongate, subhedral to euhedral grains with pyramidal terminations. CL images show oscillatory and sector zoning with some grains having probable inherited centres. All fourteen ^{206}Pb/^{238}U ages obtained are Ordovician but there is some dispersion with a bimodal distribution. Nine analyses yielded a weighted mean of 461 ± 4 Ma, which is interpreted as the magmatic age; the other five areas are slightly older at 477 ± 5 Ma, indicating the presence of an inherited component (Fig. 6).

CY21C is a garnet-bearing metasedimentary rock from a banded sequence exposed in the northern part of Quebrada del Burro. Band thickness varies from a couple of centimetres to a few decimetres. The sample, from one of the less siliceous bands, is fine-grained with a granoblastic texture, and is mainly composed of quartz, sericitized feldspar and secondary calcite. Minor components are poikiloblastic garnet (up to a few mm) with quartz, feldspar and calcite inclusions, as well as epidote and chlorite. Accessory minerals are titanite and zircon. Zircon grains are relatively small, mostly less than *c.* 100 μm in length. They comprise a heterogeneous population including prominent round to sub-round elongate grains as well as some euhedral crystals. The CL images show a variety of igneous and metamorphic internal structures. Only 20 grains were analysed but the data are generally concordant with ages from 1140 to 1710 Ma (with a single younger age of 935 Ma and another at *c.* 2660 Ma). There is a prominent grouping at *c.* 1460 Ma (Fig. 5).

FO1131 is a quartzite from Quebrada del Burro. Irregularly shaped quartz grains (10%) are set in a well crystallized, polygonized groundmass of quartz (40%), albite (40%), K-feldspar (5%), with scarce oriented biotite crystals (partially chloritized). Round zircon grains are very conspicuous in thin section, and apatite and opaque minerals are also accessories. The separated zircon is a heterogeneous collection of grains that range from very coarse round grains (*c.* 300–400 μm) to relatively fine (*c.* 50 or so μm), round, sub-round and euhedral crystals. The CL images (Fig. 3) similarly highlight the heterogeneous nature with a wide range of igneous and metamorphic internal structures. The apparent ages range from *c.* 950 Ma to *c.* 2550 Ma, are generally concordant, and appear to form discrete clusters at about 950–1000 Ma, 1100–1200 Ma and 1450–1500 Ma, with scattered older dates. A single anomalous younger grain is considered discordant and has no geological significance. The probability density plot shows a significant age grouping at *c.* 1460 Ma, as in sample CY21C (Fig. 5).

4.1.5. Sierra Limón Verde

Morandé (2014) reported LA-ICP-MS zircon chronology showing that the Limón Verde metamorphic complex as originally defined by Baeza (1984) comprises at least four units of different age as slivers or slices in a shear zone with a strike-slip component: a) diamictites with matrix having a maximum depositional age of *c.* 1060 Ma, similar to the 1050 Ma age presented by Hervé et al. (2010) for a pebble in the conglomerate, b) Pampa Quenante stratified quartzite and amphibolite (which occur as large inclusions in granitoids) with *c.* 470 Ma as maximum possible sedimentation age, c) low-grade metamorphic greywackes, also with a *c.* 470 Ma maximum sedimentation age, and d) the Limón Verde metamorphic complex sensu stricto composed of high P–high T schists and amphibolites (Lucassen et al., 2000; Soto, 2013) which have detrital igneous zircons as young as 300 Ma and metamorphic zircon ages of *c.* 288 Ma (Soto, 2013). Two groups of plutonic rocks intruding these units are Mississippian (325–322 Ma) and Early Permian (300–287 Ma) according to Morandé (2014).

FO0926 is a granitic clast from diamictite in the Limón Verde area, previously studied by Hervé et al. (2010). The cataclastic granitoid is composed of coarse (10 mm or more) aggregates of quartz with undulose extinction, sub-grains, and irregular shapes, intergrown with plagioclase and chlorite. The latter is mainly present in late veins, as well as carbonates. Accessory minerals are opaques, epidote, zircon and apatite. Zircons comprise a somewhat mixed population ranging from elongate euhedral grains with pyramidal terminations (up to 300 μm), to irregular and at times sub-round fragments. The CL images show primarily igneous internal structure; many are oscillatory zoned, but with possible older inherited central areas. The U–Pb zircon data are generally concordant (Fig. 7), with ^{207}Pb/^{206}Pb ages spread between 1030 and 1150 Ma (youngest group of four at *c.* 1040 Ma); the Sambridge and Compston (1994) un-mixing analysis suggests two major components at *c.* 1080 and 1130 Ma and these are considered to represent igneous crystallization events.

FO0908 and *FO0913* are white mica–garnet micaschists from the outcrop of high-grade metamorphic rocks at the type locality of the Limón Verde metamorphic complex as defined by Baeza (1984). Polycrystalline quartz aggregates with undulose extinction predominate, with dispersed plagioclase and garnet crystals. Garnets are irregular in shape, some with quartz inclusions, the plagioclase is somewhat sericitized. Biotite and white mica form well-orientated, isolated flakes within the quartz aggregates. Opaque minerals, zircon and rutile are accessories. U–Pb SHRIMP data for these samples were reported by Soto (2013) and are revised slightly here. The zircons in both samples are elongate subhedral grains which under CL imaging show dominant metamorphic rims on a variety of inherited older components (see Fig. 8). The metamorphic rims have very low Th, low to moderate

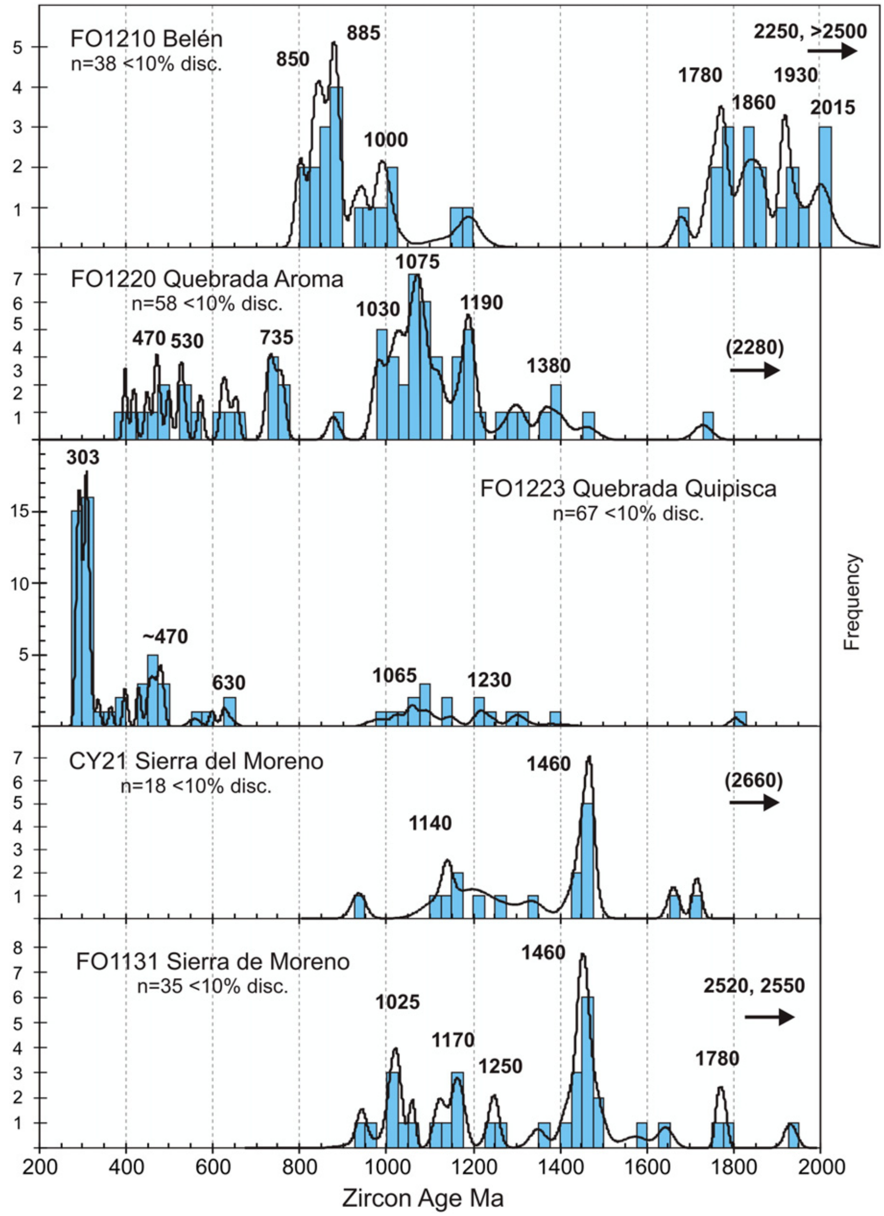

Fig. 5. Probability density curves and stacked histograms of detrital zircon ages for Norte Grande basement rocks, as in Fig. 4.

U and the Th/U ratios are predominantly <0.01; i.e., clearly metamorphic zircon. Both samples yield well-defined Permian age peaks of 283 ± 2 Ma and 280 ± 2 Ma, respectively, for the metamorphism with a range for older zircon cores of *c.* 320, 470, 625 and 950–1130 Ma) albeit from just a very limited sampling of inherited zircon (Figs. 8, 9, 10). Two pulses of Sierra Limón Verde granitoid crystallization were dated as 322–325 Ma and 287–300 Ma by Morandé (2014): these overlap with, or are slightly older than, the metamorphic rim ages reported here.

