Detrital zircon provenance from the Neuquén Basin (south-central Andes): Cretaceous geodynamic evolution and sedimentary response in a retroarc-foreland basin

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ABSTRACT

The surface response, in terms of drainage pattern changes, to the Cretaceous geodynamic reorganization of the Andean subduction zone between 36°S and 41°S is reconstructed through the geochronology-based provenance study of alluvial detrital zircons. The age spectra obtained by 500 spot U-Pb ages record an eastward provenance of detritus coming from the foreland during the Early Cretaceous backarc extensional stage, followed by westward-sourced clastics coming from the Cordillera during the Cenomanian. This drainage pattern reversal fits the regional unconformity in the sedimentary record that is linked to the geodynamic reorganization of the continental margin from an extensional to a compressional regime, forcing the Neuquén Basin to evolve from a retroarc to a foreland stage. After this inversion, the clastic systems progressively returned to be mainly fed by the foreland, due to the uplift of the peripheral bulge as a consequence of the Late Cretaceous thrust front migration. This tectonic evolution of the Neuquén Basin and the related response of the drainage pattern are thought to be the surface expression of the dip decrease of the Benioff subduction zone.

INTRODUCTION

Convergent margins are characterized by a tight link between deep lithospheric and shallow geomorphic processes (e.g., Husson, 2006). Along the modern Pacific margin of South America, the connection between segments of shallow-dipping Benioff zones at depth and gaps in the surface arc volcanism is well documented, as well as their link with subsidence in the retroarc region, landward shift of tectonic activity, and foreland thrust faulting (e.g., Jordan et al., 1983).

In the geodynamic evolution of the south-central Andes between 36°S and 41°S, several episodes of advancement and retreat of the volcanic arc, with alternating periods of compression and extension in the backarc region, have been documented (Ramos and Folguera, 2005). These episodes have been interpreted as the results of the repeated increase and decrease of subduction dip, due to changes in the obliquity of the convergence vector relative to the subduction margin (Ramos and Kay, 2006, and references therein; Mosquera and Ramos, 2006).

This paper aims to study the reaction to these lithospheric events of the surface drainage pattern of the Neuquén retroarc-foreland basin. We document this response in the Cretaceous detrital record through U-Pb geochronology of detrital zircons preserved in the Albian–Santonian continental sedimentary sequence.

GEOLOGICAL SETTING AND STRATIGRAPHY

The Neuquén Basin is a complex retroarc-foreland basin that developed along the Andean margin east of the Principal Cordillera between 36°S and 41°S (Fig. 1). Ten kilometers of Triassic to Pliocene sedimentary rocks record ~220 m.y. of subsidence and detrital input from the surrounding Cordilleras and crystalline massifs.

In this study, we focus on an Albian to Campanian clastic continental succession spanning ~15 m.y. from the Albian to Campanian. This succession includes the uppermost formation of the Aptian–Albian Bajada del Agrio Group (Rayoso Formation) and the overlying Cenomanian–Campanian Neuquén Group (Fig. 2).

The Bajada del Agrio and Neuquén Groups are divided by a paraconformity, which becomes an angular unconformity close to the Andean thrust front (Legarreta and Uliana, 1998). This regional surface marks the transition from an extensional to a compressional tectonic regime in the continental margin (Uliana and Biddle, 1988; Leanza and Hugo, 1997).

The formations in the Neuquén Group record the cyclic repetition of braided and meandering river channel facies and fine-grained alluvial plain deposits related to changes in river energy, and discharge may be in response to base level changes (Legarreta and Uliana, 1998). At a larger scale, this cyclic stacking pattern is organized into a fining-upward trend, which

