Mid to Late Cambrian docking of the Río de la Plata craton to southwestern Gondwana: age constraints from U–Pb SHRIMP detrital zircon ages from Sierras de Ambato and Velasco (Sierras Pampeanas, Argentina)

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Running title: Docking of the Río de la Plata craton

Abstract

The Early Palaeozoic stratigraphy and ~~the~~ tectonic history of the Eastern Sierras Pampeanas of central Argentina are complicated by metamorphism and deformation resulting from the Pampean (545–510 Ma) and Famatinian (490–440 Ma) orogenies. We report U–Pb SHRIMP dating of detrital zircons in two metasedimentary successions exposed at Quebrada de La Cébila (*c*. 28º45'S; 66º25'W): the Ambato and the La Cébila metamorphic complexes. The Ambato zircons record age peaks corresponding to Pampean (530 ±10 Ma), Brasiliano (~570 and ~640 Ma), ~~and~~ Grenville (~950 to ~1025 Ma) and minor Neoarchaean ages. Similar peaks are also apparent in the La Cébila sample but it additionally contains Palaeoproterozoic zircons (~2.1 Ga) corresponding to the age of the Rio de la Plata craton, from which they are considered to have been sourced. Our interpretation is that the protolith of the Ambato was deposited prior to juxtaposition with the craton and is older than the Early Ordovician La Cébila metamorphic complex. We infer that the craton reached its current relative position in the Mid to Late Cambrian, after the main Pampean tectonothermal event (530–520 Ma) and before deposition of the La Cébila protolith and the Achavil Formation (Sierra de Famatina), which contain comparable detrital zircon populations.

The Palaeoproterozoic Río de la Plata craton of central-eastern Argentina and southern Uruguay has an important role in the tectonic framework of Southwestern Gondwana. Historically, this craton was considered the upper plate in collisional models for the Neoproterozoic to Early Cambrian Pampean orogeny (545–510 Ma) during the amalgamation of Gondwana (Escayola *et al*. 2007; Schwartz *et al*. 2008; Ramos *et al*. 2010). However, Schwartz and& Gromet (2004) and Rapela *et al*. (2007) observed that the pre-Pampean sedimentary rocks, the largely turbiditic Puncoviscana Formation of Late Neoproterozoic to Early Cambrian age (for a review about the significance and age of this formation see Zimmermann 2005), did not contain zircons of Rio de la Plata craton age (c. 2.05–2.25 Ga) as should be expected from models involving orthogonal collision. Therefore the present position of the Rio de la Plata craton had to be attained during or after the Pampean orogeny. From this evidence a new geotectonic model for the Pampean orogeny was developed by Rapela *et al*. (2007), involving significant right-lateral displacements of continental masses during oblique subduction that preceded collision.

In this work, we present new U–Pb SHRIMP detrital zircon ages from high-grade metasedimentary successions from Quebrada de La Cébila (southern Sierra de Ambato and northeast Sierra de Velasco): the Ambato and La Cébila metamorphic complexes (Figs. 1 and 2). Provenance patterns, combined with existing geochronological data relevant to Neoproterozoic to Early Palaeozoic metasedimentary successions elsewhere in the Sierras Pampeanas (Rapela *et al*. 2007; Collo *et al*. 2009), constrain the time of docking of the Río de la Plata craton to southwest Gondwana., i.e., This is considered to signifythe moment when this craton became available as a source of sediments for late to post-Pampean basins.

Comment [M1]: Sentence too long, consider revising

Geological setting

Outcrops and samples from drill-holes of the Río de la Plata craton suggest that it consists of a mosaic of Palaeoproterozoic igneous and metamorphic terranes of 2260 to 2020 Ma (e.g. Tandilia belt, Pando belt, Piedra Alta terrane) (Fig. 1; Ramos 1996; Rapela *et al*. 2007; Oyhantçabal *et al*. 2010 and references therein). Its present position was probably reached through large-scale dextral strike-slip movement (present coordinates will be considered throughout the paper) relative to the Puncoviscana Formation that forms the bulk of the sedimentary involved in the Pampean orogen. The latter formation which overlies an unexposed basement, is thought to have originated on the margin of the Kalahari craton and