4.1.6. Cordón de Lila

The Cordón de Lila Igneous and Sedimentary Complex (Breitkreuz, 1986; Niemeyer, 1989) largely consists of low- to very low-grade metavolcanic rocks (ranging from basaltic to rhyolitic in composition), interbedded with marine sedimentary rocks and cut by a number of calc-alkaline plutons. Fossiliferous units indicate Ordovician, Silurian and Devonian deposition (Niemeyer, 1989; Benedetto et al., 2008; Niemeyer et al., 2010) over older basement. Early dating of the igneous rocks by various methods yielded ages ranging from *c.* 500 to *c.* 340 Ma (Mpodozis et al., 1983; Damm et al., 1986, 1990). More recently Palacios et al. (2013) used LA-ICP-MS to date zircon from a monzogranite pluton and a crosscutting porphyry dyke at 484 ± 3 and 466 ± 3 Ma, respectively, bracketing the development of cataclastic deformation in the pluton. Niemeyer et al. (2014) used the same methodology on nine individually mapped tonalite–granodiorite–monzonite plutons, obtaining ages ranging from 467 ± 3 to 484 ± 4 Ma, contemporaneous with Famatinian magmatism in the Argentine Puna. Augustsson et al. (2015) reported detrital zircon age patterns for two sedimentary rocks from Cordón de Lila: an Early Ordovician sample showed peaks at *c.* 480, 490, 520, 640 and *c.* 1200 Ma (as well as a few older Mesoproterozoic and even Paleoproterozoic ages), whereas one from the younger Quebrada Ancha Formation gave 430–440, 510, 560 and *c.* 980 Ma. Similar Ordovician, Cambrian, Ediacaran and (minor) Grenville-age provenance, but with younger components as well, was reported by these authors for the Carboniferous Zorritas Formation approximately 80 km farther south. We have analysed three samples from

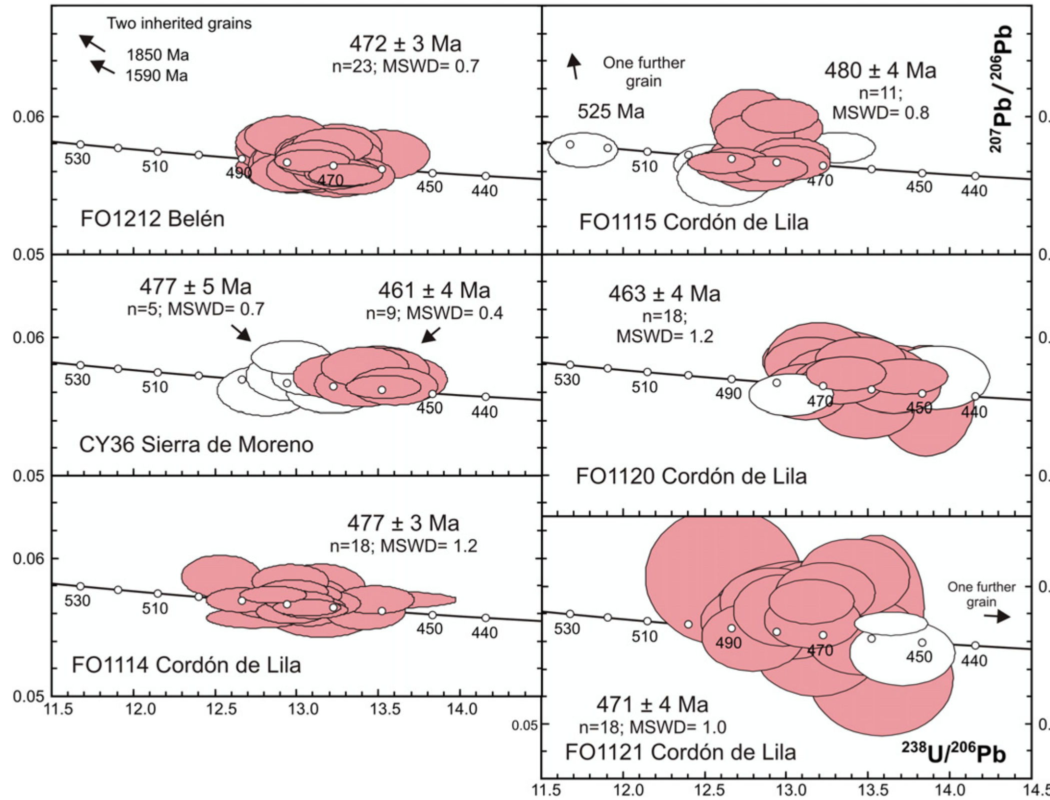

Fig. 6. Tera–Wasserburg plots of uncorrected U–Pb data for Ordovician intrusive rocks in the basement of Norte Grande. White ellipses represent data points not included in the calculation of the crystallization ages as weighted mean $^{238}U–^{206}Pb$ ages after common Pb correction based on the ^{207}Pb method.

the Cordón de Lila Igneous and Sedimentary Complex at Quebrada El León: a biotite gneiss and two crosscutting plutonic igneous rocks (granite and tonalite).

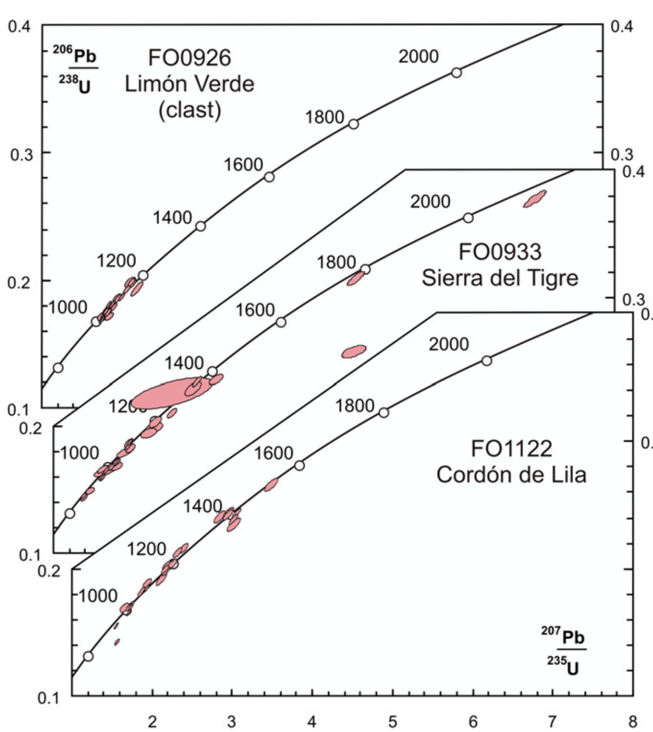

Fig. 7. Wetherill concordia plots of ^{204}Pb-corrrected U–Pb data for the older provenance detrital zircons from Norte Grande basement rocks (continued from Fig. 4). The younger part of the age spectrum is included in Fig. 10.

FO1122 is the gneiss sample. Field relationships indicate that this is an inclusion in the coarse-grained foliated leucogranite described below. The sample has a granoblastic aggregate of microcline, quartz and plagioclase, with irregular bands richer in biotite with zircon inclusions. White mica, epidote, chlorite, carbonate and opaque minerals appear related to sericitization of feldspars. The zircons are notably heterogeneous in morphology, size and internal CL structure; some have high-U rims, whilst others have very thin, low-U overgrowths. Four high-U rims yield Early Paleozoic ages, three in the range *c.* 475 to 490 Ma. The remaining areas analysed, including both complex nuclei and low Th/U metamorphic zircon, are generally concordant (Fig. 7), with ages ranging from *c.* 930 to 1520 Ma; the main peaks in the distribution are at *c.* 1015 and *c.* 1180 Ma but with a significant cluster around 1380 to 1450 Ma (Fig. 10). This pattern differs from those reported by Augustsson et al. (2015) in the abundance of Mesoproterozoic zircon and the absence of 500–650 Ma zircon.

FO1120 is a coarse-grained foliated leucogranite and *FO1121* a fine-grained tonalitic inclusion in the foliated granite. The zircons from both samples are elongate euhedral grains with bipyramidal terminations and the CL images show predominantly oscillatory internal zoning. However, zircon grains from sample FO1120 have higher U contents and a relatively simpler internal structure; a weighted mean for 18 of 20 grains analysed gives 463 ± 3 Ma (MSWD $= 1.15$; Fig. 6). The zircons from FO1121 are significantly lower in U, although under CL there are some high U areas, variously enclosing or enclosed by the low U component. There is also some radiogenic Pb loss and the weighted mean age for 18 of 21 grains is 470 ± 4 Ma (MSWD $= 1.02$; see Fig. 6). These samples are considered to correspond to the El León and Tambillo plutons, for which Niemeyer et al. (2014) obtained ages of 467 ± 3 and 484 ± 4 Ma, respectively.

Two volcanic samples were collected from Quebrada del Viento as well as a perlite dyke from Quebrada Almohadillas. *FO1114* is a rhyolite composed of embayed quartz and sub-automorphic plagioclase phenocrysts, which together with biotite are embedded in very fine-grained,

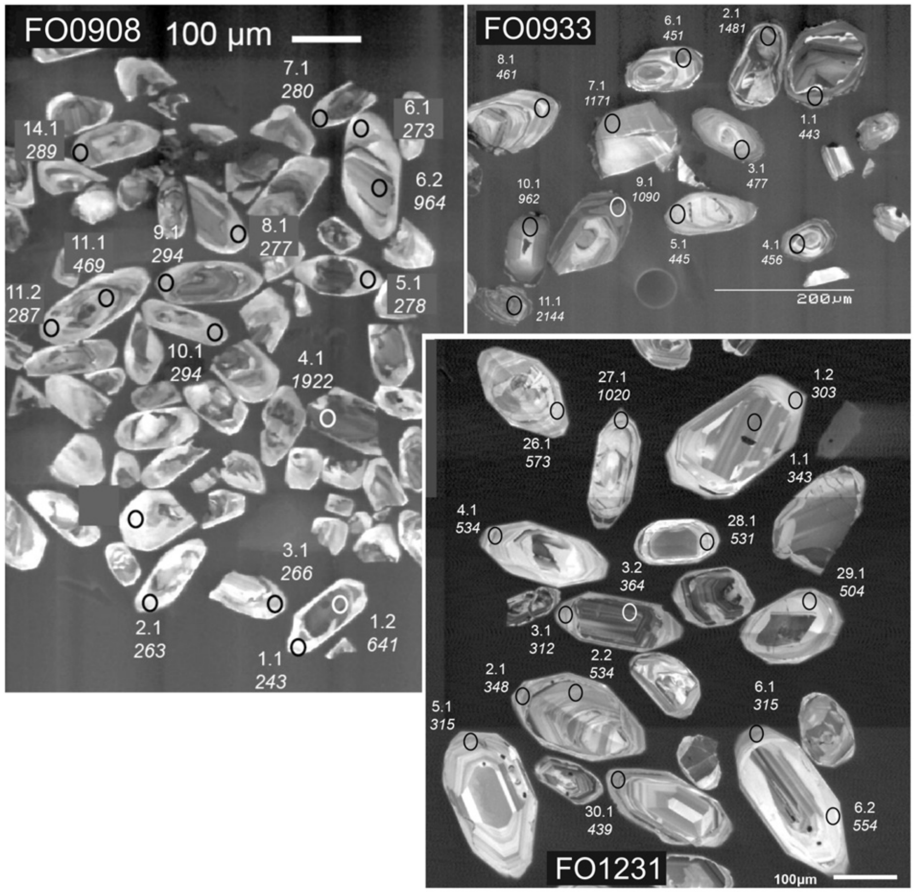

Fig. 8. Illustrative cathodoluminescence images of dated zircon grains (U–Pb ages in italic type) from samples of Limón Verde schist (FO0908), Río Loa gneiss (FO1231) and Sierra del Tigre schist (FO0933).

devitrified groundmass composed of felsic minerals, carbonate and opaques. The zircons are sub-equant to elongate, euhedral grains and fragments, many with pyramidal terminations. The more elongate grains range to *c*. 300 μm in length and usually have central cavities commonly seen in volcanic zircon; under CL they have length-parallel zoning. In contrast the sub-equant grains have oscillatory zoning often with older inherited cores (which were not analysed in this study). This rhyolite has rather simple zircon U–Pb systematics (Fig. 6) with a single dominant age calculated at 477 ± 3 (MSWD = 1.15 for 18 of 20 grains). *FO1115* is a dacite, composed of corroded quartz phenocrysts and automorphic plagioclase, set in a fluidal groundmass composed of a quartz–feldspar aggregate with interspersed carbonate and opaque minerals. The zircons, whilst similar to those of FO1114, are predominantly elongate to sub-equant grains that under CL show oscillatory zoned outer areas, often enclosing likely older inherited zircon. The dacite has more complex zircon U–Pb systematics (Fig. 6) with the main magmatic age of 480 ± 4 Ma (MSWD = 0.57 for 10 of 15 analyses) with one inherited zircon age of *c*. 525 Ma as well as a possible *c*. 490 Ma component.