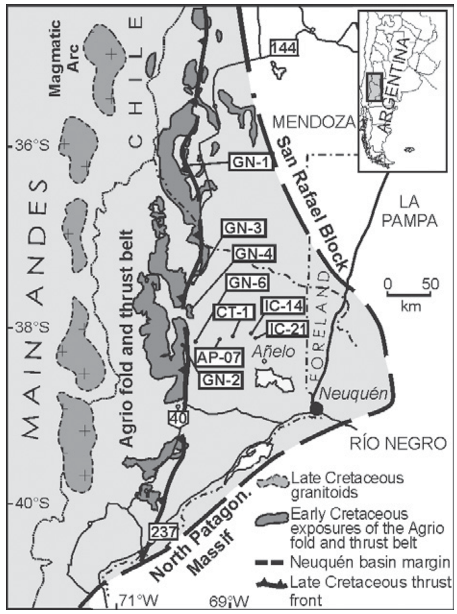

Figure 1. Location map of the Neuquén Basin (south-central Andes), including studied sample locations. Details about sampling localities are reported in the Data Repository (see footnote 1).

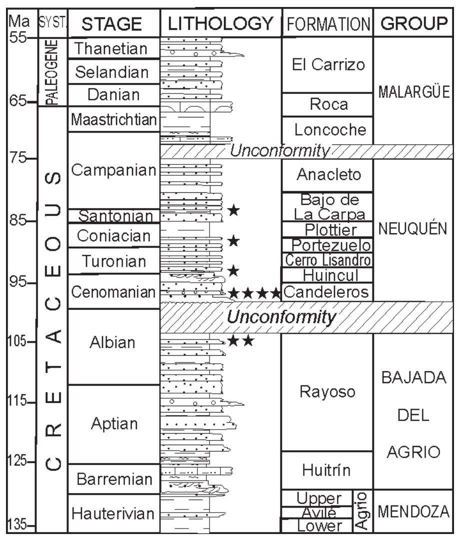

Figure 2. Schematic stratigraphy of the composite studied sections and stratigraphic positions (stars) of the studied samples.

culminates in the first marine transgression (Maastrichtian–Paleocene) from the Atlantic Ocean (Aguirre-Urreta et al., 2008).

Therefore, the Rayoso Formation–Neuquén Group succession provides a nearly continuous record of the clastic input discharged to the Neuquén Basin from the surrounding mountain belts and massifs.

POTENTIAL SOURCES FOR DETRITAL ZIRCONS

The possible detrital sources that could deliver clastic sediment to the Neuquén Basin in Albian to Campanian time are the Main Cordillera to the west, the North Patagonian Massif, and the San Rafael Block, including its southern subsurface extension, to the east (Fig. 1).

Main Cordillera

Scattered outcrops of metamorphic and igneous rocks of the Colohuincul Complex represent the basement of the Patagonian Cordillera at the Neuquén latitudes. The age of these metamorphic rocks is late Paleozoic based on the studies of Basei et al. (1999) and Pankhurst et al. (2006), who found metamorphic rocks and granitoids of 420–345 Ma age (U-Pb in zircon). Basei et al. (2005) interpreted 360 Ma U-Pb ages in titanite together with 375–310 Ma K-Ar ages in biotite as cooling ages of the metamorphic peak. The igneous emplacement and the peak metamorphism of these rocks span Devonian to Early Permian time, but with a conspicuous lack of Neoproterozoic to early Paleozoic ages. A similar late Paleozoic age was obtained for a metasedimentary unit, the Piedra Santa Formation, which yields 400–364 Ma U-Pb zircon ages (Ramos et al., 2010) and 370–310 Ma K-Ar ages in whole-rock fine fractions (Franzese, 1995). This unit is widely intruded by the 310–280 Ma Chachil Plutonic Complex, and represents the basement of the present-day southwestern margin of the Neuquén Basin exposed in the Andean foothills (Franzese and Spalletti, 2001).

North Patagonian Massif

The metamorphic basement of the North Patagonian Massif consists of the Cushamen Metamorphic Complex and the Mamil Choique granitoids. The first reliable U-Pb ages from these rocks were in the range of 286–272 Ma (Varela et al., 2005). A muscovite migmatite, located west of Mamil Choique, is 281 ± 2 Ma (U-Pb sensitive high-resolution ion microprobe [SHRIMP] age; Pankhurst et al., 2006). Along the southeastern margin of the Neuquén Basin, most of the North Patagonian Massif postcollisional granitoids are 290–273 Ma (Ramos, 2008). Ordovician metamorphic and plutonic stocks are reported farther to the east, along the Atlantic side (Pankhurst et al., 2006).

