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Detrital-zircon geochronology and provenance of the Ocloyic synorogenic clastic wedge, and Ordovician accretion of the Argentine Precordillera terrane

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ABSTRACT

The Precordillera terrane in northwestern Argentina is interpreted to be an exotic (Laurentian) continental fragment that was accreted to western Gondwana during the Ordovician. One prominent manifestation of the subduction and collision process is a Middle–Upper Ordovician clastic wedge, which overlies a passive-margin carbonate-platform succession in the Precordillera. U/Pb ages of detrital zircons from sandstones within the clastic wedge, as well as zircons from clasts within conglomerates, provide documentation for the composition of the sediment provenance. The ages of detrital zircons are consistent vertically through the succession, as well as laterally along and across strike of the Precordillera, indicating a single, persistent sediment source throughout deposition of the clastic wedge. The dominant mode (~1350–1000 Ma) of the detrital-zircon ages corresponds to the ages of basement rocks in the Western Sierras Pampeanas along the eastern side of the Precordillera. A secondary mode (1500–1350 Ma) corresponds in age to the Granite-Rhyolite province of Laurentia, an age range which is not known in ages of basement rocks of the Western Sierras Pampeanas; however, detritus from Granite-Rhyolite-age rocks in the basement of the Precordillera was available through recycling of synrift and passive-margin cover strata. Igneous clasts in the conglomerates have ages (647–614 Ma) that correspond to the ages of minor synrift igneous rocks in the nearby basement massifs; the same ages are represented in a minor mode (~750–570 Ma) of detrital-zircon ages. A quartzite clast in a conglomerate, as well as parts of the population of detrital zircons, indicates the importance of a source in the metasedimentary cover of the leading edge of the Precordillera. The Famatina continental-margin magmatic arc reflects pre-collision subduction of Precordillera lithosphere beneath the western Gondwana margin; however, no detrital zircons have ages that correspond to Famatina arc magmatism, indicating that sedimentary detritus from the arc may have been trapped in a forearc basin and did not reach the foreland. The indicators of sedimentary provenance for the foreland deposits are consistent with subduction of the Precordillera beneath western Gondwana, imbrication of basement rocks from either the Precordillera or Gondwana into an accretionary complex, and recycling of deformed Precordillera cover rocks.

INTRODUCTION

The Precordillera in the eastern foothills of the southern Central Andes in northwestern Argentina (Fig. 1) generally is interpreted to be an exotic terrane that was rifted from Laurentia in the Cambrian and accreted to Gondwana in the Ordovician (e.g., Ramos et al., 1986; Astini et al., 1995; Thomas and Astini, 1996; Ramos, 2004), although alternative interpretations continue to be discussed (e.g., Baldis et al., 1989; Keller et al., 1998; Keller, 1999; Aceñolaza et al., 2002; Finney, 2007). In the Precordillera, a Middle–Late Ordovician clastic wedge overlies a thick Early Cambrian–Early Ordovician passive-margin carbonate-platform succession (Fig. 2) (Astini et al., 1995; Ramos et al., 1996; Astini and Thomas, 1999). The sediment provenance and tectonic setting of the clastic wedge are keys to understanding the accretion history, as well as to evaluating the alternative interpretations of tectonic history, of the Precordillera and are the subject of this article.

A strong Laurentian connection of the Precordillera terrane is evident in the crystalline basement rocks, which are predominantly of Mesoproterozoic age (Grenville equivalent) but include some older components (e.g., Granite-Rhyolite province of Laurentia) (Astini et al., 1995; Kay et al., 1996; Ramos, 2004; Rapela et al., 2010; Thomas et al., 2012). Iapetan synrift clastic and evaporite facies (Lower Cambrian Cerro Totora Formation, Fig. 2) have an *Olenellus-Salterella* fauna, indicating a Laurentian provenance (Astini and Vaccari, 1996; Benedetto, 1998; Thomas et al., 2001, 2004; Astini et al., 2004). The Cambrian–Ordovician passive-margin carbonate succession of the Precordillera differs from Lower Cambrian–Lower Ordovician facies elsewhere in western Gondwana (e.g., Astini, 2003) but is comparable in age and stratigraphy to the Cambrian–Ordovician passive-margin carbonate succession of Laurentia (Astini et al., 1995; Keller, 1999, 2012; Thomas and Astini, 1999).