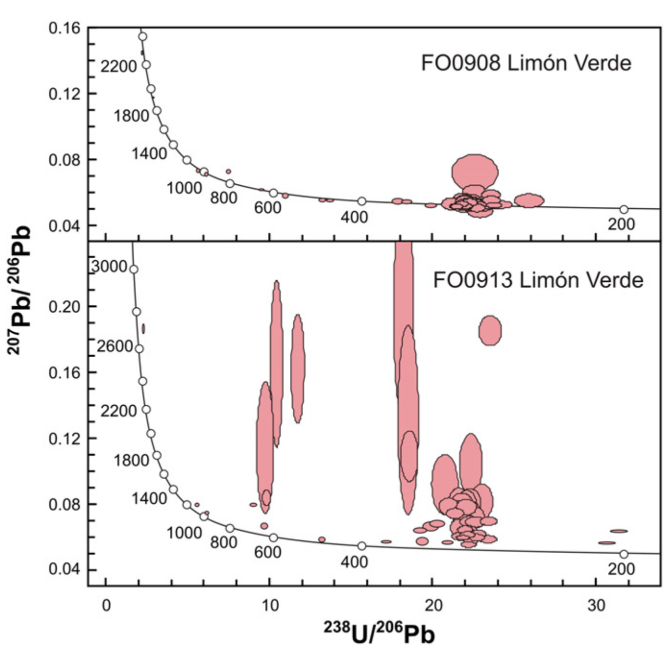

Fig. 9. Tera–Wasserburg plots of uncorrected U–Pb data for basement rocks in this study dominated by younger provenance. Provenance patterns are shown in Fig. 10.

FO1113 is a siliceous rock with perlitic structure forming a 1 m wide dyke which crosscuts Ordovician pillow basalts at Quebrada Almohadillas. Some of the rounded bodies are composed of radial acicular pyroxene (?) and others seem to be composed of zeolite, which is also present in coronas and interstices between the bodies. Late veins crosscut the rock. The zircons form a notably heterogeneous mixture, mainly comprising elongate, subhedral to euhedral grains, with oscillatory zoning or more complex internal CL structures. There are a few elongate crystals with length-parallel zoning, more typical of volcanic zircon. The U–Pb results show a wide range of ^{206}Pb/^{238}U ages (see Data Repository Table DR2): 14 of the areas analysed have ages between 6.0 to 13.1 Ma and two are *c*. 6 Ma with a group of 5 analyses around 9.3 Ma. Five others record Permo-Triassic dates (205 to 270 Ma) with another at 875 Ma. The perlite is a Miocene dyke: it is not possible to

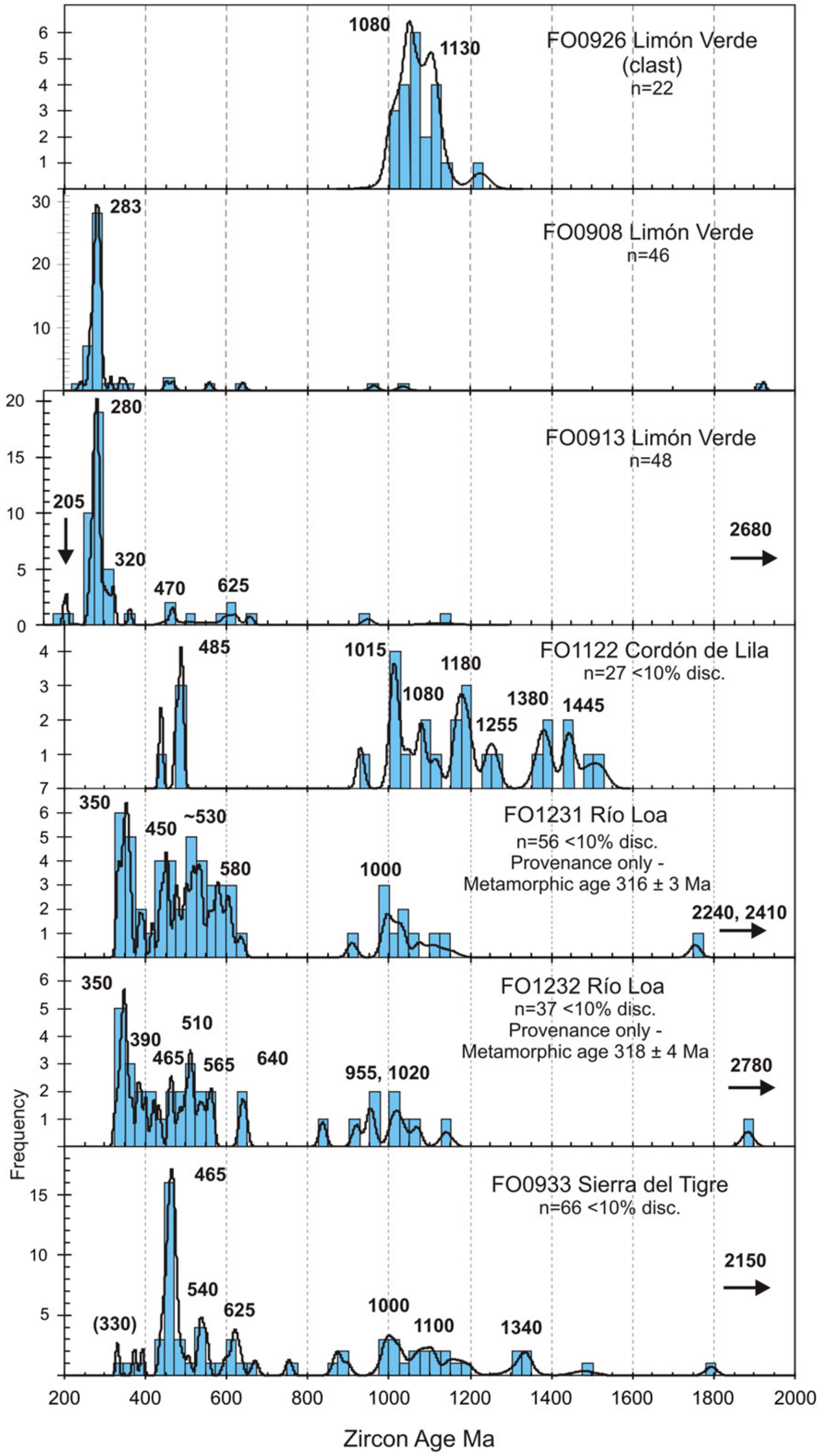

Fig. 10. Probability density curves and stacked histograms of detrital zircon ages for Norte Grande basement rocks (continued from Fig. 5).

decide whether the older ages represent true inheritance from the magma source region or contaminants picked up during ascent.

4.2. Coast range

Comparatively little work has so far been carried out on the metamorphic chronology of the sparse Coast Range outcrops in Norte Grande. Bahlburg et al. (2009) published studies that included detrital zircon dating of meta-turbidites from the El Toco Formation northeast of Tocopilla and the Las Tórtolas Formation near Chañaral (Fig. 2). All samples showed the typical "Pacific margin of Gondwana" signature with significant populations of Ordovician, 'Brasiliano'(550–750 Ma) and 'Grenvillian' (1000–1200 Ma) ages, as well as some older contributions: these were ascribed to provenance from the successive orogenic belts of the southwest Amazonian craton. The youngest zircons were mostly consistent with, but significantly older than, the presumed Late Devonian to Early Carboniferous depositional ages (Bahlburg and Breitkreuz, 1993), but one sample from Las Tórtolas had an age peak at *c.* 320 Ma and a youngest grain at *c.* 300 Ma, indicating post-Mississippian sedimentation. A further sample of the El Toco Formation analysed by Augustsson et al. (2015) gave a youngest zircon age peak of *c.* 350 Ma with older peaks at *c.* 430, 470, 530 and 1100 Ma. Detrital zircons of similar ages (Carboniferous, Early Cambrian, and Late and Early Neoproterozoic) were found by Wotzlaw et al. (2011) in Mesozoic sedimentary rocks which they considered to have been derived in part by erosion of the Belén metamorphic complex. Work on the metasedimentary rocks of the Mejillones Peninsula (Casquet et al., 2014) is referred to below in Section 6.

4.2.1. Río Loa

Wilke et al. (1997) reported K–Ar biotite ages of between *c.* 322 and 310 Ma for granites and migmatites in the lower course of Río Loa, which reaches the sea at 21°25′S. These rocks are emplaced in the El Toco Formation, a complex of low-grade metasedimentary rocks with Devonian depositional ages as indicated by both fossils and detrital zircon ages (Bahlburg et al., 2009 — see above). Three samples, two of gneiss and one of granite, were collected from near the mouth of Río Loa, immediately east of the western margin of a Mesozoic batholith.

FO1231 is a medium grained (2–5 mm) granitic rock composed of quartz (35%), plagioclase (45%), K-feldspar (10%), biotite (5%), white mica (2%), with apatite, zircon and opaque minerals as accessories. There is a faint orientation of biotite and quartz crystals, plagioclase being mainly replaced by a fine grained aggregate of sericite. Tectonic microbreccias and indented crystal boundaries testify deformation and dynamic recrystallization. A wide range of zircon morphologies is observed and there are many elongate euhedral grains with pyramidal terminations. The CL images (Fig. 8) show a variety of internal structures, often complex, but many of the grains have homogeneous metamorphic rims enclosing essentially oscillatory and sector zoned igneous components. *FO1232* is a more heterogeneous gneissic rock consisting of irregularly shaped quartz crystals (45%, 3–10 mm), which enclose tabular plagioclase (15%, 0.3 mm), and biotite crystals (10%, 1–2 mm), which are interstitial and somewhat orientated. Aggregates of biotite and white mica (20%, 1–5 mm) apparently replace K-feldspar (or cordierite?) and the white mica includes bundles of sillimanite (fibrolite). Zircon and opaque minerals are accessory. The zircons are very similar to those of FO1231, and similarly complex internal CL structures (Fig. 8) are observed with metamorphic rims enclosing older zircon components. Analyses of these two samples (Fig. 11) were carried out in two stages: first the outer zircon rims were preferentially selected to try to define the latest main igneous or metamorphic event, and then further analyses were conducted in the manner of detrital studies to obtain a representative provenance/inheritance pattern. In both samples the first stage produced predominantly, but not entirely, Carboniferous ages. Taking the metamorphic zircon areas with low Th/U ratios (mostly ≤0.015 and with low Th contents), 18 analyses for FO1231 define a weighted mean age of 316 ± 3 Ma (MSWD = 1.5) and 8 for FO1232 an undistinguishable result of 318 ± 4 Ma (MSWD = 1.3). This dates the main metamorphism of these rocks as mid-Pennsylvanian. Fig. 10 shows the distribution of ages for older zircon grains, many with igneous CL structure and normal igneous Th/U ratios. Both samples show similar patterns with significant peaks at 350 Ma, 450–470 Ma and 510–535 Ma, as well as 950–1030 Ma and scattered older ages.

