Triassic to Neogene evolution of the south-central Andean arc determined by detrital zircon U-Pb and Hf analysis of Neuquén Basin strata, central Argentina (34°S–40°S)

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ABSTRACT

The Andes Mountains provide an ideal natural laboratory to analyze the relationship between the tectonic evolution of a subduction margin, basin morphology, and volcanic activity. Magmatic output rates in Cordilleran-style orogenic systems vary through time and are characterized by high-flux magmatic events alternating with periods of low or no activity. The Neuquén Basin (34°S–40°S) of south-central Argentina is in a retroarc position and provides a geological record of sedimentation in variable tectonic settings. Strata ranging in age from Middle Jurassic to Neogene were sampled and analyzed to determine their detrital zircon U-Pb age spectra and Hf isotopic composition. When all detrital zircon data are combined, results indicate that significant pulses in magmatic activity occurred from 190 to 145 Ma, and at 129 Ma, 110 Ma, 67 Ma, 52 Ma, 16 Ma, and 7 Ma. The eHf values were highly evolved when the arc initiated at 190 Ma and transitioned into intermediate and juvenile values between ca. 160 and 150 Ma. There was a large shift toward more juvenile Hf isotopic values at 16 Ma that is consistent with renewed extension in the backarc during the Neogene. Overall geochemical trends in the Neuquén Basin section of the Andean arc are different from those observed in the central (21°S–26°S) and southern Andean arc (41°S–46°S), suggesting a segmented margin with variable tectonic settings and arc processes controlling magmatic output and chemistry along strike.

INTRODUCTION

Retroarc basins in Cordilleran-style orogenic systems provide an archive of varying tectonic regimes and accompanying arc-related processes. The Andean magmatic arc of central Chile and Argentina has been active since at least 190 Ma (Hervé et al., 1988; Franzese et al., 2003) with variable volcanic output caused by changing tectonic regimes, including extension from the Late Triassic to Late Cretaceous (Sagripanti et al., 2013), contraction from the Late Cretaceous to Eocene (Tunik et al., 2010; Di Giulio et al., 2012), and variable extension and contraction along strike in the late Paleogene to Neogene (Ramos and Kay, 2006). The Neuquén Basin (34°S–40°S) is in a retroarc position and provides a stratigraphic sequence ranging in age from the Late Triassic to Neogene (Howell et al., 2005) and thus preserves a detrital record of arc activity during variable tectonic conditions.

The detrital zircon U-Pb signatures from strata in retroarc basins closely resemble the age distribution produced through in situ sampling of intermediate and felsic volcanic and plutonic units, specifically when it comes to identification of high-flux magmatic events (Kay et al., 2005; Ducea et al., 2015; Paterson and Ducea, 2015). Furthermore, plutonic units of varying compositions and depths within arc complexes also show the same major age populations as those recorded in detrital studies (Ducea et al., 2015). Zircons are dominantly found in intermediate and felsic igneous rock, meaning that mafic units, especially mafic volcanic units, will be underrepresented in the zircon record. However, even though there may be mafic volcanism during magmatic lulls (i.e., lulls in zircons) those times do not seem to be significant to the overall volumetric additions to the arc that are well recorded in the detrital zircon patterns (Ducea et al., 2015; Paterson and Ducea, 2015). Changes in arc magmatic behavior (i.e., high-flux events and lulls) and geochemistry have been correlated with regional shortening, crustal thickening, flat-slab subduction, and lithospheric removal (Kay et al., 2005; Cembrano and Lara 2009; DeCelles et al., 2009, 2015; Ducea et al., 2015; Paterson and Ducea, 2015). The Hf isotopic composition of detrital zircons records crustal-scale processes of addition, removal, and recycling of crust: zircons with positive εHf similar to the depleted mantle originate from juvenile crust, whereas zircons with negative εHf crystallize from melts derived from old recycled crust (e.g., Hildreth and Moorbath, 1988). By combining detrital zircon Hf and U-Pb analyses we can assess timing and periodicity of high-flux events as well as their relationship to the input of juvenile material throughout the arc’s history.