transferred laterally during oblique subduction of the ephemeral Clymene Ocean (Trindade *et al.* 2006; Rapela *et al.* 2007). In this interpretation, the final stage is represented by the oblique collision in Cambrian times of a large, probably allochthonous, Mesoproterozoic to Palaeoproterozoic terrane in the west that embraced the Western Sierras Pampeanas (Sierra de Pie de Palo and Sierra de Maz), the Arequipa block (southern Peru; Ramos 2008 and references therein; Casquet et al., 2010) and Amazonia among other continental blocks (Rapela *et al.* 2007; Casquet *et al.* 2009). This collision resulted in the Pampean orogenic belt (545–510 Ma, Rapela *et al.* 1998; Schwartz *et al.* 2008) in the Eastern Sierras Pampeanas, juxtaposed with the Río de la Plata craton across a major fault (Fig. 1).

Alternative models for the Pampean orogeny involve either Late Neoproterozoic to Early Cambrian orthogonal collision or ridge subduction against the Río de la Plata craton (Ramos & Vujovich 1993; Escayola *et al.* 2007; Schwartz *et al.* 2008; Ramos *et al.* 2010). Folding and the development of foliation took place in the Early Cambrian and were accompanied by low- to high-grade regional metamorphism under low-to-medium pressure between 530 and 520 Ma. Intrusion of calc-alkaline I-type plutons and S-type granites (magmatic arc) started at *c.* 545 Ma (Lira *et al.* 1997; Rapela *et al.* 1998, 2002; Schwartz *et al.* 2008; Martino *et al.* 2009).

The Sierras Pampeanas are blocks of pre-Andean basement tilted during Late Cenozoic flat-slab subduction of the Nazca plate beneath the Central Andean continental margin between 27° and 33°30' S, (Jordan & Allmendinger 1986; Ramos *et al.* 2002). Two successive orogenies have long been recognized in the Eastern Sierras Pampeanas, i.e., the Pampean orogeny referred to above, and the accretionary Famatinian orogeny (Aceñolaza & Toselli 1977; Pankhurst *et al.* 1998; Rapela *et al.* 1998; Dahlquist *et al.* 2008; Fig. 1). The Famatinian belt lies to the west of the Pampean belt and developed mainly between the Late Cambrian and the Early Silurian (490-440 Ma) (e.g. Pankhurst *et al.* 1998, 2000; Astini and Davila 2004). This orogeny partially reworked the Pampean foreland to the east, and extended well into the Western Sierras Pampeanas on the west (e.g. Rapela *et al.* 1998; Pankhurst *et al.* 2000; Baldo *et al.* 2006; Casquet *et al.* 2008). The Famatinian belt is characterized by Late Cambrian to Early-Middle Ordovician marine and volcaniclastic successions, Early to Mid Ordovician I- and S-type intrusions (magmatic arcs), minor tonalite–trondhjemite–granodiorite suites in the foreland and low- to high-grade, low-to-intermediate pressure, metamorphism coeval with foliation development, folding and thrusting (e.g. Pankhurst *et al.* 1998, 2000; Rapela *et al.* 2001; Casquet *et al.* 2001, 2008; Astini 2003 and references therein;

Astini & Davila 2004; Büttner *et al.* 2005; Verdecchia *et al.* 2007; Dahlquist *et al.* 2008; Otamendi *et al.* 2008, 2009; Collo *et al.* 2009). ~~On the other hand,~~ Tthe Western Sierras Pampeanas close to the Andes consist of a Proterozoic basement of Grenville age (*c*. 1.0–1.3 Ga) that was pervasively reworked by the Famatinian orogeny (Pankhurst & Rapela 1998; Varela *et al.* 2004; Vujovich *et al.* 2004; Casquet *et al.* 2001, 2008; Rapela *et al.* 2010). Evidence for Pampean-age tectonothermal activity in the Western Sierras Pampeanas is provided by U-Pb data, both conventional and SHRIMP, and Ar-Ar determinations (e.g. Lucassen & Becchio 2003; Mulcahy *et al.* 2007; Casquet *et al.* 2008)

Comment [M2]: Do you mean TIMS?