FO1234 is a red quartz diorite with isotropic 2–3 mm aggregates of quartz (25%), sericitized plagioclase (50%) and biotite (20%), crossed by carbonate–opaque mineral veinlets. Opaque minerals occur replacing biotite or dispersed in the rock. The zircons are mostly coarse, euhedral grains with bipyramidal terminations. The CL images show both sector and oscillatory zoning; often there is a thin oscillatory zoned outer portion enclosing the sector-zoned interior. Discrete grains record the presence of Late Jurassic inheritance *c.* 145 Ma, with a dominant Early Cretaceous magmatic age 130.0 ± 1.4 Ma (MSWD = 0.73 for 14 analyses; see Fig. 12).

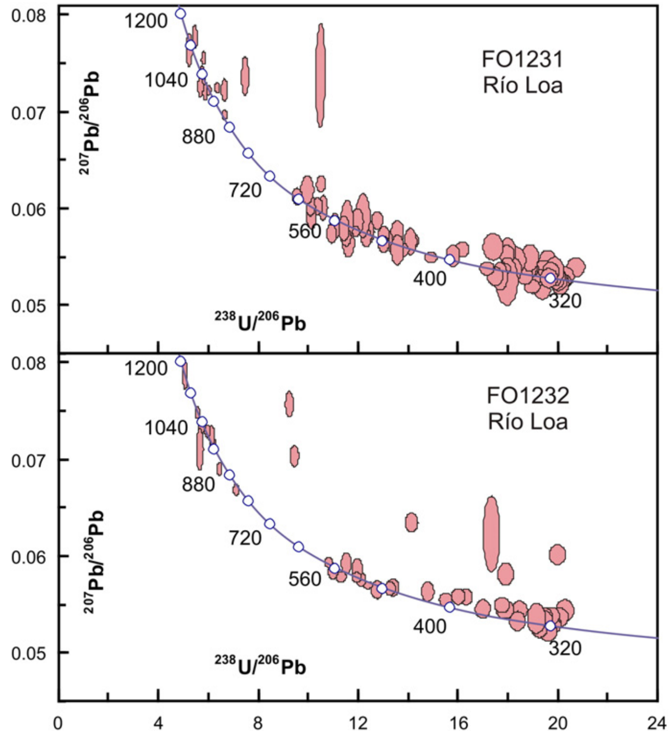

Fig. 11. Tera–Wasserburg plots of uncorrected U–Pb data for the Carboniferous gneisses of Río Loa (see provenance patterns in Fig. 10).

4.2.2. Sierra del Tigre

Paleozoic rocks in the Salar de Navidad region east of Antofagasta (Niemeyer et al., 1997) consist of deformed and metamorphosed

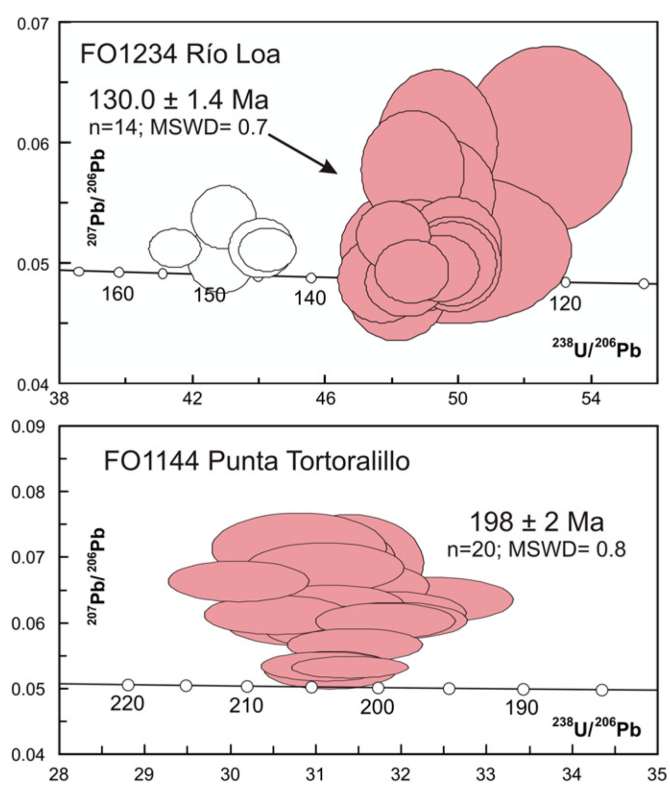

Fig. 12. Tera–Wasserburg plots of uncorrected U–Pb data for Mesozoic intrusive rocks in the basement of Norte Grande (Río Loa granite and Punta Totoralillo tonalite). The crystallization ages are calculated as weighted mean ^{238}U–^{206}Pb ages after common Pb correction based on the ^{207}Pb method.

sandstones of the supposedly Devonian Sierra del Tigre Formation and the unmetamorphosed Permian Cerros de Cuevitas Formation. Detrital zircon age patterns of each were presented by Augustsson et al. (2015); the former showed a probable minimum age of *c.* 410 Ma and provenance at *c.* 440, 530, 610 and 1100 Ma, the latter a minimum age of *c.* 350 Ma with peaks at 450–470, 500, 600, 630, 710 and *c.* 1100, with minor ones at *c.* 1300 and perhaps *c.* 1700 Ma.

FO0933 is a foliated and banded schist from the Sierra del Tigre Formation, with quartz-rich and biotite- and white-mica rich bands. Albite is present in small porphyroblasts and quartz aggregates are present in lenses wrapped by the main foliation. Opaque minerals and zircons are accessories. The zircons are generally elongate to sub-equant grains with round to sub-round terminations, although a few euhedral grains are present. The CL images (Fig. 8) reveal a variety of internal structures ranging from simple oscillatory zoning to complex internal structures with often irregular, homogeneous metamorphic rims enclosing older igneous and metamorphic zircon cores. There is a wide range of apparent ages (330–2150 Ma), with a prominent grouping at 450–480 Ma and then lesser groups around *c.* 550 Ma, *c.* 610–640 Ma and 1000–1340 Ma (Fig. 10). No geological significance can be placed on the three youngest dates that scatter between *c.* 330 Ma and *c.* 395 Ma. The Silurian 410–440 Ma ages found by Augustsson et al. (2015) are not apparent; instead, there is a prominent grouping at *c.* 465 Ma comprising 18 grains and from the current data-set this is taken as the maximum possible age for deposition. Minor peaks in the Mesoproterozoic spectrum are at 1000, 1100–1200 and 1340 Ma.

4.2.3. Punta Totoralillo

A pluton at this locality north of Caldera is mapped as Palaeozoic on the 1:1,000,000 Geological Map of Chile (SERNAGEOMIN, 1990 version). *FO1144* is a sample of granite. Separated zircons are coarse, elongate, euhedral crystals with simple magmatic internal CL structure. All 20 analysed grains are Early Jurassic, with a weighted mean $^{206}Pb/^{238}U$ age of 198 ± 2 Ma (MSWD = 0.78), which is interpreted as the emplacement age of the granite (Fig. 12).

5. Hf and O isotope data

Whilst U–Pb ages and provenance patterns are a basis for characterisation, tracing and possible correlations, they provide only first-order constraints. A further stage involves Lu–Hf and O isotope analyses of those dated zircon grains to investigate characteristics of the igneous rocks and to understand the source of the magmas from which such igneous zircons crystallized. Lu/Hf is reduced by fractionation in the crust compared to depleted mantle and $^{18}O/^{16}O$ increases during the upper crustal surface processes of erosion and sedimentation. This approach

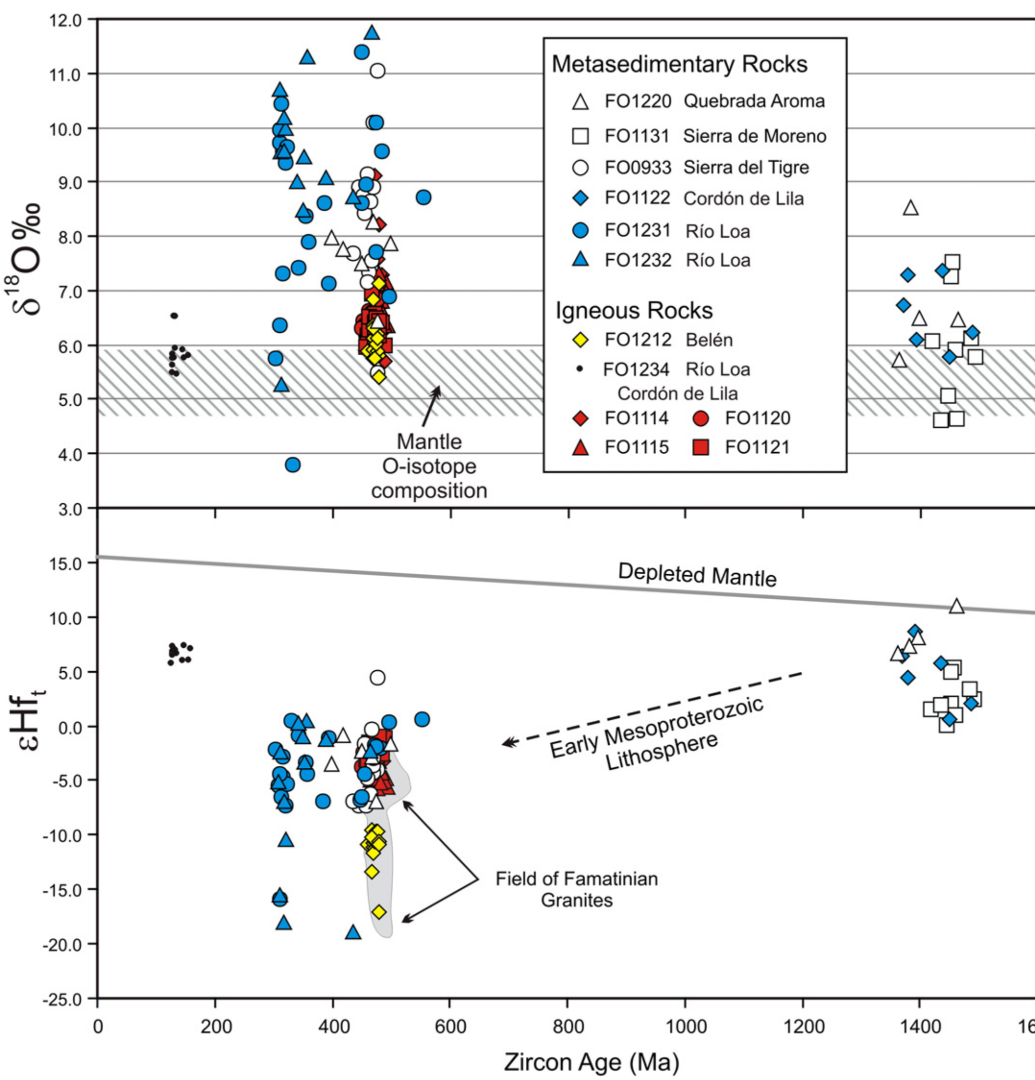

Fig. 13. Hf- and O-isotope values of SHRIMP-dated zircon components from selected samples, measured in the same position as the U–Pb measurements. The field for zircon with mantle $\delta^{18}O$ is taken from Valley et al. (1998). Lu–Hf isotope system parameters are given in the Supplementary data table: the arrow indicates the trajectory of Mesoproterozoic lithosphere with an average $^{176}Lu/^{177}Hf$ ratio of 0.015. The field for Hf isotopes in Famatinian granites is based on data from Chernicoff et al. (2010) and Dahlquist et al. (2013).