Studies of arc behavior and chemistry from the central Andes (21°S–26°S; Haschke et al., 2002, 2006, and references therein) show an eastward migration of the volcanic arc from 200 Ma to present. Periods of regional shortening and crustal thickening in northern Argentina

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and southern Bolivia correlate with high-flux events and periods of lithospheric removal (DeCelles et al., 2009, 2015). According to these models, the underthrusting of continental lower crust and mantle lithosphere under the arc produces periodic high-flux magmatism characterized by more evolved isotopic compositions because of melting of crustal material (Ducaea, 2001; Haschke et al., 2002).

In the southern Andes of Chile (41°S–46°S) the volcanic arc was relatively stationary from 190 to 120 Ma (Haschke et al., 2006); a pronounced eastward migration of the arc occurred between 120 and 75 Ma (Folguera and Ramos, 2011; Gianni et al., 2015; Orts et al., 2015; Echaurren et al., 2016). Between 50 and 28 Ma there was a widening event in the magmatic arc that has been related to trench retreat (Haschke et al., 2006). The arc narrowed again between 28 and 8 Ma, was inactive from 8 to 3 Ma, and volcanism from the Pliocene to the present is concentrated in a narrow zone (Herve et al., 1988; Haschke et al., 2006). Initial Sr and Nd isotopes between 200 and 20 Ma evolved from crust-like to mantle-like ratios, with a reversal at 20 Ma to more diffuse and crust-like ratios (Haschke et al., 2006).

Compared to the central Andes, the southern Andes are topographically lower, and have thinner crust (Intocasco et al., 1992; Ramos, 2004). Insofar as orogenic growth is driven by the process of continental underthrusting, which in turn controls high-flux events in the magmatic arc, the prediction would be that longer arc cycles and less evolved isotopic signatures should characterize the southern Andes (e.g., Hildreth and Moorbath, 1988; McMillan et al., 1989; Kay et al., 1991; Kay and Mpodozis, 2001).

In order to assess arc behavior through time and its relations with orogenic scale processes, I sampled and analyzed Middle Jurassic to Neogene strata from the Neuquén Basin to determine detrital zircon U-Pb age spectra and Hf isotopic compositions. The goals of this study are to (1) identify the geochronologic and geochemical markers associated with variable tectonic regimes in a Cordilleran-style volcanic arc by comparing and analyzing the retroarc basin detrital record; and (2) evaluate the detrital record of magmatism along strike by comparing the Neuquén Andes (34°S–40°S) with the central (21°S–26°S) and southern (41°S–46°S) Andes.

**GEOLOGIC SETTING AND STRATIGRAPHY**

The Neuquén Basin is located in a retroarc position and is characterized by a variable tectonic history, including (1) extension during the Late Triassic–Middle Jurassic as manifested by isolated rift basins (Franzese et al., 2006; Franzese and Spalletti, 2001); (2) a Middle Jurassic–Early Cretaceous backarc basin (Spalletti and Franzese, 2000; Howell et al., 2005); (3) a Late Cretaceous (95 Ma) to Eocene retroarc foreland basin (Vergani et al., 1995; Howell et al., 2005; Tunik et al., 2010; Di Giulio et al., 2012, 2016; Balgord and Carrapa, 2016; Fennell et al., 2015); and (4) variable extension and contraction along the length of the Neuquén Basin with extension dominant from 28 to 18 Ma (Spagnuolo et al., 2012), shortening from 17 to 6 Ma (Silvestro and Atencio, 2009), and extension from 6 Ma to present (Ramos and Kay, 2006, and references therein).

**Crustal Assembly and Geochemistry**

The Chilenia, Cuyania, Pampia, and Patagonia terranes compose the basement of the Neuquén Basin, and were accreted onto the Rio de la Plata craton on the southwestern margin of Gondwana during the Neoproterozoic and early Paleozoic (Fig. 1; Ramos, 2010).