San Rafael Block and Its Southern Extension

Another possible source for detrital zircons during the Cretaceous along the eastern margin of the basin is the San Rafael Block and its southern subsurface extension. The basement of this block is part of the Cuyania terrane, a Laurentian microcontinent accreted to the Gondwana margin during Ordovician time (Ramos and Kay, 2006). The basement rocks record emplacement of the Famatinian magmatic arc (490–450 Ma), formed by Ordovician granitoids and metamorphic rocks emplaced into Grenville-age basement (1000–1200 Ma; Ramos, 2004). Immediately to the east, the old Gondwana margin is developed on the Pampia terrane, which records a Late Proterozoic–Early Cambrian arc composed of 640–514 Ma metamorphic rocks (Escayola et al., 2007). Along the San Rafael Block, magmatic arc granitoids and extension-related volcanic rocks of the Choyoi Group span between 280 and 250 Ma (Rocha Campos et al., 2011). Late Triassic within-plate volcanic rocks and related 226–180 Ma granites unconformably cover the basement (Kay et al., 1989).

MATERIALS AND METHOD

Two composite sections in two areas of the Neuquén Basin were measured and sampled in order to obtain a picture of the detrital input representative of the whole basin (details of section locations are in the GSA Data Repository[1]). The first section (north-south) is located between southern Mendoza (36°S) and southern Neuquén (39°S) and spans from the uppermost part of the Bajada del Agrio Group to the lower part of Neuquén Group (Candeleros Formation). Five sandstone samples were selected in order to constrain provenance changes across the unconformity dividing the two groups. In particular, two samples were collected from the Rayoso Formation and three from the Candeleros Formation (Fig. 2). The second section (east-west) is located in the depocenter of the Neuquén Basin, in the Aguada Pichana area (Leanza and Hugo, 1997); it spans from the Candeleros Formation to the Bajo de la Carpa Formation of the Neuquén Group. Four sandstone samples were selected from Candeleros, Huincul, Portezuelo, and Bajo de la Carpa Formations in order to collect data at relatively constant depositional time steps (Fig. 2).

Zircons were separated from samples and dated with laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at Laboratorio de Geocronologia, Universitade de Brasilia (Brazil), and in the CNR Istituto di Geoscienze e Georisorse, Università di Pavia (Italy), following the method described by Matteini et al. (2010) and Tiepolo (2003), respectively (see Table DR2 in the Data Repository for further details). We carried out a total of 615 age determinations, and we considered for provenance purposes only 500 concordant or subconcordant results (concordance better than 3%; Fig. 3).

[1]GSA Data Repository item 2012160, Table DR1 (location of selected samples), Table DR2 (detrial zircons from studied samples), and supplemental figures, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

RESULTS

According to the age of the Neuquén Group inferred from biostratigraphic data (Leanza et al., 2004, and references therein), syndepositional zircons only occur in the oldest samples from the Neuquén Group. Particularly, seven concordant ages from Candeleros Formation samples give ages of 102 ± 2 Ma and 100 ± 8 Ma. Conversely, syndepositional comagmatic zircons were not found either in the Rayoso Formation or in the youngest formations of the Neuquén Group (Portezuelo and Bajo de la Carpa).

Cretaceous–Jurassic zircon grains with clear magmatic features (oscillatory zoning and well-preserved prismatic habits; see Corfù et al., 2003) occur in the Rayoso, Candeleros, and Huincul Formations, but only predominate in the Candeleros Formation, where they range in age from 105 Ma to ca. 196 Ma.