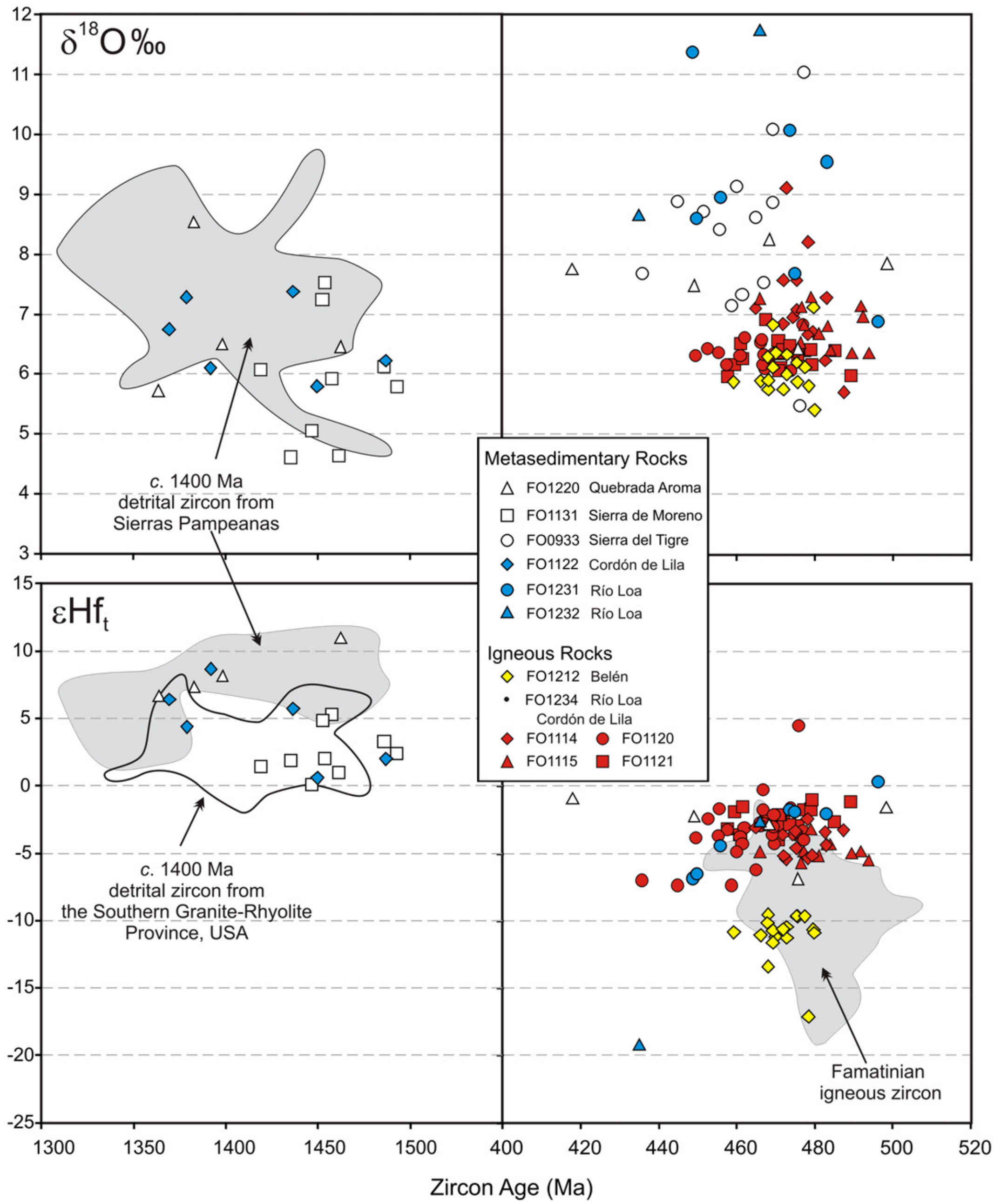

Fig. 14. Expanded details of Hf- and O-isotope plots vs. age for the *c.* 1350–1480 Ma (left) and Ordovician (right) groups. Fields for the Sierras Pampeanas basement rocks are from Rapela et al. (2015) and for the Southern Granite–Rhyolite Province of the southeastern USA from Goodge and Vervoort (2006). Data sources for the Famatinian granite Hf data as in Fig. 13.

can thus provide a multidimensional basis for tracing source(s) for detrital igneous zircon grains. We determined Lu–Hf and O isotope compositions in selected samples and grains with two main objectives: to compare Ordovician detritus in metasedimentary rocks with the widespread Ordovician igneous rocks, and to characterise the provenance of the *c.* 1380–1460 Ma zircon found in a number of the samples, since this is also a distinctive detrital zircon age group in the Western Sierra Pampeanas (Rapela et al., 2015). The Cretaceous igneous zircons (FO1234) and both metamorphic and igneous Carboniferous components in the Río Loa gneissic rocks (FO1231 and FO1232) were also analysed and, whilst the results are presented here, they are not discussed in detail. Analytical data are plotted in Fig. 13, with the specific age ranges of interest enlarged in Fig. 14. Full data are provided in Supplementary publication Table DR3, with summarized results in Table 2.

Most of the analysed *c.* 1450 zircon grains from sample FO1131 (Sierra de Moreno quartzite) have low δ^{18}O values of +4.6 to +6.1‰ (with two higher values up to +7.5‰), largely within the range for zircon with mantle oxygen isotope ratios (Fig. 13). They have εHf_t values of +0.1 to +3.3 (again with two outliers at +4.9 and +5.4) that equally indicate a rather juvenile source. Samples FO1220 (Quebrada Aroma schist) and FO1122 (Cordón de Lila gneiss) have slightly more positive δ^{18}O values of +5.7 to +7.4‰ (one analysis at +8.5‰) and εHf_t values of +0.6 to +11, the latter even suggesting a depleted mantle source (Fig. 13). Overall, the combined O–Hf data indicate a dominant juvenile source for these magmatic zircons. Comparisons can be made with data published by Rapela et al. (2015) for detrital zircons of similar age in the Sierras Pampeanas, Argentina. There is considerable overlap in both O and Hf values (Fig. 14) implying a common source for these *c.* 1450 Ma igneous zircon grains. There is also a close overlap

Table 2
Summary of Hf and O isotope results.

Sample	Lithology	εHf_t	T_{DM}[a] (Ga)	δO‰	
				Range	Mean
a. Ordovician zircon (t = 470 Ma)					
Belén metamorphic complex					
FO1212	Gneiss	−9.7 to −17.1	2.0–2.4	+5.4 to +7.1	+6.0
Aroma Formation					
FO1220	Schist	−0.9 to −6.9	1.5	+6.4 to +8.3	+7.6
Cordón de Lila					
FO1120	Granite	−1.6 to −3.8	1.5	+6.1 to +6.8	+6.3
FO1121	Tonalite	−1.1 to −4.0	1.5	+6.0 to +6.9	+6.3
FO1114	Rhyolite	−2.4 to −5.4	1.6	+5.7 to +9.1	
FO1115	Dacite	−3.2 to −5.7	1.7	+6.4 to +7.3	+6.8
Río Loa					
FO1231	Gneiss	+0.4 to −6.8[†]	1.5	+6.9 to +11.4	
FO1232	Gneiss	−2.5 to −18.2[#]	1.3–2.5	+5.2 to +10.7	
FO1234	Granite	+7[¥]	0.65	+5.7 to +6.6	+5.9
Sierra del Tigre					
FO0933	Schist	−0.3 to −7.4	1.6	+5.5 to +11.1	
b. Mesoproterozoic zircon (t = 1400 Ma)					
Aroma Formation					
FO1220	Schist	+6.7 to +11	1.6	+5.7 to +8.5	+6.7
Sierra de Moreno					
FO1131	Quartzite	+0.1 to +5.4	1.8–2.1	+4.6 to +7.5	+5.9
Cordón de Lila					
FO1122	Gneiss	+0.6 to +8.7	1.5–2.1	+5.8 to +7.4	+6.6

[a] Model age for separation from depleted mantle.
[†] Ordovician grains, n = 7.
[#] εHf for Carboniferous zircon, n = 6.
[¥] εHf calculated at 130 Ma.

with Hf-isotope data for early Mesoproterozoic A-type igneous rocks of the Southern Granite–Rhyolite province of southeastern Laurentia (Fig. 14); Rapela et al. (2015) took this as evidence that the *c*. 1450 Ma detrital zircons in the Sierras Pampeanas were derived from the Paleoproterozoic basement of MARA, thought to have been contiguous with Laurentia in Neoproterozoic times.

The Ordovician igneous rocks from Cordón de Lila have εHf_t values (mostly −2 to −5) that form a fairly compact group and $\delta^{18}O$ values also with a rather limited range, predominantly from +5.7 to +7.3‰, although the rhyolite (FO1114) extends this up to +9.1‰. As shown in Fig. 13 the Hf data imply old fractionated sources, possibly of Early Mesoproterozoic age, but the O data show that the source has not interacted with highly evolved crust. The Ordovician amphibole orthogneiss from Belén (FO1212) also has uniform and rather low $\delta^{18}O$ (5.4‰ to around 6.4‰, with two higher values up to 7.1‰). These values are within the range for the igneous rocks from Cordon de Lila and equally showing that the source has not mixed significantly with upper crustal rocks. However, εHf_t values for the Belén Ordovician zircons are quite distinct, ranging from −9.7 to −11.6 with two outliers at −13.4 and −17.0 (Fig. 13), indicating significantly earlier separation of the magmatic source from the depleted mantle, quite possibly Paleoproterozoic. The combination of Hf- and O-isotope data for the Ordovician igneous rocks of Norte Grande thus imply long residence in a reservoir with fractionated Lu/Hf ratios but with very little interaction with upper crustal oxygen; this source is most probably the low crustal lithosphere.