Willner et al. (2008) and Lucassen et al. (2004) identified three episodes of juvenile crustal development in southern Gondwana during the Precambrian: 3.4–2.7 Ga, 2.4–1.9 Ga, and 1.5–0.8 Ga, based on the geochemistry of detrital zircons from the Carboniferous accretionary prism and batholiths in the Mesozoic volcanic arc. During the Paleozoic, zircons from arc-related calc-alkaline magmas were derived from a recycled crustal reservoir of Mesoproterozoic age, probably represented by the Chilenia terrane (Willner et al., 2008). Following the early Paleozoic accretionary events, a magmatic arc and accretionary prism developed along the western and southern margin of Gondwana between 320 and 250 Ma (Hervé et al., 1988; Willner et al., 2005, 2008).

Widespread magmatism associated with orogenic collapse following the early Carboniferous Gondwana orogeny (Ramos, 1984) led to the formation of abundant late Permian to Early Triassic rhyolites and granites known as the Choiyoi igneous complex, volcanism was extension related (Kleiman and Japas, 2009). In some areas the youngest phase of Choiyoi igneous activity was followed by rift-related volcanism related to the opening of the Neuquén Basin (ca. 230 Ma; Howell et al., 2005) that coincided with widespread extension throughout South America during the breakup of Gondwana.

The oldest Mesozoic magmatic rocks in the Coastal Cordillera (Fig. 1) are small-volume Late Triassic granitic batholiths (Hervé et al., 1988) that mark the initiation of subduction along the western margin of South America. Jurassic to recent arc-related volcanic and intrusive rocks are abundant along the Chile-Argentina border (Fig. 1; Rapela and Kay, 1988).

**Stratigraphy**

The middle Jurassic to lower Cretaceous sedimentary units analyzed in this study include the middle Jurassic Las Lajas Formation, the upper Jurassic Lotena and Tordillo Formations, the upper Jurassic to lower Cretaceous Vaca Muerta and Picun Liufu Formations, and the lower Cretaceous Agrio, Huitrín, and Rayoso Formations (Figs. 2 and 3; Howell et al., 2005). Conversely, the upper Cretaceous Neuquén Group in the central Neuquén Basin (Leanza and Hugo, 2001; Leanza et al., 2004), and correlative Diamante Formation (Balgord and Carrapa, 2016) in the northern Neuquén Basin, are dominantly fluviatile and lacustrine in nature. There are minor marine deposits in the Loncoche and Roca Formations of the upper Cretaceous–Paleocene Malargüe Group (Barrió, 1990a, 1990b). The upper Malargüe Group (Pircalla and Coihueco Formations) comprises fluviatile deposits (Figs. 2 and 3; Barrió, 1990a, 1990b). The Tristeza Formation is composed of coarse sandstones and conglomerates derived from the uplifted Mesozoic units to the west that were deposited during active shortening in the late Miocene (Yrioygen, 1993; Silvestro and Atencio, 2009; Sagripanti et al., 2011). The Arroyo Palao Formation is age equivalent, or slightly younger than the Tristeza Formation, but is 100 km south and west, within an active zone of Neogene extension and volcanism (Rovere et al., 2000).

The transition from extension to compression and therefore backarc basin (thermally controlled subsidence) to foreland basin (flexurally controlled subsidence) sedimentation was between 100 and 95 Ma along the length of the Neuquén Basin (Vergani et al., 1995; Howell et al., 2005; Tunik et al., 2010; Di Giulio et al., 2012; Balgord and Carrapa, 2016; Fennell et al., 2015).
Influence of Andean Shortening on Magmatism and Basin Evolution in Argentina

Figure 1. (A) Generalized geologic map of the research area that shows the location of Permian–Triassic, Jurassic, Cretaceous, and latest Cretaceous to Paleogene igneous units as well as Jurassic–Late Cretaceous and Neogene sedimentary units (modified from Sagripanti et al., 2011). (B) Map showing the location of the Neuquén Basin and central and southern Andes segments from Haschke et al. (2006) as well as the location of active volcanoes along the southern Andes. Samples were collected from the following locations: 1—Malargüe Group Hf samples, 2—Arroyo Palao Formation and Tordillo Formation, and 3—Pecun Leufu Formation, Las Lajas Formation, and the Lotena Formation detrital and tuff samples.