Triassic–Permian grains (210–270 Ma) with elongated habit and oscillatory zoning occur in all samples. Grains ranging in age from ca. 350 to 300 Ma occur in most samples, except the youngest studied sample, from the Bajo de la Carpa Formation; these grains show magmatic oscillatory zoning and angular shape. A broad range of early Paleozoic ages (500–370 Ma) occurs in all samples; these grains are both magmatic (angular with oscillatory zoning) and metamorphic in origin (well-rounded without oscillatory zoning).

Proterozoic–Cambrian zircons (1800–500 Ma) occur in samples from the Rayoso Formation as well as in the youngest samples of Neuquén Group (Portezuelo and Bajo de la Carpa Formations). These grains display different internal structures that suggest provenance from low-grade metasedimentary rocks that delivered a mixture of inherited very old magmatic zircon grains, and grains affected by metamorphic resorption. This is supported by the occurrence of late Neoproterozoic–Cambrian rim ages (600–500 Ma) in zircons with Meso/Paleoproterozoic–Neoproterozoic cores (1800–800 Ma).

DISCUSSION AND CONCLUSIONS

The detrital zircon age spectra record the evolution of the drainage systems providing detrital sediment to the Neuquén Basin during

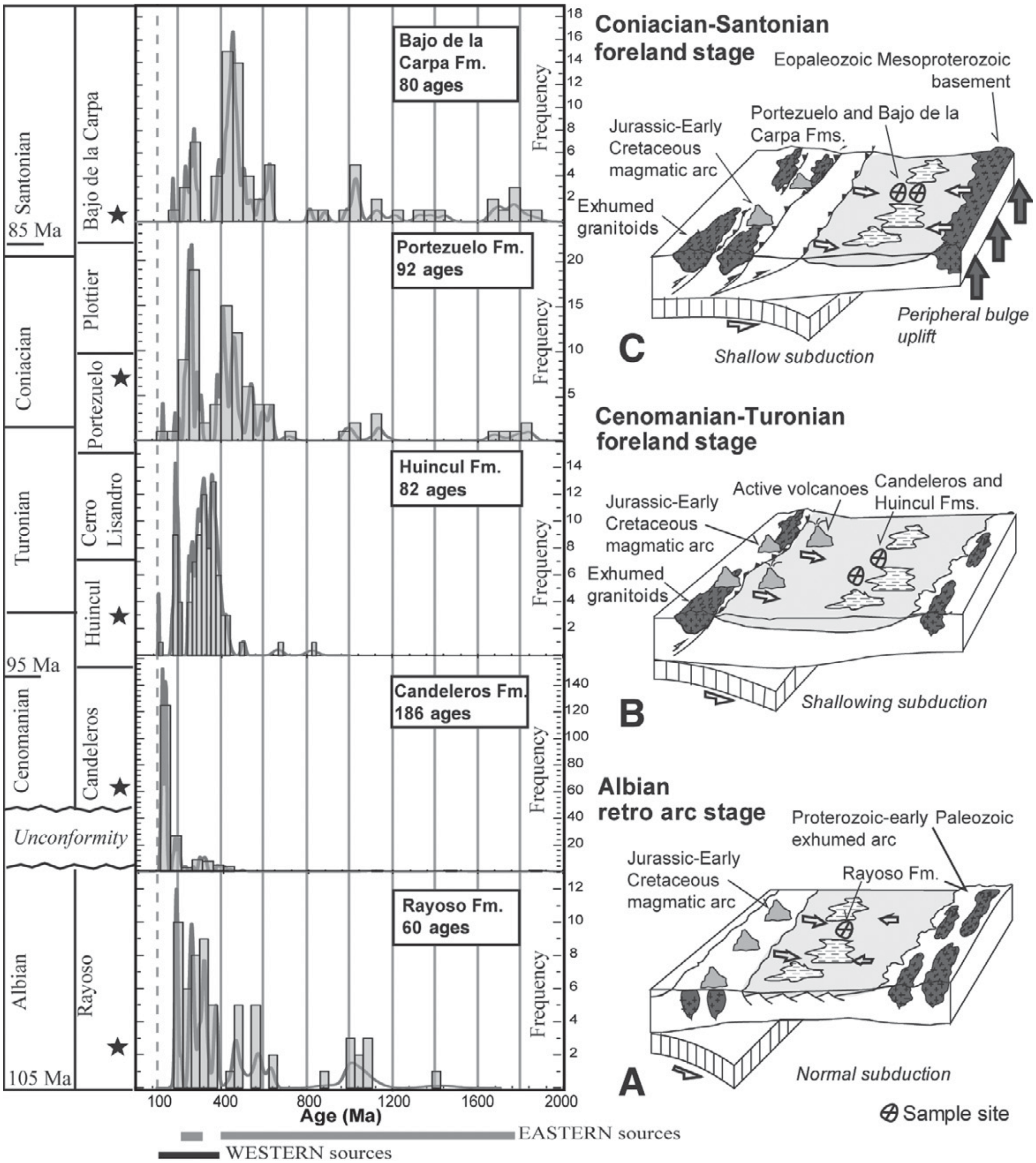

Figure 3. Frequency histograms showing the variation of the different potential sources through time. Each histogram is representative of a single formation; histograms of Rayoso and Candeleros Formations show the combined ages of two and four samples, respectively. Note the important change at mid-Cretaceous time (ca. 100 Ma) in this conceptual scheme linking the evolution of the drainage system feeding the Neuquén Basin with the geodynamic evolution of the Pacific subduction zone between 36°S and 41°S since 120–65 Ma. A–C: Paleogeographic stages and evolution of the Neuquén Basin. A: During the Albian, magmatic arcs exhumed in the Neoproterozoic and early Paleozoic were the main source of detritus. B: Deformation during the Cenomanian–Turonian. The granitoids and volcanic rocks from the Cordillera seem to be the main source for detrital zircon. C: In the Coniacian–Santonian compressive stage, the uplift of the peripheral bulge provides again old detritus from the east. Fm.—Formation.

