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The crustal evolution of South America from a zircon Hf-isotope perspective

Carita Augustsson,[1] Arne P. Willner,[2] Tobias Rüsing,[3] Hans Niemeyer,[4] Axel Gerdes,[5] Christopher J. Adams[6] and Hubert Miller[7]

[1]*Institutt for Petroleumsteknologi, Universitetet i Stavanger, Stavanger 4036, Norway;* [2]*Institut für Geologie, Mineralogie und Geophysik, Ruhr-Universität, Bochum 44780, Germany;* [3]*Institut für Geologie und Paläontologie, Westfälische Wilhelms-Universität, Corrensstrasse 24, Münster 48149, Germany;* [4]*Departamento de Ciencias Geológicas, Universidad Católica del Norte, Casilla 1280, Antofagasta Chile;* [5]*Institut für Geowissenschaften, Johann Wolfgang Goethe-Universität Frankfurt, Altenhöferallee 1, Frankfurt am Main 60438, Germany;* [6]*GNS Science, Private Bag 1930, Dunedin 9054, New Zealand;* [7]*Department für Geo- und Umweltwissenschaften, Ludwig-Maximilian-Universität, Luisenstraße 37, München 80333, Germany*

ABSTRACT

Hf-isotope data of >1100 detrital zircon grains from the Palaeozoic, south-central Andean Gondwana margin record the complete crustal evolution of South America, which was the predominant source. The oldest grains, with crustal residence ages of 3.8–4.0 Ga, are consistent with complete recycling of existing continental crust around 4 Ga. We confirm three major Archaean, Palaeoproterozoic (Transamazonian) and late Mesoproterozoic to early Neoproterozoic crust-addition phases as well as six igneous phases during Proterozoic to Palaeozoic time involving mixing of juvenile and crustally reworked material. A late Mesoproterozoic to early Neoproterozoic, Grenville-age igneous belt can be postulated along the palaeo-margin of South America. This belt was the basement for later magmatic arcs and accreted allochthonous microcontinents as recorded by similar crustal residence ages. Crustal reworking likely dominated over juvenile addition during the Palaeozoic era, and Proterozoic and Archaean zircon was mainly crustally reworked from the eroding, thickened Ordovician Famatinian arc.

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Introduction

Several studies argue that active continental margins are major sites of juvenile crust addition, crustal reworking and continental growth (e.g. Lucassen *et al.*, 2004; Franz *et al.*, 2006; Cawood and Buchan, 2007; Condie, 2007). The Andean margin of South America has been a classical convergent margin since at least Cambrian time (Ramos, 2009). In the south-central Andes, several magmatic arcs contributed to the growth of Gondwana during early Palaeozoic time. This is reflected in the detritus of basins that evolved from east to west in Ediacaran–Cambrian time mainly in an accretionary prism in northwest Argentina, in Ordovician–Devonian time in retroarc and forearc environments, and in late Palaeozoic time in accretionary prisms of the Coastal Cordillera of Chile. In these basins, zircon assembled from all major orogenic periods of the entire continent.

Correspondence: Carita Augustsson, Institutt for Petroleumsteknologi, Universitetet i Stavanger, Stavanger 4036, Norway. Tel.: +47 518 317 62; e-mail: carita.augustsson@uis.no

Zircon analysis is a valuable tool for understanding processes related to crustal growth and evolution (e.g. Kinny and Maas, 2003; Scherer *et al.*, 2007). In particular, the Hf-isotope composition of U–Pb-dated detrital grains can be used to infer the geochemical characteristics of the crust (Scherer *et al.*, 2007). The crustal history of the protolith material of individual zircon grains can be reconstructed back to its fractionation from a depleted mantle. As such, zircon of different ages grown from material with a similar crustal history can be detected (e.g. Gerdes and Zeh, 2006, 2009; Kemp *et al.*, 2006). Hence, the Hf-isotope compositions of detrital zircon grains from deposits with broad zircon age spectra allow a reconstruction of the growth history of an entire continent.

In this study, we concentrate on siliciclastic sedimentary rocks of the Palaeozoic continental margin of South America at 22–36°S (Fig. 1), where magmatism is mainly related to an Ordovician (Famatinian) and a Late Carboniferous to Permian magmatic arc (e.g. Rapela *et al.*, 1998; Lucassen *et al.*, 1999). Our aim was to track the Eoarchaean to Palaeozoic crustal growth of South America from detrital data and to monitor the change in Hf-isotope signatures with time using a large dataset of >1100 laser ablation inductively coupled plasma mass spectrometry Hf-isotope compositions of detrital zircon from 30 siliciclastic rocks of Cambrian to Permian age (Table 1). Furthermore, we trace crustal addition throughout the entire Palaeozoic era for the present-day south-central Andes. We combine the Hf data with published U–Pb ages from the same grains (Adams *et al.*, 2008, 2011; Willner *et al.*, 2008; Augustsson *et al.*, 2011, 2015).