Figure 2. Stratigraphic sections from the Neuquén Basin with sampled strata marked with maximum depositional ages (our data and Balgord and Carrapa, 2016). Lithostratigraphy modified from Howell et al. (2005) is based on descriptions from Legarreta and Gulisano (1989) and Legarreta et al. (1991). E—Eocene; O—Oligocene; Fm—formation; Gp—group.
A. Rift Phase (230-210 Ma)

B. Backarc Phase (190-100 Ma)

C. Foreland Phase (100-50 Ma)

D. Mixed Phase (20 Ma-present)

Deep marine sedimentation
Shallow marine sedimentation
Continental sedimentation
Oligocene-early Miocene
Normal fault inverted in the Late Miocene
Active thrust fault

Figure 3. Generalized diagrams depicting the tectonic setting. (A) During active rifting (220–200 Ma). (B) During post-rift thermal subsidence (190–100 Ma). (C) During initial shortening and foreland basin development (100–50 Ma). (D) During mixed extension and contraction (20 Ma–present; Sagripani et al., 2011; Horton and Fuentes, 2016). Major types of sedimentation are shown in various shades of gray and are general over each time period, so they will not accurately show all depositional environments (i.e., continental sedimentation during deposition of the Tordillo, Huitrin, and Rayoso Formations during B, 190–100 Ma, and marine deposition during Malargüe Group deposition during C, 100–50 Ma). The locations for detrital samples used in the combined probability density curves shown in Figures 4 and 5 are depicted with numbers in the various time slices, and references are as follows: 1a—Pecun Leufu Formation, Las Lajas Formation, and the Lotena Formation detrital and tuff samples, this study; 1b—Tordillo Formation, this study; 2—Tordillo Formation, from Naupauer et al. (2015); 1c—Arroyo Palao Formation, this study; 3—Tristeza Formation, from Horton and Fuentes (2016). Samples between 100 and 50 Ma include samples from this study, Balgord and Carrapa (2015). The Neogene tectonic history of the Neuquén Basin is complicated by variable extension and contraction along strike as well as proposed flat-slab subduction north of 38°S between 20 and 5 Ma (Fig. 3; Ramos and Kay, 2006; Litvak et al., 2015).

METHODS

This study presents 419 new U-Pb ages and 207 Hf analyses from detrital zircons in the Neuquén Basin. Samples were taken from a stratigraphic range covering ~160 m.y. from the Middle Jurassic to Miocene (Fig. 2). These new data are combined with published U-Pb detrital zircon data from Balgord and Carrapa (2016), Tunik et al. (2010), Di Giulio et al. (2012), Naupauer et al. (2015), Pepper et al. (2016), and Horton and Fuentes (2016) to create the combined probability density curves (Figs. 3–5).

U-Pb Analytical Methods

U-Pb geochronologic analysis of detrital zircons was conducted by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center (www.laserchron.org) using analytical methods described by Gehrels et al. (2006, 2008) and Gehrels and Pecha (2014). The analyses involve ablation of zircon...
with a Photon Machines Analyte G2 excimer laser using a spot diameter of 30 µm. Cathodoluminescence or backscatter electron images, acquired with a Gatan Chroma CL2 system (www.geosemarizona.org), were used to ensure that analyses were conducted on homogeneous portions of zircon grains.

U-Pb analytical data are reported in Data Repository Tables DR1–DR6. These tables present the isotopic ratios, concentrations, calculated ages, and uncertainties for each analysis. For each analysis, the errors in determining $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{206}\text{Pb}$ result in a measurement error of $-1\%$--$-2\%$ ($2\sigma$) in the $^{206}\text{Pb}/^{238}\text{U}$ age. The errors in measurement of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ also result in $-1\%$--$-2\%$ ($2\sigma$) uncertainty in age for grains that are older than 1.0 Ga, but are substantially larger for younger grains because of the low intensity of the $^{207}\text{Pb}$ signal. For most analyses, the crossover in precision of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages occurs ca. 1.0 Ga. Reported for each analysis is the best age, which is based on $^{206}\text{Pb}/^{238}\text{U}$ for grains younger than 900 Ma and $^{206}\text{Pb}/^{207}\text{Pb}$ for grains older than 900 Ma.