Cretaceous time. Detrital zircon age distribution dramatically changes across the intra-Cretaceous unconformity (Fig. 3). Below, the Rayoso Formation records Precambrian–Paleozoic crystalline sources located in the eastern foreland, but above, the oldest samples from the Neuquén Group (Candeleros and Huincul Formations) show detrital zircon age distributions indicative of a source linked to the exhumation of magmatic granitoids and volcanic rocks in the Andean Cordillera, to the west. In fact, the Cordillera seems to be the main, possibly the only, source for detrital zircon to the Neuquén Basin during Cenomanian time.

Within the Neuquén Group, the detrital system records a progressive change in zircon age spectra, due to an increasing contribution from eastern Paleozoic and Precambrian basement sources. Although the 210–270 Ma and the 300–350 Ma age peaks are nonunique (these ages occur east and west of the basin), the 600–450 Ma zircon grains can only be derived from the Famatinian (490–450 Ma) and Pampean (640–514 Ma) magmatic arcs preserved in Cuyania and Pampia terranes. The Grenville-age zircon grains (1200–1000 Ma) could be derived either from the basement of the Andes or from the Cuyania terrane, but their occurrence with Cambrian and Ordovician zircon grains, without syndepositional zircon grains, requires provenance in the eastern region.

The evolution of the drainage system feeding the Neuquén Basin represents the surface response to the change from a retroarc extensional setting in the continental margin, to a compressive foreland basin, possibly linked with an episode of shallowing of the subduction zone (Ramos and Folguera, 2005).

This first-order geodynamic change is registered in the stratigraphic record by a regional unconformity. In addition, this study demonstrates that it is coupled with an inversion of the detrital drainage pattern that switches from the eastern foreland to the western Cordillera at ca. 100 Ma (Figs. 3A and 3B).

Following the shift to western provenance, the progressive return of the main detrital source to the foreland is likely related to the uplift of the peripheral bulge, as a consequence of the Late Cretaceous eastward thrust front migration of the Agrio fold-and-thrust belt (Fig. 3C).