Geological framework: crustal growth of South America

During the Palaeoproterozoic Transamazonian Orogeny (2.25–1.8 Ga), zircon formed within amalgamated Archaean cratons, in the Río Apa and the Río de la Plata cratons (Fig. 1; Tassinari and Macambira, 1999; Rapela *et al.*, 2007; Cordani *et al.*, 2009). Further Palaeoproterozoic and Mesoproterozoic orogenic activity at 1.8–1.3 Ga was followed by late Mesoproterozoic to early Neoproterozoic Grenville-age processes (1.2–0.9 Ga) that

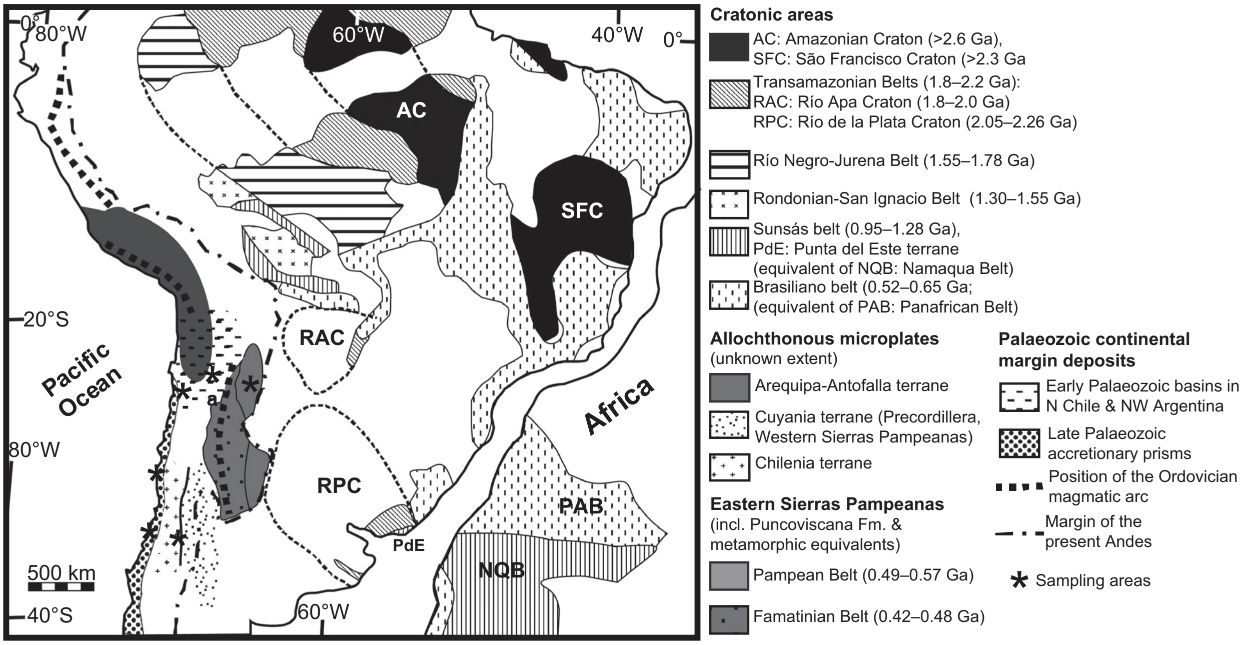

Fig. 1 Compilation of tectonic environments in central South America (with present-day longitudes and latitudes for South America) based on de Wit *et al.* (1988), including information from Tassinari and Macambira (1999), Cordani *et al.* (2009) and Ramos (2009).

are represented in the allochthonous Arequipa Massif, the Sunsás Belt, the Western Sierras Pampeanas, and the Punta del Este Terrane (Fig. 1; Tassinari and Macambira, 1999; Basei *et al.*, 2000; Martignole and Martelat, 2003; Casquet *et al.*, 2005; Chew *et al.*, 2007; Cordani *et al.*, 2009). Western Gondwanan amalgamation of the Brazilian Craton ended with the Cryogenian–Early Palaeozoic Brasiliano Orogeny at *c*. 650–520 Ma (Basei *et al.*, 2000) partly concomitant with the break-up of Rodinia (Dalziel, 1997).

Extensive Ediacaran to early Cambrian turbiditic sediment (Puncoviscana Formation and equivalents; Table 1) was deposited on the palaeo-continental margin in northwestern Argentina, continuously accreted during the Pampean Orogeny at *c*. 570 to *c*. 520–490 Ma (Ježek *et al.*, 1985; Willner *et al.*, 1987; Rapela *et al.*, 1998), and partly incorporated in a magmatic arc (Rapela, 2000; Escayola *et al.*, 2011). Younger, Cambrian to Permian, deposits (Table 1) were transported dominantly from the Eastern Sierras Pampeanas and other areas affected by time-equivalent processes and the Ordovician Famatinian Orogeny (*c*. 510–490 Ma to *c*. 460 Ma; e.g. Pankhurst *et al.*, 1998; Augustsson *et al.*, 2011, 2015), which is part of an extensive magmatic arc along major parts of Andean South America (Pankhurst *et al.*, 2006; Chew *et al.*, 2007; Horton *et al.*, 2010). The Famatinian arc, exposed at mid-crustal level, had excess crustal thickness comparable to that of the present-day central Andes (Lucassen and Franz, 2005; de los Hoyos *et al.*, 2011). Magmatism ceased during Silurian to Devonian time in northern Chile (Bahlburg and Hervé, 1997).