The Data Repository tables do not include analyses that are highly (>20%) discordant or highly (>10%) reverse discordant, and analyses with >10% uncertainty. These filters are not applied to grains with $^{206}\text{Pb}/^{207}\text{Pb}$* ages younger than 600 Ma and $^{206}\text{Pb}/^{204}\text{Pb}$* ages younger than 100 Ma.

Figure 4. Combined probability density functions for all samples (top) retroarc foreland (middle) and backarc (bottom) basin samples. Samples are only shown from 500 Ma to present because there is a lack of older grains in all samples (<15% of total grains).

Figure 5. $^{176}\text{Hf}/^{177}\text{Hf}$ values and U-Pb probability density function for all samples combined from 250 Ma to present. Reference lines on the Hf plot are as follows: depleted mantle (DM), calculated using $^{176}\text{Hf}/^{177}\text{Hf}_{0} = 0.28325$ and $^{176}\text{Lu}/^{177}\text{Hf}_{0} = 0.038512$ (Vervoort and Blichert-Toft, 1999); CHUR—chondritic uniform reservoir, calculated using $^{176}\text{Hf}/^{177}\text{Hf} = 0.282785$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0336$ (Bouvier et al., 2008). Labeled arrow shows interpreted crustal evolution trajectories assuming present-day $^{176}\text{Lu}/^{177}\text{Hf} = 0.0093$ (Vervoort and Patchett, 1996; Vervoort et al., 1999; Bahlburg et al., 2011). Normalized probability density plots are vertically overlaid on the various Hf populations to show their distributions, which are then used to create arrows in Fig. 6. Dark gray lines show the timing of various tectonic events in the Neuquén Basin. U-Pb probability density plot has a vertical access that goes from 0 to 1; magmatic lulls are indicated during periods of time when the curve is below 0.2. FTB—fold-thrust belt.

GSA Data Repository Item 2017170, which contains Tables DR1–DR6: Detrital zircon U-Pb data tables for all new samples analyzed in this study, and Table DR7: Hf data, is available at http://www.geosociety.org/datarepository/2017, or on request from editing@geosociety.org.
Probability density plots were created using the diagrams and routines in Isoplot (Ludwig, 2008). Composite age probability plots are made from an in-house Excel program (see Analysis Tools at www.laserchron.org) that normalizes each curve according to the number of constituent analyses, such that each curve contains the same area, and then stacks the probability curves (Figs. 4 and 5). Maximum depositional ages were calculated by taking the youngest age components, generally three or more grains, that overlap in age within error and calculating a mean and standard deviation taking into account the original uncertainty based on recommendations from Dickinson and Gehrels (2009). Total error was calculated by quadratic addition of random error and systematic error contributions (reported in Fig. 2). Age peaks shown in Figures 1 and 5 and reported in the Results discussion are meant to represent the average age of high-flux magmatic events, which may have long durations and do not necessarily have normal distributions, even though they are listed using averages and standard deviations.

**Hf Analytical Methods**

Hf isotopic analyses were also conducted by LA-VC-ICP-MS (Arizona LaserChron Center) connected to a Photon Machines Analyte G2 excimer laser, using methods described by Cecil et al. (2011) and Gehrels and Pecha (2014), and are reported in Table DR7. Laser ablation analyses were conducted with a laser beam diameter of 40 µm, with ablation pits located on top of or immediately adjacent to the U-Pb analysis pits to ensure that at least initial Hf isotopic data were obtained from the same domain as the U-Pb data. Each acquisition consisted of one 40 s integration on backgrounds (on peaks with no laser firing) followed by 60 integrations of 1 s with the laser firing. Each standard is analyzed once for every ~20 unknowns.