The εHf_t data for Ordovician detrital zircons (Quebrada Aroma metasandstone, Sierra del Tigre schist, and Rio Loa gneiss) dominantly overlap with the igneous zircon data from the Cordon de Lila (Fig. 13), but are clearly distinguished from the lower εHf_t values of the Belen amphibole gneiss. On the other hand, these detrital zircons show a much wider range of O-isotope composition, +5 to +12‰ (predominantly >+7), in this case indicating large-scale crustal reworking of the source material. Thus, although the Hf-isotope data seem to be compatible with derivation from the Ordovician igneous rocks exposed at Cordón de Lila, the addition of O-isotope analysis shows that this is unlikely to be the case. A more varied source area is suggested by general overlap in Hf-isotope data with Ordovician magmatic rocks of the Famatinian arc in Argentina, which exhibit a wide range of εHf_t (mostly −4 to −9, Fig. 14).

The Carboniferous detrital zircon in the Río Loa gneisses shows an extremely wide range of both εHf_t and $\delta^{18}O$ values indicating complexity in source characteristics (and probably a multiple metamorphic evolution). Only the other hand, the Cretaceous granite from Río Loa (FO1234) shows a consistently mantle-like range of $\delta^{18}O$ with a mean of +5.9‰, together with a mean εHf_t value of +7 that confirms a juvenile source for the magma.

6. Discussion

Pre-Mesozoic metamorphic rocks in the Norte Grande precordillera upthrust belt mostly show a wide range of detrital zircon ages, indicating that they were originally sedimentary. The minimum ages of igneous detrital zircons range from *c*. 850 Ma at Belén, the northernmost outcrop, to 1000–1100 Ma at outcrops in Sierra de Moreno and Cordón de Lila. The lack of younger detrital zircon, combined with our Hf–O isotope data, suggests that these are Neoproterozoic sediments derived from early Mesoproterozoic basement. This would also be consistent with a Cryogenian age for the diamictites at Limón Verde, suggested by Morandé (2014) in comparison with Neoproterozoic diamictite sequences of inferred glaciogenic origin elsewhere in South America, notably the Chiquerio Formation of southern Peru (see Chew et al., 2007). However, the dominance of *c*. 1800–2000 Ma detrital zircon at Belén compared to other localities (Fig. 5) suggests a contribution from a relatively nearby Paleoproterozoic source, such as the AAB in southern Peru as suggested by Wörner et al. (2000) — see also Loewy et al. (2004) and Casquet et al. (2010), or its supposedly equivalent MARA crustal block (Casquet et al., 2012), rather than the more distant Paleoproterozoic orogenic belts of Brazil. This, and the paucity of a Grenville-age contribution, point to a different provenance to that of the Sierra de Moreno metasedimentary rocks. In fact, south of Belén, indications of pre-Mesoproterozoic detritus are restricted to very few grains (*c*. 1850–2050, only occasionally 2600 Ma or older) — a possible indication that the southern limit of unexposed Paleoproterozoic basement lies at 20–21°S. In contrast, the dominant grouping of igneous detrital zircon in the Sierra de Moreno is *c*. 1460 Ma, and similar ages are observed in the reworked material at Quebrada Aroma and as far south as Cordón de Lila. Protolith of this age could be the Rondonia–San Ignacio belt of Brazil (as proposed by Bahlburg et al., 2009), but similar detrital zircon in the Western Sierras Pampeanas of Argentina (Rapela et al., 2015) has been ascribed to provenance from the Granite–Rhyolite Province of southeastern USA when MARA was juxtaposed with Laurentia during the Grenville orogeny. Our Hf–O data are consistent with this alternative source. Thus the original Neoproterozoic sediments of Norte Grande could well have been derived from Laurentia (i.e., from the west in present day terms) or MARA, part of which may form the underlying basement. Although Mesoproterozoic detrital zircons are present in some analysed samples from Norte Chico (e.g., Alvarez et al., 2011), direct evidence for Proterozoic sedimentation is not found south of 27°S.

The Neoproterozoic rocks of Norte Grande are intruded by widespread Ordovician granitoid plutons, as well as more mafic rocks at Belén and andesite and dacite at Cordón de Lila, all belonging to a well defined 465–490 Ma igneous event. This is synchronous with the Famatinian magmatic arc on the Argentine side of the Andes to the south, formed at the active Gondwana margin by east-directed subduction (Pankhurst et al., 1998; Dahlquist et al., 2012). This magmatism is well represented in all metasedimentary outcrop areas but especially at Cordón de Lila, where plutonism was accompanied in the early stage by volcanic andesite and dacite (Niemeyer et al., 2014; this study). Zimmermann et al. (2010) argued that this arc developed over a thinned Mesoproterozoic continental crust. The Hf- and O-isotope data for Ordovician zircon in the metasedimentary rocks analysed here are consistent with this proposal, although the distinct εHf_t values at Belén suggest an older lithospheric contribution (Paleoproterozoic or even Archaean) in the extreme north. Detritus must have flooded the sedimentary basins to the west during or after the main igneous activity of the arc, but specific source rocks are not uniquely identified.

No magmatic sources in the age range 460 Ma to 360 Ma have been identified in Norte Grande south of Cordón de Lila, in keeping with the Devonian lull in magmatic activity in the area suggested by Bahlburg and Hervé (1997). During Early Carboniferous times extension-related A-type granite in the Sierras Pampeanas of Argentina (Alasino et al., 2012; Dahlquist et al., 2013) was contemporaneous with subduction of the continental margin and I-type magmatism to the west. At Limón Verde (Norte Grande) and the Elqui mountains (Norte Chico), Carboniferous, Permian and Triassic plutons intrude metasedimentary rocks of variable, late Carboniferous-to-Triassic depositional ages. Famatinian and Mesoproterozoic detritus became less important in the metasedimentary successions of the southern areas studied here, perhaps indicating that potential sources were buried and/or that an orographic barrier excluded transport from Ordovician outcrops in northernmost Chile and Argentina.

A depositional age no older than *c.* 400 Ma for the Quebrada Aroma low-grade metamorphic complex suggests post-Silurian folding and metamorphism, which could be coeval with the deformation and metamorphism affecting the coastal turbiditic apron, mainly of Late Devonian to Early Carboniferous sedimentary age (see Charrier et al., 2007). These rocks are covered by the Juan de Morales marine sediments which contain *c.* 300 Ma detrital zircons, but only a few of 460–480 Ma, probably indicating that the Late Carboniferous magmatic products had already covered most of the eroding area at that time.

Rocks studied here whose detrital zircon content indicate sedimentation ages coeval with or even younger than the unmetamorphosed fossiliferous Early Permian Juan de Morales samples occur at Limón Verde, but they have been metamorphosed to amphibolite grade, in a low-P/high-T environment uncharacteristic of accretionary prism metamorphism (Soto, 2013). Post-Early Carboniferous metasedimentary rocks in the precordillera upthrust belt occur in the southeastern Cordillera de Domeyko at 26° to 26°30′S. From the latter locality, Maksaev et al. (2015) presented LA-ICP-MS dating of two samples of the greenschist facies El Jardín schist, which show a youngest group of U–Pb zircon ages at 310–330 Ma and important peaks at *c.* 470 Ma, 530 Ma and 630 Ma, with some 1000–1100 older and even Archaean peaks. Similar age patterns, but with a *c.* 300 Ma minimum age were obtained from samples in Quebrada del Carrizo 50 km to the north. The schists were interpreted as part of a Late Paleozoic accretionary complex that experienced Early Permian metamorphism and igneous intrusion.

In the Coast Range, metasedimentary rocks forming part of the same Late Paleozoic accretionary prism are intruded by Pennsylvanian plutonic rocks at Río Loa. Late Paleozoic, Permian and Triassic plutons in the Coast Range father south at 25–27°S have been reported on the basis of Rb–Sr and K–Ar dating (e.g., Brook et al., 1987), but systematic U–Pb dating in this area has not yet been attempted. A pluton mapped as Palaeozoic on the Geological Map of Chile (Scale 1:1.000.000) north of Caldera, has been dated as Jurassic in this paper (FO1144: 198 $\pm$ 3 Ma), thus raising doubts about the real distribution of Late Paleozoic magmatic rocks mapped as such before the advent of more reliable U–Pb zircon dating. It has been suggested that Late Paleozoic to Triassic plutonic outcrops in the Coast Range split from the batholiths in the precordillera upthrust belt during Mesozoic and later Andean extension (Pankhurst et al., 1988).

In northern Chile, Late Carboniferous to Triassic magmatism developed west of the Ordovician arc, indicating that during this time interval the margin was accretionary. These conditions apparently persisted until the Triassic and earliest Jurassic intrusive rocks are recognised near the present coastline in the Mejillones Peninsula (Casquet et al., 2014). Subsequently, from the Jurassic until the present, the northern portion of the Chilean continental margin became erosional (Rutland, 1971). This change in the tectonic regime of the Chilean margin from mainly accretionary in Paleozoic to Triassic times to erosional since the Early Jurassic, is perhaps a first order difference between the Andes and the previous orogens along this margin.

7. Conclusions

There is no direct evidence for exposed Precambrian igneous or orthogneissic rocks in Chile. The oldest metasedimentary rocks, at Belén, Sierra de Moreno and Sierra Limón Verde, seem to have been deposited (on an unseen substrate) during latest Mesoproterozoic to earliest Neoproterozoic times as they contain abundant detritus from a Stenian (1.0 to 1.2 Ga) magmatic protolith, usually as the youngest detrital component, together with Paleoproterozoic and Archaean components, especially at Belén. The notable absence of Brasiliano (750–550 Ma) or Pampean (530–500 Ma) detritus suggests provenance from the Rondonia–San Ignacio province of Brazil to the east, or from Laurentia or MARA to the west, prior to the Pampean collision (Casquet et al., 2012).

Elsewhere Proterozoic detritus in the metasedimentary rocks is mixed with material eroded from Early Paleozoic plutonic igneous rocks. At Cordón de Lila (24°S) our schist sample contains only Early Ordovician metamorphic zircon in addition to the Proterozoic provenance, but samples analysed by Augustsson et al. (2015) also have Brasiliano, Pampean and Ordovician–Silurian zircon, which they ascribed to input from uplifted basement to the east as well as the extinct Famatinian arc. This switch from mainly older Proterozoic (and Ordovician) to provenance that includes late Neoproterozoic, Ediacaran and Cambrian sources towards the south is consistent with most of Norte Grande being underlain by the Arequipa–Antofalla block, which has sparse outcrops with *c.* 1050 Ma rocks in Peru and Bolivia. Data presented here imply a possible Paleoproterozoic crustal basement as far as 20–21°S. South of 27°S the Chilenia terrane, supposedly accreted to the margin in Devonian times, is thought to constitute the underlying crust. A Carboniferous and younger accretionary prism accreted in basal mode, which forms the leading edge of the continental margin south of 32°S, crops out sporadically between 32° and 28°S but not north of that, although Pennsylvanian metamorphism of Mississippian igneous rocks was noted at Río Loa (*c.* 21°30′S). This probably reflects progressively more advanced tectonic erosion northwards along the continental margin, as suggested by Rutland (1971). An apparent major switch from a relatively passive margin in Silurian and Devonian times to a renewed subducting margin in the Early Carboniferous could be related to global geodynamics, since this is when Gondwana began to impinge on Laurasia, forming the transitory Pangea stage of continental tectonics (Stampfli et al., 2013). Subsequently, Triassic maximum possible sedimentation ages for metamorphic rocks have been determined in the Mejillones Peninsula (along with latest Triassic and earliest Jurassic intrusions, Casquet et al., 2014). The latter area lies west of the Atacama Fault zone, a prominent strike slip structure which has been active from the Jurassic to the present, and can be considered as belonging to a displaced terrane ('Mejillonia'), whose original location along the continental margin is not well established. The continental margin changed from accretionary mode to tectonic erosional mode at the onset of the Andean orogeny, and persisted thereafter, at least in northern Chile.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2015.11.009.