The allochthonous Cuyania Terrane, exposed in the Argentine Precordillera (Fig. 1), collided with South America at 29–36°S during Middle Ordovician time (*c*. 472–455 Ma; Casquet *et al.*, 2001; Ramos, 2009; Mulcahy *et al.*, 2011; van Staal *et al.*, 2011; Garber *et al.*, 2014). Continental collision zones with high-pressure metamorphism are present on the eastern and western flanks of the terrane (Davis *et al.*, 1999; Casquet *et al.*, 2001; van Staal *et al.*, 2011; Willner *et al.*, 2011; Garber *et al.*, 2014). The western flank represents a Devonian (*c*. 390 Ma; Willner *et al.*, 2011) collision zone with the Chilenia terrane (Fig. 1; Ramos *et al.*, 1986). Continuous accretion and arc development in central and northern Chile reoccurred at *c*. 320–220 Ma (Willner *et al.*, 2005).

Results: Hf-isotope compositions

Most Archaean grains have $\varepsilon_{Hf}(t)$ of −10 to +5. An oldest Palaeoproterozoic igneous phase of approximately Transamazonian age (*c*. 2.2–1.7 Ga) and a Mesoproterozoic (*c*. 1.6–1.3 Ga) igneous phase mainly include zircon with $\varepsilon_{Hf}(t)$ of −15 to +10 (Mp1, Mp2 in Fig. 2), with the highest values corresponding to the depleted mantle (ε_{Hf} = 0 at 4.07 Ga and +14 today). Late Mesoproterozoic to early Neoproterozoic (*c*. 1.2–0.9 Ga; Mp3) and Cryogenian to Cambrian (0.8–0.5 Ga; Mp4) phases are proven by zircon with $\varepsilon_{Hf}(t)$ of −20 to +10 (Mp3, Mp4; Fig. 2, 3). A fifth igneous phase is late Cambrian to Silurian (*c*. 500–400 Ma) with main $\varepsilon_{Hf}(t)$ of −10 to +5 and a few grains with values down to −20 (Mp5; Figs 2 and 3). The youngest magmatic phase (Mp6) similarly is represented by zircon with main ε_{Hf}(t) of −10 to +5 for grains of 400–350 Ma age but with $\varepsilon_{Hf}(t)$ of −5 to +5 for younger zircon (Fig. 3). All data are part of the same Hf-isotope compositional trends, irrespec-

Table 1 Descriptions of the studied units.

Geological unit	Depositional age	Dating objects	Depositional setting	Ref.	Sampled lithology
Puncoviscana Fm	Ediacaran to Early Cambrian	Trace fossils, detrital zircon	Turbiditic	1	Metagreywacke
Guarguaráz Complex	Late Ediacaran to Early Palaeozoic	Detrital zircon	Marine, passive margin	2, 3	Garnet mica schist
Mesón Group	Mainly Middle Cambrian	Acritarchs in overlying strata, detrital zircon	Shallow-marine, tidal	4	Quartz arenite
CISL	Early Ordovician	Zircon in lava	Marine, turbiditic, forearc to intra arc	5	Greywacke
Puna Turbidite Complex: Lower Turbidite System	Middle Ordovician	Graptolites	Deep-marine, turbiditic, retro arc	6	Greywacke
Salar del Rincón Fm	Latest Ordovician to earliest Silurian	Spores, brachiopods	Shallow-marine	7, 8	Arenite
Quebrada Ancha Fm	Latest Ordovician to early Silurian	Brachiopods	Shallow-marine, sub-tidal	9	Red arenite
Zapla Formation, upper Mbr	Early Silurian	Chitinozoans	Fluvial channels of coastal alluvial fans	10, 11	Arenite
Lipeón Fm	Early to late Silurian	Chitinozoans, bivalves	Shallow-marine, sub-tidal	10, 12	Quartz arenite
Sierra del Tigre Fm	Devonian	Brachiopods	Open-marine, turbiditic	13, 14	Greywacke
Zorritas Fm, Lower Mbr	Middle Devonian	Brachiopods	Shallow-marine, tidal	15, 16	Quartz arenite
El Toco Fm	Late Devonian	Plants	Deep-marine shelf, turbiditic	14, 17	Arenite
Sierra Argomedo Fm	Late Devonian to Early Carboniferous	Detrital zircon, bivalves, intrusion	Shallow-marine, shoreface	18	Arenite
Zorritas Fm, Upper Mbr	Early Carboniferous	Brachiopods	Marine, deltaic distributary channels	15, 19	Quartz arenite
Cerro Oscuro Fm	Late Carboniferous	Plants	Braided river, retro arc	7, 20	Arenite
Arrayán Fm	Early Carboniferous	Detrital zircon	Distal submarine fan, turbiditic	3, 21	Fine-grained metagreywacke
Western Series	Carboniferous	Detrital zircon, mica	Marine, turbiditic	3, 22	Metagreywacke
Eastern Series	Carboniferous	Detrital zircon, mica	Marine, turbiditic	3, 22	Metagreywacke
Agua Dulce Metaturbidite	Carboniferous	Detrital zircon	Distal submarine fan	3, 21	Fine-grained metagreywacke
Choapa Complex	Late Late Carboniferous	Detrital zircon	Turbiditic	3, 23	Metagreywacke
Cerro de Cuevitas Fm	Late Late Carboniferous to early Permian	Invertebrates	Shallow-marine, coastal	13	Arenite