Isotope fractionation is accounted for using the method of Woodhead et al. (2004); δHf is determined from the measured 179Hf/177Hf; δYb is determined from the measured 173Yb/171Yb (except for very low Yb signals); δLu is assumed to be the same as δYb; and an exponential formula is used for fractionation correction (Gehrels and Pecha, 2014). Yb and Lu interferences are corrected by measurement of 176Yb/171Yb and 176Lu/173Lu, respectively, based on methodology from Woodhead et al. (2004). Critical isotope ratios used in data reduction are 179Hf/177Hf = 0.73250 (Patchett and Tatsumoto, 1980); 173Yb/171Yb = 1.132338 (Vervoort et al., 2004); 178Yb/171Yb = 0.901691 (Vervoort et al., 2004); 176Lu/173Lu = 0.02653 (Patchett, 1983); and the decay constant of 176Lu = 1.867e-11 (Scherer et al., 2001; Söderlund et al., 2004). For very low Yb signals, δHf is used for fractionation of Yb isotopes (Gehrels and Pecha, 2014). The corrected 179Hf/177Hf values are filtered for outliers (2σ filter), and the average and standard error are calculated from the resulting ~58 integrations.

Hf data were plotted using the in-house Excel program (see Analysis Tools at www.laserchron.org) that normalizes each curve according to the number of constituent analyses, such that each curve contains the same area, and then stacks the probability curves (Fig. 5) in order to visualize the range of Hf values within various age populations.

**RESULTS**

**U-Pb Age Distributions**

The dominant pre-arc (older than 190 Ma) detrital zircon U-Pb populations in the backarc stratigraphy (strata between 190 and 100 Ma) have age peaks between 260 and 250 Ma and 220 ± 11.3 Ma with smaller populations at 313 Ma and 283 Ma (Fig. 4). The pre-arc populations in the foreland basin stratigraphy are similar, with notably larger 290 Ma and 310 Ma populations and very few grains ca. 220 Ma (Fig. 4).

The combined probability density plots show more or less continuous volcanism from 190 to 140 Ma, followed by major age populations at 128 ± 7 Ma, 108 ± 8.3 Ma, 67 ± 5 Ma, 52 ± 3.8 Ma, and two closely spaced populations with age-distribution peaks at 16 ± 3.5 and 7 ± 1 Ma (Figs. 4 and 5). During the lifetime of the volcanic arc, the 6 main populations exhibit corresponding relative lulls in volcanic activity ranging in duration from 20 to 40 m.y. (Fig. 5). Volcanic hiatuses during backarc deposition range between 10 and 20 m.y., whereas lulls are much longer during the retroarc foreland basin deposition, with a 40 m.y. hiatus between 110 Ma and the first high-flux event after initial shortening at 70 Ma, and another 30 m.y. lull between 50 and 20 Ma (Fig. 5). Overall, fewer than 15% of the grains reviewed in this study are older than 500 Ma (see Tables DR1–DR6 for data).

**Hf Analysis**

Overall the Hf isotopic values derived from the detrital zircons out of Neuquén Basin stratigraphy are relatively juvenile in composition with very few (6 of 207) analyses greater than 20 ε values units away from depleted mantle values.

Grains that crystallized in association with the upper Choiyoi igneous complex (250–240 Ma, n = 12) and Neuquén rifting (ca. 239–190 Ma, n = 56) have Hf values between +5 and −10, relatively evolved compared to most, with an average of 3.5. Grains derived from early arc magmatism (ca. 190–165 Ma) were the most evolved of those studied, with an average εHf value of −3. An abrupt shift of +10 epsilon units toward more juvenile values occurred ca. 160 Ma. Between 100 and 68 Ma there was a general transition toward more evolved Hf values with samples plotting between 1.5 and 8 (31 of 33 grains). The youngest grains analyzed are much more juvenile with most grains (95%, 40 of 42) displaying values within 10 epsilon units of the depleted mantle.