This work is focused on the southern tip of the Sierra de Ambato and east tip of Sierra de Velasco in the Eastern Sierras Pampeanas (Fig. 2), which underwent Famatinian deformation and metamorphism. Two metasedimentary successions are recognized, yielding contrasting detrital zircon ages. The Ambato metamorphic complex (Fig. 2b) mainly consists of high-grade metasedimentary rocks (migmatites and gneisses) and discordant granitic and pegmatitic bodies (Caminos 1979). Larrovere (2009) obtained an Early to Mid Ordovician metamorphic age on monazite from one migmatite from the central-northern part of the sierra. However, the ages of igneous rocks and sedimentary protoliths in this region are still unknown. At the southern tip of the Sierra de Ambato, the metamorphic complex overlies the low-grade successions of the La Cébila metamorphic complex across a west-directed Cenozoic reverse fault (Fig. 2b).

The La Cébila metamorphic complex consists of a low- to high-grade metasedimentary succession, peraluminous granites and pegmatitic bodies (Espizúa & Caminos 1979; Verdecchia 2009; Fig. 2b) that crop out discontinuously along the eastern edge of the Sierra de Velasco with the main outcrops along the Quebrada de La Cébila (Fig. 2b). The Sierra de Velasco is a large igneous massif consisting of Ordovician peraluminous to metaluminous granites (Pankhurst *et al.* 2000; Toselli *et al.* 2007) that underwent shearing to produce mylonites in the Devonian (e.g. TIPA shear zone, Hockenreiner *et al.* 2003), and undeformed Carboniferous A-type granitic plutons (Dahlquist *et al.* 2006; Grosse *et al.* 2008; Dahlquist *et al.* 2010). The LCMC consists of phyllites, metapsammites, quartzites, mica- and quartz-schists, gneisses and migmatites with minor calcsilicate rocks, graphite-schist layers and discordant pegmatite bodies (Espizúa & Caminos 1979; Verdecchia 2009). The metamorphic grade increases from very low in the east to high in the west, towards the contact with the Punta del Negro pluton, giving rise to a succession of metamorphic zones (chlorite, biotite, cordierite, andalusite, andalusite–K-feldspar, sillimanite–K-feldspar and cordierite–K-

Comment [M3]: Restructure sentence or shorten.

feldspar) roughly parallel to the contact (Verdecchia 2009; Fig. 2b). South of the studied area at Quebrada de la Rioja (Fig. 2a) one granitoid that intrudes rocks equivalent to the La Cébila metamorphic complex has yielded an age of 476.4 ± 1.5 Ma (U–Pb ID-TIMS on monazite; De los Hoyos *et al.* 2008). Although the age of metamorphism is unknown, Verdecchia (2009) suggested on geological and petrological grounds that Ordovician magmatism was roughly coeval.

An Early Ordovician depositional age for the protoliths of the La Cébila metamorphic complex has been determined from biostratigraphy in quartzites from the sillimanite–K-feldspar zone that preserve a shelly fauna (Verdecchia *et al.* 2007). This age is compatible with U–Pb detrital zircon ages that yielded a maximum sedimentation age of *c*. 530 Ma (sample QCE-6004, Rapela *et al.* 2007; Fig. 2b). A shallow-water marine siliciclastic platform, in a foreland position relative to the Famatinian magmatic arc to the west, was previously suggested for protoliths of the La Cébila metamorphic complex (Astini *et al.* 2003 2004; Verdecchia *et al.* 2007; Verdecchia & Baldo 2010).

Samples

One sample from each metamorphic complex referred to above was selected for U–Pb SHRIMP zircon dating.

Sample CEB-392 is a banded migmatite from southern Sierra de Ambato (28°50'29.10"S; 66°20'39.40"W, see Fig. 2b). The mineral association consists of plagioclase, biotite, quartz, K-feldspar and secondary muscovite and chlorite, with accessory zircon (both in the matrix and as inclusions in biotite), apatite and scarce opaque minerals. The migmatite is a stromatite with alternation of leucosome and melanosome concordant with the foliation. The melanosome is composed of aligned biotite layers (<3–5 mm thick), whereas the leucosome layers (<30 mm thick) have an interlobate mosaic of quartz, plagioclase, K-feldspar and subordinate biotite.