Westward progradation of the Middle–Late Ordovician synorogenic clastic wedge (Fig. 2) in the Precordillera documents the demise of the carbonate platform during subsidence of a peripheral foreland basin in response to tectonic loading as the Precordillera microcontinent entered an east-dipping subduction zone (present coordinates) beneath an accretionary subduction complex, including the Famatina continental-margin magmatic arc along the western

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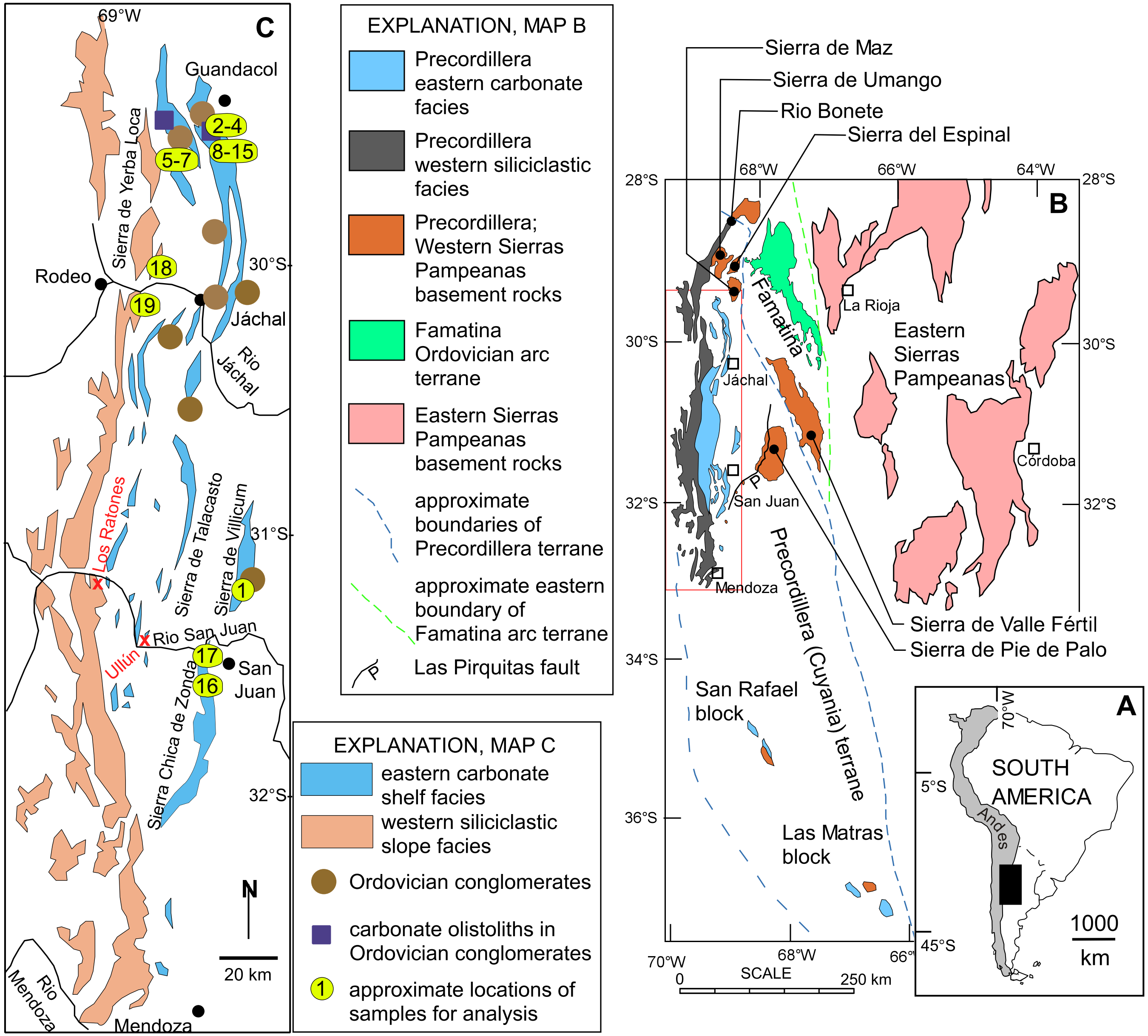

Figure 1. Location maps (adapted from Astini, 2003, and Chernicoff et al., 2009). Map A shows location of map B by black rectangle. Map B shows locations of the Precordillera terrane, basement massifs of the Western Sierras Pampeanas, Famatina arc, and map C by red outline. Map C shows approximate locations of samples for analysis of zircons (locations documented in Supplemental Tables 1 and 2 [see footnotes 2 and 3]) and the locations of the Los Ratones olistolith and the Ullún xenoliths in red; the Ordovician clastic wedge overlies the eastern carbonate shelf facies of the Precordillera.