Acknowledgements

This research has been supported by FONDECYT grants 1095099 and 1130227 and associated International Cooperation Grants. Juan Vargas, Geology Department, Universidad de Chile, separated the zircons that were analysed. F. Munizaga and V. Maksaev, Universidad de Chile, contributed initial analyses of two zircon samples in the Sao Paulo

University SHRIMP. Cesar Casquet and Gerhard Wörner are thanked for perceptive and helpful reviews.

References

Alasino, P.H., Dahlquist, J.A., Pankhurst, R.J., Galindo, C., Casquet, C., Rapela, C.W., Larrovere, M., Fanning, C.M., 2012. Early Carboniferous sub- to mid-alkaline magmatism in the Eastern Sierras Pampeanas. NW Argentina: a record of crustal growth by the incorporation of mantle-derived material in an extensional setting. Gondwana Res. 22, 992–1008.

Alvarez, J., Mpodozis, C., Arriagada, C., Astini, R., Morata, D., Salazar, E., Valencia, V.A., Vervoort, J.D., 2011. Detrital zircons from late Paleozoic accretionary complexes in north-central Chile (28°–32° S): possible fingerprints of the Chilenia Terrane. J. S. Am. Earth Sci. 32, 460–476. http://dx.doi.org/10.1016/j.jsames.2011.06.002.

Álvarez, J., Mpodozis, C., Blanco-Quintero, I.F., García-Casco, A., Morata, D., Arriagada, C., 2013. U/Pb geochronology and P-T-t path of the La Pampa Gneisses, implications for the evolution of the Chilenia Terrane and Permo-Triassic tectonics of North-Central Chile. J. S. Am. Earth Sci. 47, 100–115.

Arancibia, J., 2014. Geocronología y significado de los Esquistos de El Jardin y del Complejo Metamórfico de la Quebrada Carrizo, Region de Atacama, Chile. Memoria de Título de Geólogo. Departamento de Geología, Universidad de Chile, Santiago (82 pp.).

Augustsson, C., Rüsing, T., Niemeyer, H., Kooijman, E., Berndt, J., Bahlburg, H., Zimmermann, U., 2015. 0.3 byr of drainage stability along the Palaeozoic palaeo-Pacific Gondwana margin; a detrital zircon study. J. Geol. Soc. Lond. http://dx.doi.org/10.1144/jgs2014-065.

Baeza, L., 1984. Petrography and tectonics of the plutonic and metamorphic complexes of Limón Verde and Mejillones Peninsula (PhD Thesis) Eberhard Karls Universitat, Tubingen.

Bahlburg, H., Breitkreuz, C., 1993. Differential response of a Devonian–Carboniferous platform-deeper basin system to sea-level change and tectonics, N. Chilean Andes. Basin Res. 5, 21–40.

Bahlburg, H., Hervé, F., 1997. Geodynamic evolution and tectonostratigraphic terranes of northwestern Argentina and northern Chile. Geol. Soc. Am. Bull. 109, 869–884.

Bahlburg, H., Vervoort, J.D., DuFrane, S.A., Bock, B., Augustsson, C., 2009. Timing of accretion and crustal recycling at accretionary orogens: insights learned from the western margin of South America. Earth Sci. Rev. 97, 227–253.

Basei, M.A.S., Charrier, R., Hervé, F., 1996. New ages (U–Pb, Rb–Sr, K–Ar) from supposed pre-Cambrian units in northern Chile: some geotectonic implications. Third International Symposium on Andean Geodynamics, St Malo, France, Extended Abstracts. ORSTOM, Paris, pp. 763–766.

Benedetto, J.L., Niemeyer, H., González, J., Brussa, E.D., 2008. Primer registro de braquiópodos y graptolitos ordovícicos en el Cordón de Lila (Puna de Atacama), norte de Chile. Ameghiniana 45, 3–12.

Blanco, N., Vasquez, P., Sepúlveda, F., Tomlinson, A., Ladino, M., 2012 Levantamiento geológico para el fomento y la exploración de recursos minerales e hídricos de la Cordillera de la Costa, Depresión Central y precordillera de la Región de Tarapacá (20°–21°S). Servicio Nacional de Geología y Minería, 93 p., 6 mapas escala 1: 100.000., Santiago.

Breitkreuz, C., 1986. Das Paläozoikum in den Kordilleren Nordchiles (21°–25°). Geotekt. Forsch. 70, 1–88.

Brook, M., Pankhurst, R., Shepherd, T., Shapiro, B., 1987. Andchron: Andean geochronology and metallogenesis. Overseas Development Administration, British Geological Survey, Keyworth, UK (Open File Report, 83 pp.).

Casquet, C., Fanning, C.M., Galindo, C., Pankhurst, R.J., Rapela, C.W., Torres, P., 2010. The Arequipa Massif of Peru: new SHRIMP and isotope constraints on a Paleoproterozoic inlier in the Grenvillian orogen. J. S. Am. Earth Sci. 29, 128–142.

Casquet, C., Rapela, C.W., Pankhurst, R.J., Baldo, E.G., Galindo, C., Fanning, C.M., Dahlquist, J.A., Saavedra, J., 2012. A history of Proterozoic terranes in southern South America: from Rodinia to Gondwana. Geosci. Front. 3, 137–145. http://dx.doi.org/10.1016/j.gsf.2011.11.004.

Casquet, C., Hervé, F., Pankhurst, R.J., Baldo, E., Calderón, Fanning, C.M., Rapela, C.W., Dahlquist, J., 2014. The Mejillonia suspect terrane: Late Triassic fast burial and metamorphism of sediments in a magmatic arc environment extending into the Early Jurassic. Gondwana Res. 25, 1272–1286. http://dx.doi.org/10.1016/j.gr.2013.05.016.

Cawood, P.A., 2005. Terra Australis orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic. Earth Sci. Rev. 69, 249–279.

Charrier, R., Pinto, L., Rodríguez, M.P., 2007. Tectonostratigraphic evolution of the Andean orogen in Chile. In: Moreno, T., Gibbons, W. (Eds.), The Geology of Chile. The Geological Society, London, pp. 21–114.

Chernicoff, C.J., Zappettini, E.O., Santos, J.O.S., Allchurch, S., McNaughton, N.J., 2010. The southern segment of the Famatinian magmatic arc, La Pampa Province, Argentina. Gondwana Res. 17, 662–675.

Chew, D.M., Kirkland, C.L., Schalteger, U., Goodhue, R., 2007. Neoproterozoic glaciation in the Proto-Andes: tectonic implications and global correlation. Geology 35, 1095–1099.

Cohen, K.M., Finney, S.C., Gibbard, P.L., Fan, J.-X., 2013. Updated. The ICS International Chronostratigraphic Chart. Episodes 36, 199–204.

Cordani, U.G., Sato, K., Teixeira, W., Tassinari, C.C.G., Basei, M.A.S., 2000. Crustal evolution of the South American platform. In: Cordani, U.G., Milani, E.J., Thomaz-Filho, A., Campos, D.A. (Eds.), Tectonic Evolution of South America. 31st International Geological Congress, Rio de Janeiro, Brazil, pp. 19–40.

Dahlquist, J.A., Rapela, C.W., Pankhurst, R.J., Fanning, C.M., Vervoort, J.D., Hart, G., Baldo, E.G., Murra, J.A., Alasino, P., Colombo, F., 2012. Age and magmatic evolution of the Famatinian granitic rocks of Sierra de Ancasti, Sierras Pampeanas, NW Argentina. J. S. Am. Earth Sci. 34, 10–25.

Dahlquist, J.A., Pankhurst, R.J., Gaschnig, R.M., Rapela, C.W., Casquet, C., Alasino, P.H., Galindo, C., Baldo, E., 2013. Hf and Nd isotopes in Early Ordovician to Early Carboniferous granites as monitors of crustal growth in the Proto-Andean margin of Gondwana. Gondwana Res. 23, 1617–1630.

Dalziel, I.W.D., 1994. Precambrian Scotland as a Laurentia-Gondwana link—origin and significance of cratonic promontories. Geology 22, 589–592.

Dalziel, I.W.D., 1997. Overview: Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol. Soc. Am. Bull. 109, 16–42.

Damm, K.-W., Pichowiak, S., Todt, W., 1986. Geochemie, Petrologie und Geochronologie der Plutonite und des metamorphen Grundgebirges in Nord-Chile. Berl. Geowiss. Abh. A/66, 73–146.

Damm, K.-W., Pichowiak, S., Harmon, R.S., Todt, W., Kelley, S., Omarini, R., Niemeyer, H., 1990. Pre-Mesozoic evolution in the central Andes; the basement revisited. In: Kay, S.M., Rapela, C.W. (Eds.), Plutonism from Antarctica to Alsaka. Geological Society of America Special Paper 241, pp. 101–126.

Deckart, K., Hervé, F., Fanning, C.N., Ramírez, V., Calderón, M., Godoy, E., 2014. U–Pb geochronology and Hf–O isotopes of zircons from the Pennsylvanian coastal batholith, South-Central Chile. Andean Geol. 41, 49–82.

Diaz-Martínez, E., Mamet, B., Isaacson, P.E., Grader, G.W., 2000. Permian marine sedimentation in northern Chile; new paleontological evidence from the Juan de Morales Formation, and regional paleogeographic implications. J. S. Am. Earth Sci. 13, 511–525.

Duhart, P., Mc Donough, M., Muñoz, J., Martin, M., Villeneuve, M., 2001. El Complejo Metamórfico Bahía Mansa en la Cordillera de la Costa del centro-sur de Chile (39°30′–42°S): geocronología K-Ar, 40Ar/39Ar y U–Pb, implicancias en la evolución del margen sur-occidental de Gondwana. Rev. Geol. Chile 28, 179–208.

Fu, B., Bröcker, M., Ireland, T., Holden, P., Kinsley, L.P.J., 2014. Zircon U–Pb, O, and Hf isotopic constraints on Mesozoic magmatism in the Cyclades, Aegean Sea, Greece. Int. J. Earth Sci. (Geogr. Rundsch.) http://dx.doi.org/10.1007/s00531-014-1064-z (online).

Goodge, J.W., Vervoort, J.D., 2006. Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence. Earth Planet. Sci. Lett. 243, 711–731. http://dx.doi.org/10.1016/j.epsl.2006.01.040.