More generally, the Neuquén Basin demonstrates how the surface response of the drainage patterns as documented by the changing provenance of detrital minerals in retroarc-foreland basins can record the evolution of the overall geodynamic system through time.

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REFERENCES CITED

Aguirre-Urreta, M.B., Pazos, P.J., Lazo, D.G., Fanning, C.M., and Litvak, V.D., 2008, First U-Pb SHRIMP age of the Hauterivian stage, Neuquén Basin, Argentina: Journal of South American Earth Sciences, v. 26, p. 91–99, doi:10.1016/j.jsames.2008.01.001.

Basei, M.A.S., Brito Neves, B.B., Varela, R., Teixeira, W., Siga, G., Jr., Sato, A.M., and Cingolani, C.A., 1999, Isotopic dating on the crystalline basement rocks of the Bariloche Region, Río Negro, Argentina. 2º Simposio sudamericano de geología isotópica (Carlos Paz), Servicio Geológico Minero Argentino: Anales, v. 34, p. 15–18.

Basei, M.A., Varela, R., Passarelli, C., Siga, O., Jr., Cingolani, C., Sato, A., and Gonzalez, P.D., 2005, The crystalline basement in the north of Patagonia: Isotopic ages and regional characteristics, *in* Pankhurst, R., and Veiga, G., eds., Gondwana 12: Geological and biological heritage of Gondwana [abstract]: Córdoba, Academia Nacional de Ciencias, p. 62.

Corfù, F., Hanchar, J.M., Hoskin, P.W.O., and Kinny, P., 2003, Atlas of zircon textures: Reviews in Mineralogy and Geochemistry, v. 53, p. 469–500, doi:10.2113/0530469.

Escayola, M.P., Pimentel, M., and Armstrong, R., 2007, Neoproterozoic backarc basin: Sensitive high-resolution ion microprobe U-Pb and Sm-Nd isotopic evidence from the Eastern Pampean Ranges, Argentina: Geology, v. 35, p. 495–498, doi:10.1130/G23549A.1.

Franzese, J.R., 1995, El Complejo Piedra Santa (Neuquén, Argentina): Parte de un cinturón metamórfico neoplaeozoico del Gondwana suroccidental: Revista Geológica de Chile, v. 22, no. 2, p. 193–202.

Franzese, J.R., and Spalletti, L.A., 2001, Late Triassic–Early Jurassic continental extension in southwestern Gondwana: Tectonic segmentation and pre-break-up rifting: Journal of South American Earth Sciences, v. 14, p. 257–270, doi:10.1016/S0895-9811(01)00029-3.

Husson, L., 2006, Dynamic topography above retreating subduction zones: Geology, v. 34, p. 741–744, doi:10.1130/G22436.1.

Jordan, T., Isacks, B., Ramos, V.A., and Allmendinger, R.W., 1983, Mountain building model: The Central Andes: Episodes, v. 3, p. 20–26.

Kay, S.M., Ramos, V.A., Mpodozis, C., and Sruoga, P., 1989, Late Paleozoic to Jurassic silicic magmatism at the Gondwana margin: Analogy to the Middle Proterozoic in North America?: Geology, v. 17, p. 324–328, doi:10.1130/0091-7613(1989)017<0324:LPTJSM>2.3.CO;2.

Leanza, H.A., and Hugo, C.A., 1997, Hoja geologica 3969-III-Picun Leufù, Provincias del Neuquen y Rio Negro: Instituto de Geologia y Recursos Naturales, SEGEMAR, Boletin 218, p. 218–235.

Leanza, H.A., Apesteguia, S., Novas, F.E., and de la Fuente, M.S., 2004, Cretaceous terrestrial beds from the Neuquén Basin (Argentina) and their tetrapod assemblages: Cretaceous Research, v. 25, p. 61–87, doi:10.1016/j.cretres.2003.10.005.

Legarreta, L., and Uliana, M.A., 1998, Anatomy of hinterland depositional sequences: Upper Cretaceous fluvial strata, Neuquén basin, west-central Argentina, *in* Shanley, K.W., and McCabe, P.J., eds., Relative role of eustasy, climate, and tectonism in continental rocks: SEPM (Society for Sedimentary Geology) Special Publication 59, p. 83–92.