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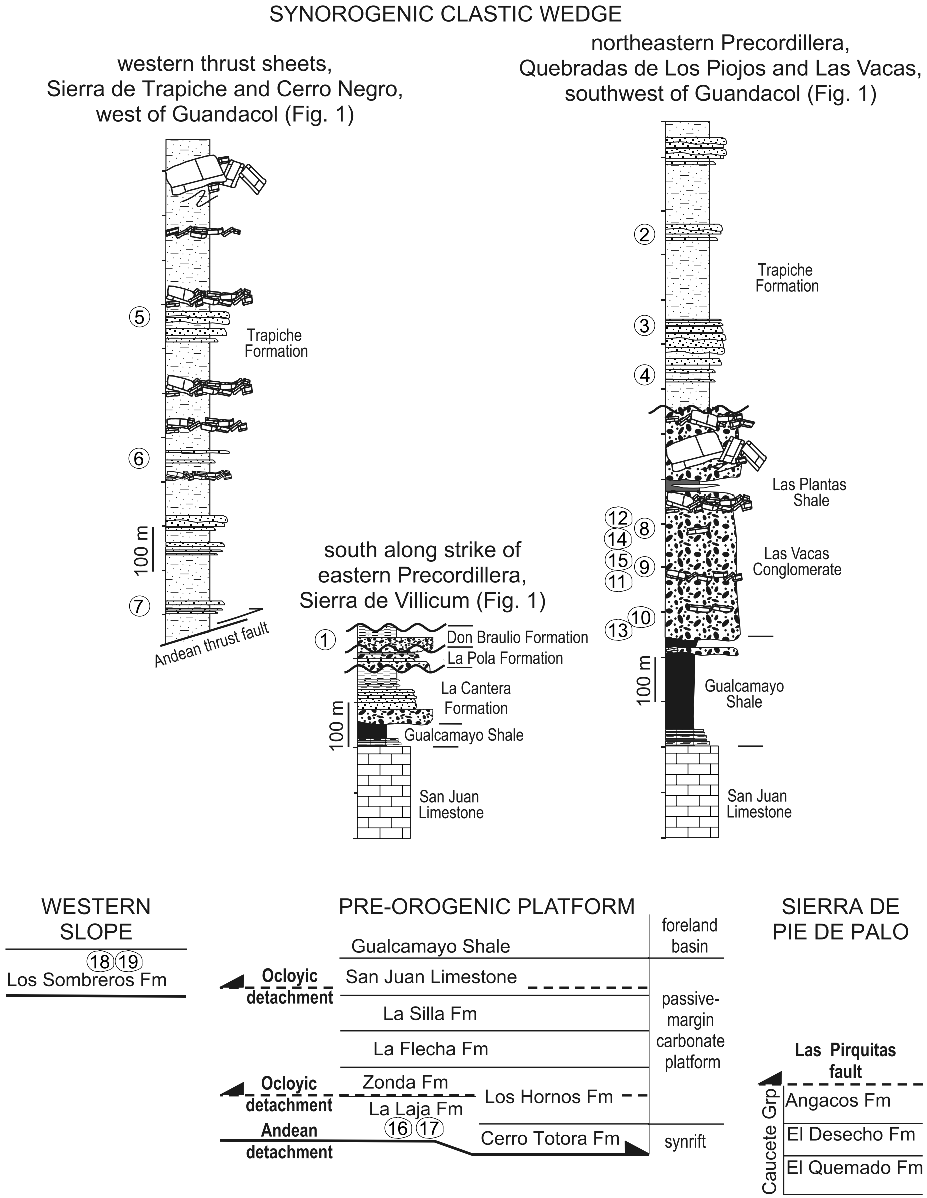

Figure 2. Diagrammatic stratigraphic sections of the Middle–Upper Ordovician clastic wedge in the northeastern Precordillera, the thinner section to the south along strike, and the Trapiche Formation to the west (adapted from Astini, 2003, and Thomas and Astini, 2007). Correlation chart of the pre-orogenic platform of the Precordillera, the western slope facies, and equivalent strata in the footwall of the Las Pirquitas fault in the Sierra de Pie de Palo (adapted from Astini, 2003, and Naipauer et al., 2010). Circled numbers show stratigraphic levels of samples for analysis.