Sample CEB-428 is a paragneiss of the inner La Cébila metamorphic complex collected near the contact with the porphyritic Punta del Negro granite (28°45'46.80"S; 66°24'29.60"W, Fig. 2b). The mineral association includes cordierite, K-feldspar, biotite, plagioclase, quartz and secondary muscovite, with accessory tourmaline, zircon, monazite, apatite and opaque minerals. Compositional banding is characterized by leucocratic layers <10 mm thick

consisting of slightly interlobate aggregates of cordierite, K-feldspar, plagioclase, quartz with minor biotite, and thin biotitic layers (<1 mm thick) with subordinate cordierite, plagioclase, K-feldspar and quartz. In both domains, a foliation is defined by biotite aligned parallel to the banding.

Analytical methods

Zircons were concentrated using standard crushing, washing, heavy liquid, and paramagnetic separation procedures as in Rapela *et al*. (2007). The zircon-rich heavy mineral concentrates were poured onto double-sided tape, mounted in epoxy together with chips of the Temora reference zircon, sectioned approximately in half, and polished. Cathodo-luminescence images were used to decipher the internal structures of the sectioned grains.

> **Comment [M4]:** What is meant by washing here? Wi lfley table?

The U–Th–Pb analyses were made using SHRIMP RG at the Research School of Earth Sciences, The Australian National University, Canberra, Australia as described by Williams (1998, and references therein). Each analysis consisted of 4 scans through the mass range, with the reference zircon analysed once for every five unknowns. Data were reduced using the SQUID Excel macro of Ludwig (2001). Since young zircons with normal U contents have low $^{207}Pb/^{235}U$ ratios and statistically highly imprecise $^{204}Pb/^{206}Pb$ ratios, common-Pb correction was made using the measured ^{204}Pb measurements only for ages older than about 1100 Ma, and ^{207}Pb measurement for younger ages (see Williams 1998); in the latter case there are no common-Pb corrected $^{207}Pb/^{235}U$ ratios reported in Table 1

Tera–Wasserburg Concordia plots (Fig. 4), probability density plots with stacked histograms (Fig. 5), and weighted-mean $^{206}Pb/^{238}U$ age calculations were carried out using ISOPLOT/Ex (Ludwig 2003). Uncertainties on all calculated ages are reported as 95% confidence limits.

U–Pb results

CEB-392 (Ambato metamorphic complex)

Zircon grains are up to 200 μm long, rounded, anhedral, but with a minority of euhedral prismatic crystals, some of the latter showing bi-pyramidal terminations (Fig. 3 a-c). Cathodo-luminescence images (CL) show irregular detrital cores and discordant low-luminescence

overgrowths, some showing faint oscillatory-zoning that is interpreted as metamorphic in origin. Sixty-one grains were analysed (Table 1). The zircons moderate Th/U ratios, mostly $\leq$ 0.5, and their ^{206}Pb/^{238}U ages range from ~460 to ~2650 Ma, with only three analyses being more than 10% discordant. The inheritance pattern shows a bimodal distribution with fifty-four ages in the range 460–1200 Ma and five Archaean ages at ~2600 Ma (for which ^{207}Pb/^{206}Pb ages are considered more reliable than ^{238}U/^{206}Pb ages). There is a notable absence of Palaeoproterozoic ages. The two youngest ages (459 $\pm$ 5 and 471 $\pm$ 5 Ma) are from rims with high U (>1000 ppm) and low Th/U (<0.05), which suggests a metamorphic origin during the Famatinian orogeny and provides a minimum age for sedimentation, although the precise age of metamorphism cannot be determined with only two results. There is a major peak at ~530 $\pm$ 10 Ma, defined by six analyses of grains showing oscillatory zoning characteristic of igneous crystallization and hence it is assumed that these are of detrital origin, constraining a maximum possible age for deposition. Other significant post-Archaean age peaks occur at ~ 570 Ma, ~640 Ma, ~900 Ma, 950–1025 Ma (concentrated at ~1015 Ma) and, perhaps ~1165 Ma.