**SUMMARY AND DISCUSSION**

**Migmatic Evolution Recorded by Zircons from Retroarc Basin Strata**

The new data set presented exhibits three major pulses of magmatic activity preceding the Jurassic to modern Andean magmatic arc (Fig. 4): (1) Carboniferous grains related to the pre-Andean subduction margin; (2) grains from the Choiyoi igneous complex, 285 Ma and 265–250 Ma; and (3) 230 and 220 Ma volcanic and plutonic signals associated with rifting of the Neuquén Basin (Fig. 4). Zircons derived from the upper Choiyoi igneous complex and Neuquén rift-related zircons have relatively evolved signatures consistent with the assimilation of older continental crust at that time (Fig. 5). The εHf values increase between 250 and 230 Ma, consistent with addition of juvenile material from continental rifting during initial Neuquén Basin extension (Fig. 5; Franzese et al., 2006; Franzese and Spalletti, 2001). Between the end of Neuquén rifting and the initiation of the Jurassic to modern Andean volcanic arc (ca. 190 Ma) the Hf signature became 5–10 epsilon units more evolved, suggesting progressive melting and reworking of older crust during early subduction (e.g., Hildreth and Mooibath 1988). The εHf values increased by 15–20 epsilon units between 160 and 150 Ma. This shift toward more juvenile values coincided with a high-flux magmatic event at 165 Ma (Fig. 5). The high magmatic output and large influence of juvenile material coincide with extensional tectonism in the volcanic arc (Charrier et al., 2002), which may have also been influenced by a reduction in convergence velocity (Maloney et al., 2013).

There was a change in the length of hiustases from 10 to 20 m.y. during backarc deposition (190 to 100 Ma) to 40 m.y. or more during retroarc foreland basin deposition (Fig. 5). The initiation of shortening in the Neuquén Basin corresponds to a lull in volcanic activity between 100 and 70 Ma that correlates with two proposed ridge subduction events (Maloney et al., 2013), which probably would have caused a prolonged
period of flat-slab subduction (Ramos, 2005; Folguera and Ramos, 2011; Spagnuolo et al., 2012; Fennell et al., 2015) and may therefore explain the lack of zircons of this age preserved within the sampled strata. The second and more pronounced hiatus between 50 and 20 Ma does not seem to correlate with the timing of a proposed flat-slab event, which is thought to have occurred ca. 7 Ma based on volcanism 500 km inboard from the subduction zone during the Miocene north of 38°S (Kay et al., 2006). The ca. 50 to 20 Ma time period correlates with low accumulation rates in the retroarc and either neutral (60–40 Ma) to extensional (40–20 Ma) tectonic regimes at these latitudes (Horton and Fuentes, 2016). It is possible that the magmatic pulse from 70 to 50 Ma corresponds with the end of flat-slab subduction at these latitudes and was followed by relative quiescence due to low convergence velocities (Maloney et al., 2013) and a period of magmatic recharge. Along with magmatic recharge processes, a change to a strike-slip boundary for a period of time can also cause a period of no magmatic activity (Ducea et al., 2015); however, there is no strong evidence for strike-slip movement at that time.

Between 250 Ma and the present, there are three times when Hf values shifted toward more juvenile compositions: 220–230 Ma, ca. 165 Ma, and 20 Ma (Fig. 5); the first two correspond to large-scale extensional events and the third is associated with localized extension in the backarc region. There are two episodes when Hf isotopic values became more evolved, 190 Ma and 110–60 Ma, both of which are associated with compression (Fig. 5).

Comparison Between the Central and Southern Andean Arc

The volcanic arc in the central Andes (21°S–26°S) underwent four eastward shifts between 200 Ma and the present (Haschke et al., 2002; Fig. 5). Each step was characterized by a repeating sequence of magmatism for 30–40 m.y. with increasing crust-like (evolved) isotopic values, followed by magmatic quiescence for 5–12 m.y. (Fig. 6; Haschke et al., 2002). Episodes of magmatic quiescence are interpreted to reflect episodes of flat-slab subduction (Haschke et al., 2006) or magmatic recharge events (DeCelles et al., 2015).

There were only two main phases of shortening at the latitudes of the Neuquén Basin in the Late Cretaceous and Miocene (Yrigoyen, 1993; Manceda and Figueroa, 1995; Silvestro et al., 2005; Zamora Valcarce et al., 2006; Giambiagi et al., 2005, 2008); they correlate directly with the two main magmatic pulses (ca. 70 and 7 Ma; Figs. 3 and 5) during retroarc foreland basin deposition. Zircons between 70 and 60 Ma record more evolved isotopic values, whereas the younger (20–7 Ma) magmatism preserved a significantly more juvenile isotopic signature (Fig. 6). The latter shift toward more juvenile compositions was caused by variable extension from Oligocene to Pliocene that was broken by only a short phase of compression from 11 to 6 Ma. It is difficult to assess isotopic variability at these latitudes during initial shortening (95 Ma) because of the lack of zircons of that age within the foreland strata (Figs. 4 and 5); however, the general trend seems to be toward more negative εHf values between 100 and 70 Ma, consistent with shortening and underthrusting leading to more evolved isotopic values in the volcanic arc.