Gondwanan margin in the Ordovician (Astini et al., 1995; Thomas and Astini, 1996, 2003, 2007; Ramos, 2009). Cooling ages of metamorphic rocks confirm Ordovician collision (Ramos et al., 1998). Collectively, the accretionary events constitute the Ocloyic orogeny (Thomas et al., 2002; Astini and Dávila, 2004). The Middle–Upper Ordovician Ocloyic clastic wedge fills the foreland basin along the eastern part of the Precordillera; laterally equivalent late-stage carbonate remnants to the west indicate a peripheral bulge (Astini et al., 1995; Astini and Thomas, 1999). The Ordovician clastic wedge is capped by glacial deposits of the uppermost Ordovician Hirnantian Stage (Don Braulio Formation, Fig. 2) (Benedetto, 1986; Peralta and Carter, 1990; Buggisch and Astini, 1993; Astini, 2001a). The Hirnantian glacial deposits overlap the Precordillera foreland and other Gondwanan basins, documenting the attachment of the Precordillera to Gondwana (Astini, 2003; Astini et al., 1995, 2005). In the northern Precordillera, Carboniferous strata overstep northward onto the Ordovician clastic wedge. East-directed Andean thrust faults have greatly modified the original geometry of the Ocloyic foreland (Astini et al., 1995).

Alternative proposals for the origin of the Precordillera include rifting of the Precordillera terrane from Laurentia in Ordovician, rather than Cambrian, time (Keller et al., 1998; Keller, 1999) and a Gondwanan, rather than Laurentian, origin (e.g., Baldis et al., 1989; Aceñolaza et al., 2002; Finney, 2007). Ordovician rifting of the Precordillera from Laurentia implies that: (1) the Ordovician clastic deposits fill synrift, isolated, fault-bounded, extensional basins on the Precordillera (e.g., Keller, 1999); (2) the clastic sediment had multiple, local sources from fault-bounded uplifts; and (3) the Precordillera was accreted to Gondwana in the Silurian or later (e.g., Rapela et al., 1998). Protracted, large-scale, dextral, strike-slip translation of the Precordillera from an original site on the Gondwana margin to the present location by Devonian time implies deposition of the Ordovician clastic succession in separate, strike-slip, pull-apart basins with local sources of clastic sediment. Neither of these alternatives accounts for the similarities of the Early Cambrian synrift rocks and the Cambrian–Ordovician passive-margin stratigraphy on the Precordillera to those around the Ouachita embayment of Laurentia (Thomas and Astini, 1996; Rapalini and Astini, 1998). An interpretation of continent-continent collision and suturing between Laurentia and Gondwana in Ordovician time (Dalla Salda et al., 1992a, 1992b; Dalziel, 1997) is consistent with subsidence and Middle–Late Ordovician filling of a foreland basin on the Precordillera ("Occidentalia terrane"), which was part of Laurentia at that time; but, that interpretation requires post-Ordovician continental rifting, leaving the Precordillera fragment of Laurentia attached to Gondwana.

STRATIGRAPHY AND DEPOSITIONAL SETTING OF THE ORDOVICIAN CLASTIC SUCCESSION IN THE PRECORDILLERA

The Middle–Upper Ordovician clastic succession above the passive-margin carbonate facies in the Precordillera is thickest on the northeast and thins to the south and west, where the clastic facies interdigitate with late-stage carbonate

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remnants (Astini et al., 1995; Astini, 2003). Black shale at the base of the clastic succession progrades westward and southward over the passive-margin carbonate succession. Westward progradation of coarser clastic sediment began in the late Middle Ordovician. The coarser grained units show pronounced along-strike variations in thickness but parallel the westward progression of the black shale (Fig. 2).

Gualcamayo Shale

Deep-water black shales (Gualcamayo Shale) overlie the Lower Ordovician San Juan Limestone at the top of the passive-margin carbonate succession (Fig. 2) (Astini et al., 1995; Astini and Thomas, 1999). The transition from shallow-marine carbonates to deep-water black shales is diachronous, beginning in the late Floian in the northeastern Precordillera, prograding westward and southward, and extending widely across the northeastern Precordillera in the Darriwilian (Astini, 1994a, 1995). Diachronous southwestward progradation of the deep-water shales documents initial subsidence of the carbonate platform into a progressively deepening and widening foreland basin, consistent with subduction of the Precordillera as a lower plate beneath the western margin of Gondwana. Abundant (>170) beds of bentonite (volcanic ash) punctuate the stratigraphic succession through the upper part of the San Juan Limestone and lower part of the Gualcamayo Shale (Fig. 2), ranging through the late Floian and Darriwilian strata (Huff et al., 1998; Thompson et al., 2012). The age, composition, and distribution of the bentonites are consistent with supply from Famatina, a continental-margin volcanic arc formed on the western margin of Gondwana during subduction of the Precordillera lithosphere (Astini, 1998a; Huff et al., 1998; Fanning et al., 2004; Astini et al., 2007).