CISL is the Cordón de Lila Igneous and Sedimentary Complex. References: (1) Ježek *et al.* (1985), Durand (1993), Adams *et al.* (2008); (2) López and Gregori (2004); (3) Willner *et al.* (2008); (4) Moya (1998), Rubinstein *et al.* (2003), Augustsson *et al.* (2011); (5) Niemeyer (1989), Zimmermann *et al.* (2010); (6) Bahlburg (1990), Bahlburg *et al.* (1990); (7) Donato and Vergani (1985); (8) Benedetto and Sánchez (1990), Rubinstein and Vaccari (2004); (9) Navarro *et al.* (2006), Niemeyer *et al.* (2010); (10) Grahn and Gutiérrez (2001); (11) Moya and Monteros (1999); (12) Andreis *et al.* (1982), Malanca *et al.* (2010); (13) Niemeyer *et al.* (1997a); (14) Bahlburg and Breitkreuz (1993); (15) Niemeyer *et al.* (1997b); (16) Boucot *et al.* (2008); (17) Moisan *et al.* (2011); (18) Breitkreuz (1985), Augustsson *et al.* (2015); (19) Isaacson and Dutro (1999); (20) Galli *et al.* (2010); (21) Rebolledo and Charrier (1994); (22) Hervé (1988), Willner *et al.* (2005); (23) Charrier *et al.* (2007).

tive of origin along the Palaeozoic Gondwana margin.

The Hf-isotope compositions follow three crustal evolution paths, representing zircon with similar model ages (Fig. 2). They are separated by gaps, particularly in juvenile zircon distribution. Mainly Archaean and Palaeoproterozoic zircon has comparable Palaeoarchaean to Mesoarchaean model ages (T_{DM} = *c.* 3.3–2.8 Ga). A second crustal evolution path, with Palaeoproterozoic, approximately Transamazonian, model ages (T_{DM} = *c.* 2.5–1.8 Ga), includes the main Palaeoproterozoic to early Mesoproterozoic cluster and some of the late Mesoproterozoic to Palaeozoic grains (Fig. 2). The third crustal evolution path (Figs 2 and 3), with Mesoproterozoic to Neoproterozoic model ages (T_{DM} = *c.* 1.6–0.8 Ga), includes the main groups of late Mesoproterozoic and younger ages. The four oldest model ages are 3.8–4.0 Ga, deriving from 3.4 to 3.1 Ga zircon.

The oldest preserved zircon and crust in South America

The rareness of Archaean zircon is due to massive dilution by younger zircon. Additional Hf-isotope data from zircon of South American provenance are similar to our data, with evolved to juvenile signatures and crustal residence ages of up to *c.* 4.0 Ga, proving Palaeoarchean crustal evolution for the first time (Fig. 4). This trend is consistent with data from an Amazonian granitoid, where ages for the oldest zircon crystals of 3.7–3.2 Ga and Sm–Nd model ages of 3.5 Ga are also reflected in modern Amazon River sand (Cordani and Sato, 1999; Tassinari and Macambira, 1999; Iizuka *et al.*, 2010). Hence, there is no evidence for crust older than about 4.0–3.7 Ga in the Amazonian craton.