The geochemical evolution of the southern Andean magmatic arc is distinctly different from what is observed in both the central and Neuquén Basin segments (Fig. 6). Between 150 and 20 Ma the Nd isotopic signature of the southern Andean arc becomes gradually more juvenile (Haschke et al., 2006). There is a switch to more evolved values that begins in the Miocene.

Figure 6. Comparison of chemistry and arc tempo between the Neuquén Basin segment of the Andean arc and the central and southern Andes. Hf isotopic vales from this study are compared to 143Nd/144Nd isotopic values reported by Haschke et al. (2002, 2006) for the central Andes and a compilation of data from Pankhurst et al. (1999), López-Escobar (1984), Muñoz et al. (2000), Lara et al. (2001), Pankhurst et al. (1992), and Pankhurst and Hervé (1994) for the southern Andes. CHUR—chondritic uniform reservoir; DM—depleted mantle.
(Haschke et al., 2006; Fig. 6), coinciding with an episode of shortening in this segment of the Andes (Ramos, 2005).

Overall, the geochemical evolution of the Neuquén Basin segment of the Andes seems to be different from the central and southern Andean segments. The Neuquén Basin segment becomes generally more evolved between 105 and 50 Ma, a trend opposite to what is observed to the south (Fig. 6). This variable behavior may be due to Late Cretaceous shortening along western margin of the Neuquén Basin (Vergani et al., 1995; Tunik et al., 2010; Di Giuli et al., 2012, 2016; Balgord and Carrapa, 2016; Fennell et al., 2015) that is also documented south of 45°S (Fildani et al., 2003), but is earlier (Early Cretaceous) and dominated by thick-skinned deformation much farther (to 500 km) from the trench between 40°S and 45°S (Echaurren et al., 2016; Gianni et al., 2015). The volcanic arc along the western margin of the Neuquén Basin and southern Andean segment has been relatively stationary through time, with only one major eastward shift in the Cretaceous (Echaurren et al., 2016; Gianni et al., 2015), and the fold and thrust belt exhibits significantly less shortening and has much lower topography than what is observed in the central Andes (Kley and Monaldi, 1998). The paucity of shortening, which corresponds with less underthrust crustal material interacting with the volcanic arc, may be what is dampening cyclic isotopic behavior in the arc.

CONCLUSIONS

The detrital record from retroarc basins provides an accessible and effective means to compare arc behaviors in variable tectonic settings. In the Neuquén Basin distinct changes in arc activity chemistry include the following.

1. There is a change in periodicity from ~10–20 m.y. to 40 m.y. or more in high-flux magmatic events following initial shortening that could be caused by either a higher frequency of flat-slab events or longer magmatic recharge during shortening (Figs. 4 and 5).

2. There are two episodes during the arc’s history where Hf isotopic values become more evolved (190 and 100–60 Ma); both are associated with compression (Fig. 5).

3. The three shifts toward more juvenile Hf isotopic values are all related to extension (Fig. 5).

4. Variable isotopic evolution patterns are observed in the central, southern, and Neuquén Andean arc sections, suggesting a segmented margin with variable tectonic settings and arc processes controlling magmatic output and chemistry through time (Fig. 6).

The detrital zircon U-Pb and Hf isotopic record of arc magmatism provides a valuable archive of variable arc and tectonic behavior through time. The well-constrained and relatively consistent tectonic setting and crustal architecture along the length of the Neuquén Basin make it ideally suited to the study of arc-tectonic interactions. However, care must be taken in sampling to ensure that there is consistency in both tectonic setting and crustal architecture along the sampled strike length; otherwise data sets can become difficult to interpret.

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