CEB-428 (La Cébila metamorphic complex)

Zircon grains are up to 100 μm in size and show a variety of rounded to euhedral prismatic shapes, some with bi-pyramidal terminations (Fig. 3 d-e). Many grains are fragments. Strong oscillatory zoning is evident in the CL images. Some grains show zoned cores overgrown by thin rims of low luminescence (Fig. 3 d-e). On the other hand, some of the anhedral zircon grains show little or no zoning. Sixty-five grains were analysed, all of which yielded ages that are mostly less than 10% discordant. The majority of the grains exhibit Th/U ratios in the range 0.2 to 1.0, which is normal for igneous zircon. The inheritance pattern shows a similar but more continuous spread of ages than that for sample CEB-392. Five youngest ages form a coherent group with a mean age of 520 $\pm$ 10 Ma, but more prominent peaks are defined at ~570, ~610 and ~660 Ma. Early Neoproterozoic ages in the range 950–1150 Ma (with a small peak at ~1015 Ma) are less common than in CEB-392, but there is a significant grouping of Palaeoproterozoic ^{207}Pb/^{206}Pb ages (1750–2200 Ma, with possible minor peaks at ~1890, ~2050 and 2150 Ma), as well as a few Archaean ages of ~2600 Ma.

Discussion

Comment [M5]: Are you quoting a 206Pb/238U age for an apparent age of 2650Ma? Generally 207Pb/206Pb ages are considered more reliable for ages in excess of ca 1000Ma.

Neoproterozoic to Early Cambrian sedimentary rocks that were involved in the Pampean orogeny are characterized by detrital zircon provenance patterns with well-developed Brasiliano age peaks between 680 and 570 Ma and Grenvillian-age peaks between 950 and 1100 Ma, but lack Pampean magmatic and metamorphic zircons with ages in the range 545–520 Ma. A minor group of Paleoproterozoic (1.7 to 2.0) and Archean (ca. 2.6 Ga) grains is also present (cf., Sims *et al*. 1998; Pankhurst *et al*. 2000; Schwartz & Gromet 2004; Escayola *et al*. 2007; Rapela *et al*. 2007; Drobe *et al*. 2009; Adams *et al*. 2011). In contrast the migmatite of the Ambato metamorphic complex records a maximum sedimentation age of 530 ± 10 Ma (CEB-392, Fig. 5). Age peaks corresponding to Brasiliano-ages (~570 and ~640 Ma) and Grenville-ages (~950 to ~1025 Ma) are present, whereas Palaeoproterozoic ages characteristic of the Río de la Plata craton (2260–2020 Ma; Rapela *et al*. 2007 and references therein) are absent. Two overgrowth ages (471 ± 5 and 459 ± 5 Ma) from the Ambato metamorphic complex sample are interpreted as the age of Famatinian metamorphic overprint and are compatible with an Early to Mid Ordovician U–Pb monazite age (*c*. 470 Ma) determined by Larrovere (2009). The protolith of the complex was thus deposited between Early Cambrian and Mid Ordovician time (ICS Stratigraphic Chart 2009).

The Ambato migmatite detrital zircon age pattern resembles that of the Middle Cambrian Negro Peinado Formation of the Sierra de Famatina (Collo *et al*. 2009), which yielded a youngest detrital zircon age of 505 ± 13 Ma (and a more significant peak at 522 ± 8 Ma) but also lacks zircons of Río de la Plata craton age (see Fig. 5). Brasiliano age peaks are present in both samples (stronger in CEB-392) and are consistent with provenance from reworking of Late Neoproterozoic sedimentary successions such as the Puncoviscana Formation (e.g. Drobe *et al*. 2009; Adams *et al*. 2011; Hauser *et al*. 2011) and the equivalent Ancasti metamorphic complex of the easternmost Sierras Pampeanas (Rapela *et al*. 2007; Murra *et al*. 2011; see Fig. 5). Provenance of the Puncoviscana Formation has been related in part to sources in the Kalahari craton (see Schwartz & Gromet 2004; Rapela *et al*. 2007). On the other hand, 1165–950 Ma zircon ages in the Ambato metamorphic complex and the Negro Peinado Formation suggest derivation from a Grenville-age basement similar to that recognized in the Western Sierras Pampeanas, probably the tip of a much larger terrane that collided during the Pampean orogeny embracing the Arequipa block and Amazonia (see Rapela *et al*. 2007; Casquet *et al*. 2008, 2010). Alternatively the Grenvillian-age grains might be derived from reworking of the underlaying Puncoviscana Formation. Collo *et al*. (2009)

Comment [M6]: These two ages do not overlap within error, so are you saying that there were two discrete events, or is this difference analytical? This should be made clear.

interpreted the Negro Peinado Formation as deposited in a Mid Cambrian foreland basin related to the Pampean orogen exposed in the east.