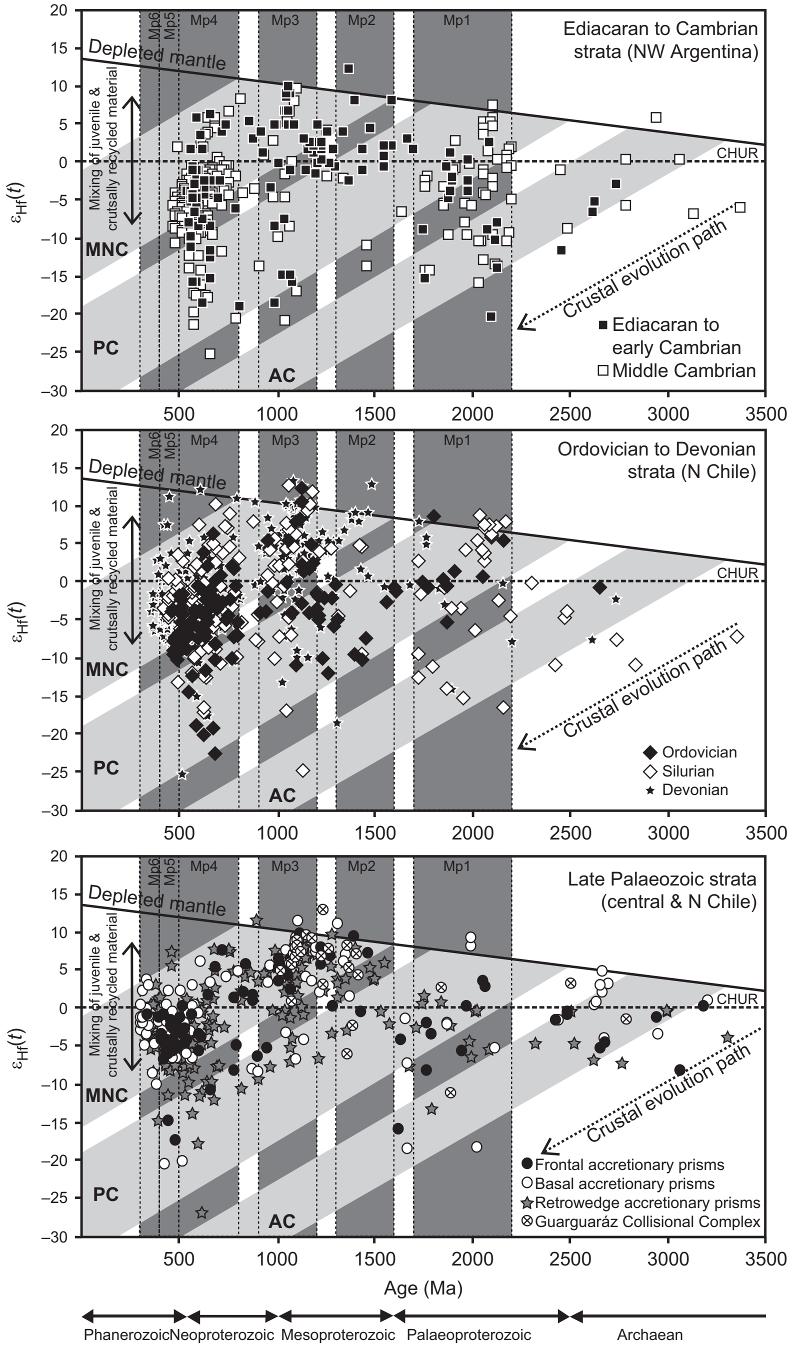

Fig. 2 $\varepsilon_{Hf}(t)$ vs. age for detrital zircon including both data from this study and recalculated data from Willner *et al.* (2008), Bahlburg *et al.* (2009), Hauser *et al.* (2011) and Hervé *et al.* (2013). 2σ errors are equal to or smaller than the symbol sizes. Note the similarity of data in the sub-figures and that the data from the Guarguaráz Complex, representing Chilenia, fall in the same crustal evolution paths as the data from the other units. The dark grey bars refer to the age intervals of the igneous phases Mp1 to Mp6 and involve time-equivalent formation of zircon from juvenile, crustally reworked and mixed material in magmatic arcs. All our Hf data were obtained with a LA-ICPMS at the Institut für Geowissenschaften of the Johann Wolfgang Goethe-Universität Frankfurt (Germany) following the method of Gerdes and Zeh (2009). The settings are identical to those in Willner *et al.* (2014). See the Supporting Information for further sample and standard information and for the standard isotope values used for the calculations. Light grey areas represent crustal evolution trends of zircon with similar model ages that might originate from common crustal domains. Particularly juvenile and the most crustal zircon was used to define the trends together with the isotopic evolution of the crust. Zircon from mixed sources has intermediate $\varepsilon_{Hf}(t)$ values, giving it meaningless model ages. AC, Archaean crust; PC, Palaeoproterozoic (Transamazonian-age) crust; MNC, Mesoproterozoic to Neoproterozoic crust; CHUR, chondritic uniform reservoir.

Detrital zircon of 3.6–3.1 Ga age has consistently been observed in Archaean and Proterozoic strata of southern Africa, Western Australia and Antarctica (compilation by Zeh *et al.*, 2008). Together with our data, these populations follow an Eoarchaean to Palaeoarchean crustal evolution path (Fig. 4) similar to that of average modern-day continental crust and to those of mixing trends (Zeh *et al.*, 2008, 2011). The Archaean path originates at *c.* 4.0 Ga, near the intersection for the depleted mantle and the chondritic uniform reservoir, and thus represents the oldest continental crust preserved on Earth. Any continental crust formed before 4 Ga, also from South America, is assumed to be completely recycled into the mantle (Zeh *et al.*, 2008, 2011; this study).

Palaeoproterozoic to early Mesoproterozoic evolution

The two major Proterozoic episodes of juvenile magma production, represented as model ages at 2.5–1.8 Ga and 1.6–0.8 Ga (Fig. 2), reflect the known formation of juvenile crust during the Transamazonian Orogeny (2.25–1.8 Ga) in continental magmatic arcs, during rift phases in the Central Amazonian Craton at 1.95–1.6 Ga, in magmatic arcs during the Rondonian–San Ignácio Orogeny (1.5–1.3 Ga), and during rifting at 1.4–1.2 Ga in areas affected by the Rio Negro–Jurmena Orogeny (Cordani and Sato, 1999; Tassinari and