Matteini, M., Junges, S.L., Dantas, E.L., Pimentel, M.M., and Bühn, B., 2010, In situ zircon U-Pb and Lu-Hf isotope systematic on magmatic rocks: Insights on the crustal evolution of the Neoproterozoic Goiás Magmatic Arc, Brasília belt, Central Brazil: Gondwana Research, v. 17, p. 1–12, doi:10.1016/j.gr.2009.05.008.

Mosquera, A., and Ramos, V.A., 2006, Intraplate deformation in the Neuquén Embayment, *in* Kay, S.M., and Ramos, V.A., eds., Evolution of an Andean margin: A tectonic and magmatic view from the Andes to the Neuquén Basin (35°–39°S lat): Geological Society of America Special Paper 407, p. 97–123.

Pankhurst, R.J., Rapela, C.W., Fanning, C.M., and Márquez, M., 2006, Gondwanide continental collision and the origin of Patagonia: Earth-Science Reviews, v. 76, p. 235–257, doi:10.1016/j.earscirev.2006.02.001.

Ramos, V.A., 2004, Cuyania, an exotic block to Gondwana: Review of a historical success and the present problems: Gondwana Research, v. 7, p. 1009–1026, doi:10.1016/S1342-937X(05)71081-9.

Ramos, V.A., 2008, Patagonia: A Paleozoic continent adrift?: Journal of South American Earth Sciences, v. 26, p. 235–251, doi:10.1016/j.jsames.2008.06.002.

Ramos, V.A., and Folguera, A., 2005, Tectonic evolution of the Andes of Neuquén: Constraints derived from the magmatic arc and foreland deformation, *in* Veiga, G.D., et al., eds., The Neuquén Basin, Argentina: A case study in sequence stratigraphy and basin dynamics: The Geological Society of London Special Publication 252, p. 15–37.

Ramos, V.A., and Kay, S.M., 2006, Overview of the tectonic evolution of the southern Central Andes of Mendoza and Neuquén (35°–39°S latitude), *in* Kay, S.M., and Ramos, V.A., eds., Evolution of an Andean margin: A tectonic and magmatic view from the Andes to the Neuquén Basin (35°–39°S lat): Geological Society of America Special Paper 407, p. 1–17.

Ramos, V.A., García Morabito, E., Hervé, F., and Fanning, M., 2010, Grenville-age sources in Cuesta de Rahue, northern Patagonia: Constraints from U/Pb SHRIMP ages from detrital zircons: International Geological Congress on the Southern Hemisphere, Mar del Plata, Argentina.

Rocha-Campos, A.C., Basei, M.A., Nutman, A.P., Kleiman, L.E., Varela, R., Llambias, E., Canile, F.M., and de C.R. da Rosa, O., 2011, 30 million years of Permian volcanism recorded in the Choiyoi igneous province (W Argentina) and their source for younger ash fall deposits in the Paraná Basin: SHRIMP U-Pb zircon geochronology evidence: Gondwana Research, v. 19, p. 509–523, doi:10.1016/j.gr.2010.07.003.

Tiepolo, M., 2003, In situ Pb geochronology of zircons with laser ablation–inductively coupled plasma–sector field mass spectrometry: Chemical Geology, v. 199, p. 159–177, doi:10.1016/S0009-2541(03)00083-4.

Uliana, M.A., and Biddle, K.T., 1988, Mesozoic–Cenozoic paleogeographic and geodynamic evolution of southern South America: Revista Brasileira de Geociencias, v. 18, p. 172–190.

Varela, R., Basei, M., Cingolani, C.A., Siga, O., Jr., and Passarelli, C.R., 2005, El basamento cristalino de los Andes norpatagónicos en Argentina: Geocronología e interpretación tectónica: Revista Geológica de Chile, v. 32, p. 167–187.

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ERRATUM

World's largest extrusive body of sand?

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