Protoliths of the La Cébila metamorphic complex are Early Ordovician according to fossil remains in quartzitic layers (Verdecchia *et al.* 2007). The provenance pattern of the paragneiss studied here is characterized by Pampean-ages (~520 to ~540 Ma), Brasiliano ages (~570 to ~660 Ma) and Grenville ages (~1015 Ma) peaks, but significantly includes Palaeoproterozoic zircons with ages that match those of the Río de la Plata craton (2.02–2.26 Ga; Hartmann *et al.* 2002; Rapela *et al.* 2007) and few older grains. Similar results were obtained on a quartzite from this same complex by Rapela *et al.* (2007) (Fig. 5), which strengthens the view that by the Early Ordovician the Rio de la Plata craton was in its present position, providing clastic detritus to wide sedimentary basins in the west that joined those resulting from the reworking of the ~~underlaying~~underlying metasedimentary rocks.

Detrital zircons with Río de la Plata craton ages of ~2100 Ma were also recorded by Collo *et al.* (2009) in the Achavil Formation, as well as Pampean (~520 Ma), Brasiliano (~630 Ma) and Grenville-age (~1040–1120 Ma) peaks, much like the La Cébila metamorphic complex provenance. The maximum age of the Achavil Formation is poorly constrained since the youngest detrital zircon age peak is 519 ± 23 Ma (1σ). The ~~M~~minimum sedimentation age however is Late Cambrian as the base of the overlying Volcancito Formation contains fossils of that age (Astini 2003; Albanesi *et al.* 2005). Collo and~~&~~ Astini (2008) and Collo *et al.* (2009) suggested that the Achavil Formation had to be late Middle to Late Cambrian and younger than the Negro Peinado Formation on the basis of stratigraphical evidence and detrital zircon age patterns. Thus the record of Rio de la Plata craton influence extends back into the Late Cambrian.

From these results we suggest here that the Ambato metamorphic complex is older than both the La Cébila metamorphic complex and the Achavil Formation, and is probably equivalent to the Middle Cambrian Negro Peinado Formation of Sierra de Famatina. Both the Ambato metamorphic complex and the Negro Peinado Formation lack detrital zircons of Rio de la Plata age (Fig. 5). On the other hand the Achavil Formation and the La Cébila metamorphic complex, although not equivalent stratigraphically, both contain detrital zircon populations with age peaks in part similar to those of the Ambato and Negro Peinado formations, but additionally include Palaeoproterozoic zircons that can be related to the Rio de la Plata craton. The latter implies that by the Mid or Late Cambrian the Rio de la Plata craton had reached a

palaeogeographical position close to present. Moreover the Rio de la Plata craton does not show evidence of deformation and metamorphism of Pampean age (Rapela *et al*. 2007) which implies that it sourced zircons to the Achavil sedimentary basin after the main Pampean tectonothermal events, i.e., between 545 and 520 Ma. Orographic barriers such as the rising Pampean orogen played a transient role sometime between 520 and 510 Ma. By the time the Achavil Formation was deposited, such a barrier did not exist and Palaeoproterozoic zircons could easily reach sedimentary realms in the west. We conclude that the Rio de la Plata craton reached a position close to present sometime between the end of the Pampean tectonothermal event (*c*. 520 Ma) and the deposition of the Achavil Formation in the Mid to Late Cambrian.