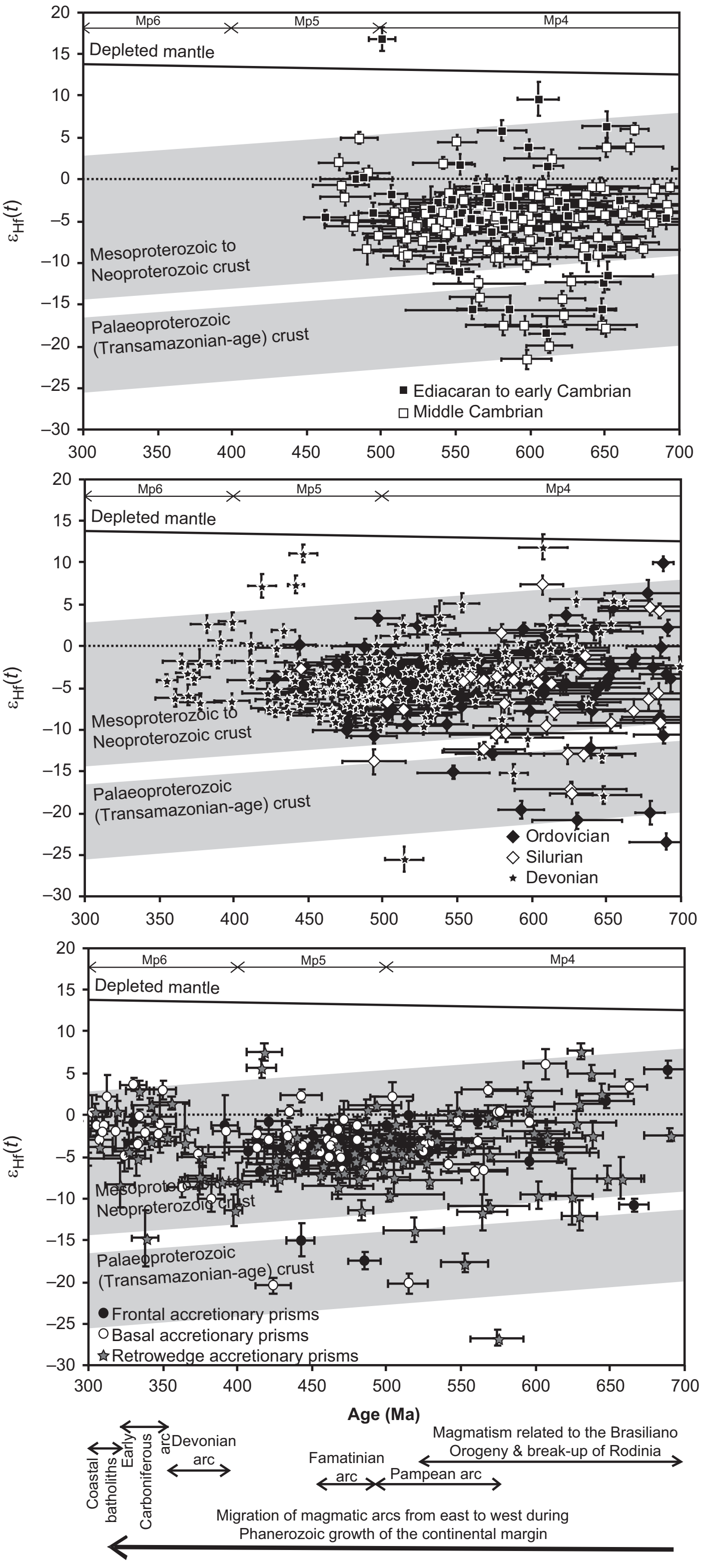

Fig. 3 $\varepsilon_{Hf}(t)$ vs. age for detrital zircon <0.7 Ga including 2σ error bars (partial amplification from Fig. 2). The timing of magmatic arcs, which continuously contributed to the Phanerozoic growth of the continent, is included. Grey fields are crustal evolution trends. Igneous phases (Mp) are the same as those in Fig. 2. See Fig. 2 for references.

Macambira, 1999; Cordani *et al.*, 2009). The two pronounced igneous mixing phases of juvenile and reworked crust at 2.2–1.7 Ga and 1.6–1.3 Ga (Mp 1 and Mp 2 in Fig. 2) correspond to calc-alkaline arc magmatism in the Central Amazonian craton during the Transamazonian, Rio Negro–Jurmena and Rondonian–San Ignácio (1.50–1.30 Ga) orogenies (Cordani and Sato, 1999; Tassinari and Macambira, 1999; Cordani *et al.*, 2009). Tassinari and Macambira (1999) reported an age minimum at 2.4–2.0 Ga in the Central Amazonian Craton that is also seen in our data (Fig. 2). During the two igneous phases, Archean and Transamazonian crust, respectively, was reworked. They are also represented by detrital zircon from the Guarguaráz Collisional Complex, likely part of Chilenia (Fig. 2, Table 1; Willner *et al.*, 2008).