Hervé, F., Faúndez, V., Calderón, M., Massone, H.-J., Willner, A.P., 2007. Metamorphic and plutonic basement complexes. In: Moreno, T., Gibbons, W. (Eds.), The Geology of Chile. The Geological Society, London, pp. 5–19.

Hervé, F., Massone, H.-J., Calderón, M., Soto, F., Fanning, C.M., 2010. Pre-Mesozoic metamorphism and tectonics in northern Chile: collisional vs. subduction zone environments. Eos. Trans. AGU 91 (26) (Meeting of the Americas Supplement, Abstract V11A – 04).

Hervé, F., Calderón, M., Fanning, C.M., Pankhurst, R.J., Godoy, E., 2013. Provenance variations in the Late Paleozoic accretionary complex of central Chile as indicated by detrital zircons. Gondwana Res. 23, 1122–1135.

Loewy, S.L., Connelly, J.N., Dalziel, I.W.D., Gower, C.F., 2003. Eastern Laurentia in Rodinia: constraints from whole-rock Pb and U/Pb geochronology. Tectonophysics 375, 169–197.

Loewy, S.L., Connelly, J.N., Dalziel, I.W.D., 2004. An orphaned basement block: the Arequipa–Antofalla basement of the central Andean margin of South America. Geol. Soc. Am. Bull. 116, 171–187.

Lucassen, F., Becchio, R., Wilke, H.G., Franz, G., Thirwall, M.F., Viramonte, J., Wemmer, K., 2000. Proterozoic–Palaeozoic development of the basement of Central Andes (18–26°)—a mobile belt of the South American craton. J. S. Am. Earth Sci. 13, 697–715.

Maksaev, V., Munizaga, F., Tassinari, C., 2014. Timing of the magmatism of the paleo-Pacific border of Gondwana: U–Pb geochronology of Late Paleozoic to Early Mesozoic igneous rocks of the north Chilean Andes between 20° and 31°S. Andean Geol. 41, 447–506.

Maksaev, V., Arancibia, J., Munizaga, F., Tassinari, C., 2015. Detrital-zircon U–Pb geochronology of the Quebrada del Carrizo Metamorphic Complex and El Jardín schists and spatially-related granitoids of the Sierra Castillo batholith. Andean Geol. 42, 285–312. http://dx.doi.org/10.5027/andgeoV42n3-a01.

Mellado, E., 2015. Origen del Complejo Metaturbidítico de Quebrada Aroma: Implicancias en la Evolución Paleozoica del Norte de Chile. Memoria de Título de Geólogo. Universidad de Chile, Santiago (72 pp.).

Morandé, J.P., 2014. El Basamento pre-Mesozoico de la Sierra Limón Verde: Implicancias Para la Evolución Tectónica del Norte de Chile. Tesis Para Optar al Grado de Magíster en Ciencias. Mención Geología, Universidad de Chile, Santiago (99 pp.).

Mpodozis, C., Hervé, F., Davidson, J., Rivano, S., 1983. Los granitoids de Cerro de Lila, manifestaciones de un episodio intrusivo y termal del Paleozóico Inferior en los Andes del Norte de Chile. Rev. Geol. Chile 18, 3–14.

Munizaga, F., Maksaev, V., Fanning, C.M., Giglio, S., Yaxley, G., Tassinari, C.C.G., 2008. Late Paleozoic-Early Triassic magmatism on the western margin of Gondwana: Collahuasi area, Northern Chile. Gondwana Res. 13, 407–427.

Niemeyer, H., 1989. El Complejo ígneo-sedimentario del Cordón de Lila, Región de Antofagasta: estratigrafía y significado tectónico. Rev. Geol. Chile 16, 163–181.

Niemeyer, H., Venegas, R., González, C.R., Aceñolaza, F.G., 1997. Los terrenos paleozoicos del Salar de Navidad, Región de Antofagasta, Chile. Rev. Geol. Chile 24, 123–143.

Niemeyer, H., Nava, M., Soto, I., 2006. Interacción entre la Granodiorita Pinchal y el xenolito kilométrico de Cerro Negro, Sierra de Moreno, Región de Antofagasta, Chile. Rev. Geol. Chile 33, 3–18.

Niemeyer, H., Alvarez, F., Boucot, A.J., Bruna, M., 2010. Brachiopods from Cordón de Lila, Lower Silurian (Llandovery) Quebrada Ancha Formation, Antofagasta Region, Chile. Spec. Pap. Palaeontol. 84, 287–307.

Niemeyer, H., Meffre, S., Guerrero, R., 2014. Zircon U–Pb geochronology of granitic rocks of the Cordón de Lila and Sierra de Almeida ranges, northern Chile: 30 m.y. of Ordovician plutonism on the western border of Gondwana. J. S. Am. Earth Sci. 56, 228–241.

Pacci, D., Hervé, F., Munizaga, F., Kawashita, K., Cordani, U., 1980. Acerca de la edad Rb–Sr precambrica de rocas de la Formacion Esquistos de Belen, Departamento de Parinacota, Chile. Rev. Geol. Chile 11, 43–50.

Palacios, M.J., Niemeyer, H., Meffre, S., 2013. Las bandas de cataclasitas ordovícicas del Monzogranito Tambillo: manifestaciones de una subfase temprana de los movimientos oclóyicos en el Cordón de Lila, norte de Chile. Andean Geol. 40, 561–570.

Pankhurst, R.J., Hole, M.J., Brook, M., 1988. Isotope evidence for the origin of Andean granites. Trans. R. Soc. Edinb. Earth Sci. 19, 123–133.

Pankhurst, R.J., Rapela, C.W., Saavedra, J., Baldo, E., Dahlquist, J., Pascua, I., Fanning, C.M., 1998. The Famatinian magmatic arc in the southern Sierras Pampeanas. In: Pankhurst, R.J., Rapela, C.W. (Eds.), The Proto-Andean Margin of gGondwana. Special publication of the geological society, London, No. 142, pp. 343–367.

Ramos, V.A., 1988. Late Proterozoic – Early Paleozoic of South America – a collisional history. Episodes 11, 168–174.

Ramos, V.A., 2004. Cuyania, an exotic block to Gondwana: review of a historical success and the present problems. Gondwana Res. 7, 1009–1026.

Ramos, V.A., Jordan, T.E., Allmendinger, R.W., Mpodozis, C., Kay, S.M., Cortes, J., Palma, M., 1986. Paleozoic terranes of the Central Argentine Chilean Andes. Tectonics 5, 855–880.

Rapela, C.W., Verdecchia, S.O., Casquet, C., Pankhurst, R.J., Baldo, E.G., Galindo, C., Murra, J.A., Dahlquist, J.A., Fanning, C.M., 2015. Identifying Laurentian and SW Gondwana sources in the Neoproterozoic to Early Paleozoic metasedimentary rocks of the Sierras Pampeanas: Paleogeographic and tectonic implications. Gondwana Res. http://dx.doi.org/10.1016/j.gr.2015.02.010.

Rutland, R.W.R., 1971. Andean orogeny and ocean floor spreading. Nature 233, 252–255. http://dx.doi.org/10.1038/233252a0.

Sambridge, M.S., Compston, W., 1994. Mixture modelling of multi-component data sets with application to ion-probe zircon ages. Earth Planet. Sci. Lett. 128, 373–390.

Skarmeta, J., 1983. The Structural Geology of the Sierra de Moreno Northern Chile (Unpubl. PhD thesis, Univ. London, 309 pp.).

Soto, M.F., 2013. Pressure–temperature–time paths of the Limón Verde metamorphic complex, Chile (Tesis) de Grado de Magister en Ciencias, Mención Geología, Departamento de Geología. Universidad de Chile, Santiago (125 pp.).

Stampfli, G.M., Hochard, C., Vérard, C., Wilhem, C., von Raumer, J., 2013. The formation of Pangea. Tectonophysics 593, 1–19. http://dx.doi.org/10.1016/j.tecto.2013.02.037.

Tosdal, R.M., 1996. The Amazon-Laurentian connection as viewed from the Middle Proterozoic rocks in the central Andes, western Bolivia and northern Chile. Tectonics 15, 827–842.

Valley, J.W., Kinny, P.D., Schulze, D.J., Spicuzza, M.J., 1998. Zircon megacrysts from kimberlite: oxygen-isotope variability among mantle melts. Contrib. Mineral. Petrol. 133, 1–11.

Vaughan, A.P.M., Pankhurst, R.J., 2008. Tectonic overview of the West Gondwana margin (focus paper). Gondwana Res. 13, 150–162. http://dx.doi.org/10.1016/j.gr.2007.07.004.

Venegas, C., Cervetto, M., Astudillo, N., Espinoza, F., 2013. Carta Sierra Vaquillas Altas, Regiones de Antofagasta y Atacama. Servicio Nacional de Geología y Minería. Carta Geológica de Chile, Serie Geología Básica 159.

Wasteneys, H.A., Clark, A.H., Farrar, E., Langridge, R.J., 1995. Grenvillian granulite-facies metamorphism in the Arequipa Massif, Peru: a Laurentia-Gondwana link. Earth Planet. Sci. Lett. 132, 63–73.

Wilke, H.G., Lucassen, F., Wemmer, A., 1997. Chemistry and isotopic ages of basement and intrusions. VIII Congreso Geologico Chleno, Actas vol. 2. Universidad Católica del Norte, Antofagasta, pp. 1593–1597.

Williams, I.S., 1998. U–Th–Pb geochronology by ion microprobe. In: McKibben, M.A., Shanks III, W.C., Ridley, W.I. (Eds.), Applications of Microanalytical Techniques to Understanding Mineralizing Processes. Reviews of Economic Geology 7, pp. 1–35.

Willner, A., Gerdes, A., Massonne, H.J., Schmidt, A., Sudo, M., Thomson, S., Vujovich, G., 2010. The geodynamics of collision of a microplate (Chilenia) in Devonian times deduced by the pressure–temperature–time evolution within part of a collisional belt (Guarguaraz complex), W Argentina. Contrib. Mineral. Petrol. 162, 303–327. http://dx.doi.org/10.1007/s00410-010-0598-8.

Wörner, G., Lezaun, J., Beck, A., Heber, V., Lucassen, F., Zinngrebe, E., Rössling, R., Wilke, H.G., 2000. Precambrian and Early Paleozoic evolution of the Andean basement at Belen (northern Chile) and Cerro Uyarani (western Bolivia Altiplano). J. S. Am. Earth Sci. 13, 717–737.

Wotzlaw, J.F., Decou, A., von Eynatten, H., Wörner, G., Frei, D., 2011. Jurassic to Palaeogene tectono-magmatic evolution of northern Chile and adjacent Bolivia from detrital zircon U–Pb geochronology and heavy mineral provenance. Terra Nova 23, 399–406. http://dx.doi.org/10.1111/j.1365-3121.2011.01025.x.

Zimmermann, U., Niemeyer, H., Meffre, S., 2010. Revealing the continental margin of Gondwana: the Ordovician arc of the Cordón de Lila (northern Chile). Int. J. Earth Sci. (Geol. Rundsch.) 99 (Suppl. 1), S39–S56. http://dx.doi.org/10.1007/s00531-009-0483-8.