One alternative source for zircons with Palaeoproterozoic ages similar to the Rio de la Plata craton might could have been in the Amazonia craton, particularly in the Maroní-Itacaiunas province of northern Amazonia (e.g. Cordani & Teixeira 2007). If a static palaeogeographical model is implied, i.e., that Amazonia were in a position similar to today relative to other cratons, basins and orogenic belts of southern South America, then zircons would have had to travel between 3000 and 4000 km from the Maroní–Itacaiunas province – all the way round the craton itself – to reach the La Cébila basin. This enormous distance might be feasible if long-range energetic submarine currents were involved, but we can also add the fact that to our knowledge there is no evidence for the anticipated string of basins similar to La Cébila (Early Ordovician) that would connect the Sierras Pampeanas with the Maroní-Itacaiunas region of Amazonia. The possibility of the Palaeoproterozoic Arequipa block of southern Peru as another alternative source to the Rio de la Plata craton is more difficult to justify: Trans-Amazonian/Eburnian ages between c. 1.8 and 2.1 Ga have been recorded from this block (Loewy *et al*. 2004; Casquet *et al*. 2010), but also sedimentary rocks with detrital zircons between c. 1.2 and 1.6 Ga that are not recorded in the La Cébila basin.

Conclusions

The metasedimentary Ambato metamorphic complex and the La Cébila metamorphic complex that crop out at the southern end of the Sierra de Ambato and northeast tip of Sierra de Velasco are Middle Cambrian and Early Ordovician respectively. They were deposited before the start of the Famatinian magmatism in the late Early Ordovician, and after the Pampean Orogeny. Sources for most detrital zircons in both formations can be found in neighbouring regions, particularly in the Pampean orogen and the Proterozoic Western Sierras

Pampeanas. However Palaeoproterozoic zircons are recorded only in the La Cébila metamorphic complex. The source for these zircons probably lay in the Rio de la Plata craton to the east. The Late Cambrian Achavil Formation also contains Palaeoproterozoic zircons.

The Rio de la Plata craton juxtaposed obliquely to the Pampean orogen, reaching a position close to present sometime between the end of the main Pampean tectonothermal event (*c*. 520 Ma) and when it became the source for Palaeoproterozoic detrital zircons in the Achavil Formation, i.e. during the Mid-to-Late Cambrian interval. The situation persisted in the lower Early Ordovician when the La Cébila sedimentary succession was deposited.

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Figure captions

Fig. 1. Digital elevation model (DEM, 90-SRTM type) of central South America showing the Neoproterozoic to Early Palaeozoic tectonic framework and inferred limit of Río de la Plata craton (modified from Cordani *et al.* 2003, Rapela *et al.* 2007 and Oyhantçabal *et al.* 2010). Abbreviation: Transbrasiliano lineament (TB), Tandilia belt (T), Pando belt (PB), Piedra Alta terrane (PA), Nico Pérez terrane (NP), Rivera block (RB), Tacuarembó block (TA), Asunción arch (AA), Eastern Sierras Pampeanas (ESP), Western Sierras Pampeanas (WSP), Precordillera terrane (P).

Fig. 2. (a) Schematic geological map of central-western Argentina (after Astini & Dávila 2004; Dahlquist *et al.* 2008; Grosse *et al.* 2008). The main metasedimentary outcrops of the La Cébila metamorphic complex are marked (Quebradas of La Cébila, Cantadero and La Rioja). (b) Geological map of Quebrada de La Cébila. New and previously published sample localities are shown.

Fig. 3. Cathodo-luminescence images showing examples of the zircon grains analyzed. (a–c) migmatite (CEB-392) from the Ambato metamorphic complex, (d–e) paragneiss (CEB-428) from the La Cébila metamorphic complex. Rims are indicated with white triangles.

Fig. 4. Tera-Wasserburg plots for U–Pb SHRIMP data for (a) migmatite sample CEB-392 from the Ambato metamorphic complex and (b) paragneiss sample CEB-428 from the La Cébila metamorphic complex.

Fig. 5. Detrital zircon U–Pb age patterns for metasedimentary samples from the La Cébila metamorphic complex (CEB-428, this work; quartzite QCE-6004, Rapela *et al.* 2007), the Ambato metamorphic complex (CEB-392, this work, excluding one discordant point from Table 1), the Ancasti metamorphic complex (schist ANC-1008, Rapela *et al.* 2007), and the Negro Peinado and Achavil formations (Collo *et al.* 2009). The position of final docking of Río de la Plata craton (RLPC) is indicated as Mid-to-Late Cambrian.