The late Mesoproterozoic to early Neoproterozoic (Grenville-age) phase

Grenville-age (1.2–0.9 Ga) detrital zircon is widespread in Ediacaran to Palaeozoic strata along the Andean continental margin at least from southern Patagonia to Colombia (e.g. Augustsson *et al.*, 2006, 2015; Adams *et al.*, 2008; Horton *et al.*, 2010; Reimann *et al.*, 2010), despite present-day fragmentary exposures of Grenville-age basement in the Sunsás Belt, the Western Sierras Pampeanas (partly related to Cuyania), the Arequipa–Antofalla Massif and the Punta del Este Terrane (Fig. 1). Our similarly aged zircon with positive $\varepsilon_{Hf}(t)$ is consistent with major juvenile input at *c.* 1.6–0.8 Ga and later crustal reworking (Mp3 in Fig. 2), in contrast to more evolved zircon with Palaeoproterozoic (Transamazonian) crustal evolution. Juvenile Grenville-age zircon is also present in the Guarguaráz Collisional Complex (Fig. 2; Willner *et al.*, 2008).

Amphibolite with a juvenile Nd-isotope composition in the Western Sierras Pampeanas represents mantle input (Kay *et al.*, 1996). Hence, the Hf-isotope signature from detrital zircon cannot be used to distinguish a different provenance for

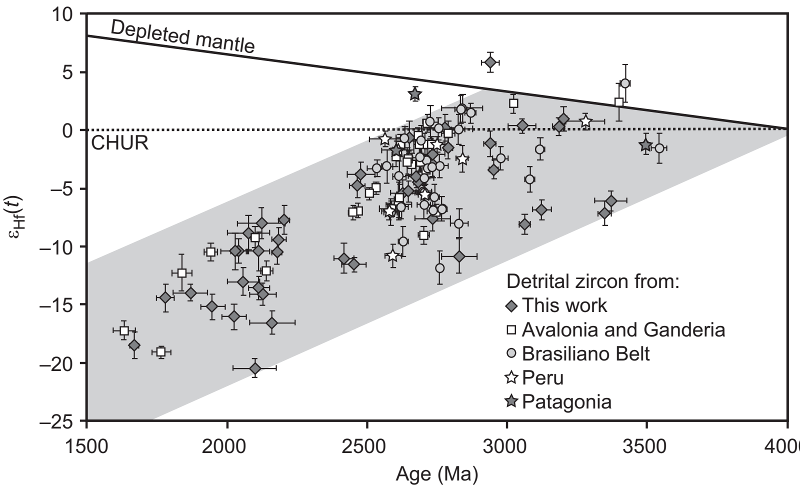

Fig. 4 $\varepsilon_{Hf}(t)$ vs. age for detrital zircon of South American provenance with crustal residence ages >2.9 Ga (2σ error bars included). A Palaeoarchaean crustal evolution trend is shown in grey. Also included are data from the microcontinents Ganderia and Avalonia, which separated from Amazonia (Willner *et al.*, 2013, 2014), data from the Brasiliano Belt (Matteini *et al.*, 2012; Rodrigues *et al.*, 2012) and data from Palaeozoic deposits from Peru (Reimann *et al.*, 2010) and Patagonia (Augustsson *et al.*, 2006). Data are represented by recalculated values for concordant ages (90–110%). Equivalent Eoarchaean to Palaeoarchaean trends are known from southern Africa, Western Australia and Antarctica (Zeh *et al.*, 2008, 2011). CHUR = chondritic uniform reservoir.

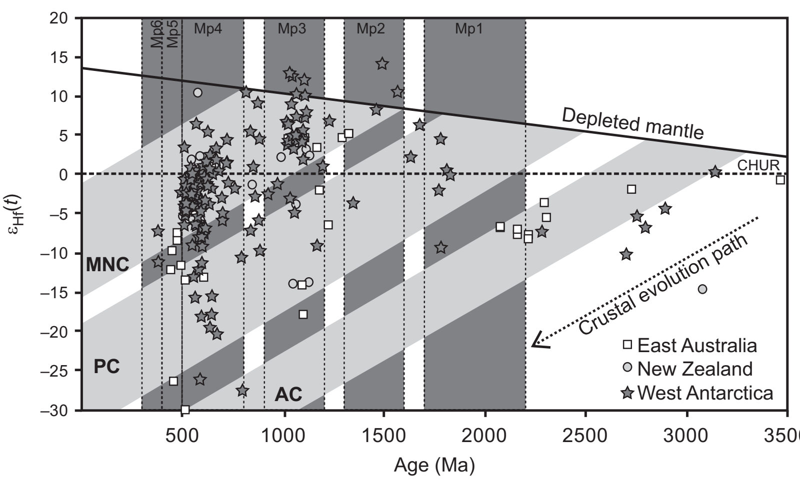

Fig. 5 $\varepsilon_{Hf}(t)$ vs. age for detrital zircon from Early Palaeozoic deposits in other Gondwana-margin areas, with data from West Antarctica (Flowerdew *et al.*, 2007), East Australia (Kemp *et al.*, 2006) and New Zealand (Nebel-Jacobsen *et al.*, 2005, 2011). Igneous phases and crustal evolution paths for South America are given for comparison. See Fig. 2 for abbreviations.

South America and the Cuyania and Chilenia terranes. More likely, a similar Grenville-age basement with both juvenile and more evolved components underlies the palaeo-margin of South America and both microcontinents. Widespread Grenville-age zircon in Ediacaran to early Cambrian strata requires an extensive Grenville-age igneous belt further east. Considering that the convergent margin of the Ordovician Famatinian Arc had excess crustal thickness (Lucassen and Franz, 2005; de los Hoyos *et al.*, 2011), the older deposits were likely thrust to the east over the adjacent Grenville-age belt. This situation is similar to that of the present Andean crust. Comparable Hf-isotope compositions are present for Grenville-age zircon of early Palaeozoic strata from the eastern Laurentia margin (Willner *et al.*, 2014).

Ediacaran to Carboniferous evolution

Igneous bodies related to the early Cambrian Pampean Orogeny in northwestern Argentina intruded the Ediacaran to early Cambrian deposits. Crustal reworking from these and detritus related to magmatic activity during the Brasiliano Orogeny (650–520 Ma; Mp4 in Figs 2 and 3), related to the break-up of Rodinia, is corroborated by crystallisation from late Mesoproterozoic to early Neoproterozoic, Grenville-age, crustal melt (recalculated Hf data, Hauser *et al.*, 2011). The studied Ordovician to Permian basins (Table 1) were mainly fed from the (active to extinct) Ordovician arc (Mp5, Fig. 2), either directly or through sedimentary recycling (Augustsson *et al.*, 2015). Our data indicate that this arc mainly formed from Grenville-age crust, implying that it developed above Famatinian thickened crust. Throughout the Palaeozoic era, Palaeozoic-age zircon derived from Grenville-age crust material, as indicated by the corresponding model ages (Fig. 2). Apparently Transamazonian crust was no longer available for crustal reworking along the palaeo-margin of Gondwana. Comparable Hf-isotope compositions also exist for early Palaeozoic strata from the New Zealand, Australia and Antarctica parts of the Gondwana margin (Fig. 5), indicating that Gondwana-assembly magmatism mainly involved recycled crust.

The Carboniferous to Permian arcs (Mp6 in Fig. 2) were crustally reworked from the same Grenville-age material. The somewhat higher $\varepsilon_{Hf}(t)$ for zircon <350 Ma than for older grains indicates mixing with mantle material, during which most Hf derived from the reworked crust. Arc magmatism had started by Early Carboniferous time (Willner *et al.*, 2008; Bahlburg *et al.*, 2009; Hervé *et al.*, 2014). The igneous bodies likely originated on Chilenia crust because of their occurrence west of its suture with Cuyania. If this arc was situated on Chilenia, then Chilenia must have been underlain by Grenville-age crust. After accretion, Cuyania and Chilenia were overlain by Palaeozoic strata (e.g. Gleason *et al.*, 2007; Bahlburg *et al.*, 2009) and likely added little detrital zircon.

Conclusions

The uniform Hf-isotope signature of detrital zircon in basins that evolved at the Pacific margin of South America during Ediacaran to Permian time records almost the entire crustal evolution of the continent. This further proves mainly South American sources. Our combined Archaean data stress a Palaeoarchaean crustal evolution, which concurs with the trends observed by Zeh *et al.* (2008, 2011), adding weight to the idea of complete recycling of existing continental crust on Earth around 4 Ga.

Formation of Proterozoic crust, reflected by zircon with positive $\varepsilon_{Hf}(t)$ and respective crustal evolution trends, concurs with data from the interior of the Amazonian Craton. Archaean crust was reworked during the Palaeoproterozoic Transamazonian igneous phase. This material in turn was partly reworked during the late Mesoproterozoic to early Neoproterozoic Grenville-age and Cryogenian to early Cambrian Brasiliano phases, and the Grenville-age material was reworked during Palaeozoic arc activity.

Grenville-age crust can be postulated to have underlain the Ediacaran–Cambrian palaeo-margin of South America as well as the microcontinents Cuyania and Chilenia. Laurentia and Gondwana were originally combined along the Grenville belt within the Rodina supercontinent. They also separated along this belt at around 700 Ma (or during the Pampean Orogeny; Casquet *et al.*, 2012), leaving several intermediate microplates behind, which partly have re-collided with South America (e.g. Dalziel, 1997; Ramos, 2010). Hence, both Gondwana-affinity and Grenville-belt-affinity zircon was deposited along the Palaeozoic continental margin.

A thickened crust under the Ordovician Famatinian Belt with slow exhumation until Carboniferous time (de los Hoyos *et al.*, 2011) is likely responsible for the remarkably similar detrital zircon input over 300 Ma during the Palaeozoic era, as reflected by our data (see also Augustsson *et al.*, 2015). This means that the main detrital zircon input from the Brazilian shield was mainly sedimentary recycled during erosion and exhumation of the Famatinian belt. Hence, the pre-Andean continental margin was a site of continuous continental growth with more crustal recycling than juvenile addition.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Hf-isotope data for detrital zircon (this study).

Table S2. Mean values for standard zircon on measuring dates (see footnote in Table S1).

Table S3. Hf-isotope data for detrital zircon from the literature.

Table S4. Hf-isotope data for detrital zircon from other continents from the literature. Only data for zircon ages with 90–110% concordance are listed and used.