Las Vacas Conglomerate

The Gualcamayo black shale grades upward into a turbidite succession of conglomerates, sandstones, and mudstones (Las Vacas Conglomerate, Fig. 2), recording progradation of coarser detritus over the platform (Astini et al., 1995; Astini, 1998a). Lenses of Las Vacas Conglomerate within the upper part of the Gualcamayo Shale mark the upward transition; however, locally at least, the basal Las Vacas rests on a scour surface/erosional unconformity that truncates part to all of the Gualcamayo (Astini, 1991; Thomas and Astini, 2007). Graptolite faunas show depositional ages ranging from late Middle to early Late Ordovician (late Darriwilian into early Sandbian) (Astini, 2003).

The Las Vacas Conglomerate contains two distinct populations of clasts defined by size and composition: (1) rounded lithic cobbles and boulders (mostly <35 cm) of igneous rocks (mainly granodiorites, tonalites, and gabbros, and a variety of volcanic rocks), metamorphic rocks (mostly quartzites, meta-arkoses, and less common gneisses and meta-igneous rocks), sedimentary rocks (mostly feldspathic and subfeldspathic sandstones, rare quartz sandstones, carbonates, and second-cycle conglomerates), and vein quartz; and (2) large blocky olistoliths (10 m scale) exclusively of San Juan Limestone and Gualcamayo Shale, in some of which the beds are folded (Astini, 1991; Thomas and Astini, 2007). The matrix of the polymictic conglomerate and the interbedded sandstones are lithic arenites to graywackes. The rounded clasts of igneous and metasedimentary rocks largely represent an extra-basinal source, whereas the limestone and shale olistoliths represent a proximal intra-basinal source and cannibalization of the Gualcamayo black shales and topmost passive-margin carbonates (San Juan Limestone). Boulders (20–30 cm) of conglomerate, containing clasts of extra-basinal rocks, indicate recycling from previously deposited conglomerates within an advancing clastic wedge.

The oldest conglomerates are in the northeastern Precordillera and are Darriwilian; widespread deposition of coarse clastic detritus mostly supplanted black mud to the south and west by Sandbian time (Astini, 2003). The clastic succession is thickest and contains generally coarser lithic clasts in the northeasternmost Precordillera, and it thins and fines southward and westward (Astini et al., 1995). To the south, along apparent strike in the Precordillera, a laterally equivalent, thinner succession includes conglomerate beds of smaller clast sizes in the La Cantera (Sandbian) and La Pola (Katian) Formations (Fig. 2) (Astini, 1991, 2001b, 2003). Separate conglomerate units are irregular in thickness and laterally discontinuous, consistent with channels in proximal subaqueous fan-delta to deep turbidite-fan facies. The lower Las Vacas (as much as 330 m thick) includes massive conglomerates and grades up into a better stratified, fining upward succession ~120 m thick. Locally, the upper part of the Las Vacas grades into a muddy facies, the Las Plantas Shale (Fig. 2) (Astini et al., 1986; Astini, 1991), suggesting an interchannel setting between turbidite fans.

Most of the rounded lithic clasts represent metamorphic and igneous extra-basinal sources. The clast sizes indicate proximal sources; the clast shapes suggest extensive fluvial and shallow-marine reworking, followed by resedimentation through submarine channels (Astini, 1991). The conglomerate also contains sedimentary clasts, consistent with erosion of Precordillera cover strata as suggested by local scour surfaces. The very large, blocky olistoliths of the San Juan Limestone and Gualcamayo Shale indicate emplacement of block slides and falls from proximal sources along the leading edges of thin-skinned thrust sheets detached in the San Juan Limestone (Thomas and Astini, 2007). Stratigraphic restriction of the large olistoliths to the youngest pre-conglomerate beds of the Precordillera sedimentary cover argues against unroofing of basement uplifts as previously inferred for either extensional block faults (e.g., Keller, 1999; Astini and Thomas, 1999; Thomas and Astini, 2003) or strike-slip faults (e.g., Aceñolaza et al., 2002; Finney, 2007) within the depositional basin.

Zircons from sandstone interbeds, matrix, and clasts of the Las Vacas Conglomerate were collected and analyzed for U/Pb ages. Analyses of three sandstone interbeds represent the detrital-zircon component of the Las Vacas (Figs. 2, 3). Analyses of two igneous clasts, one quartzite clast, one red sandstone clast, and one gneiss clast represent the most common lithologic types and the diversity of igneous and metamorphic extra-basinal clasts in the Las Vacas (Figs. 4, 5). Previously reported analyses (Gleason et al., 2007; Abre et al., 2012) of detrital zircons from three sandstones in the thinner La Cantera Formation (Figs. 2, 6) to the south along strike are available for comparison with the new data.

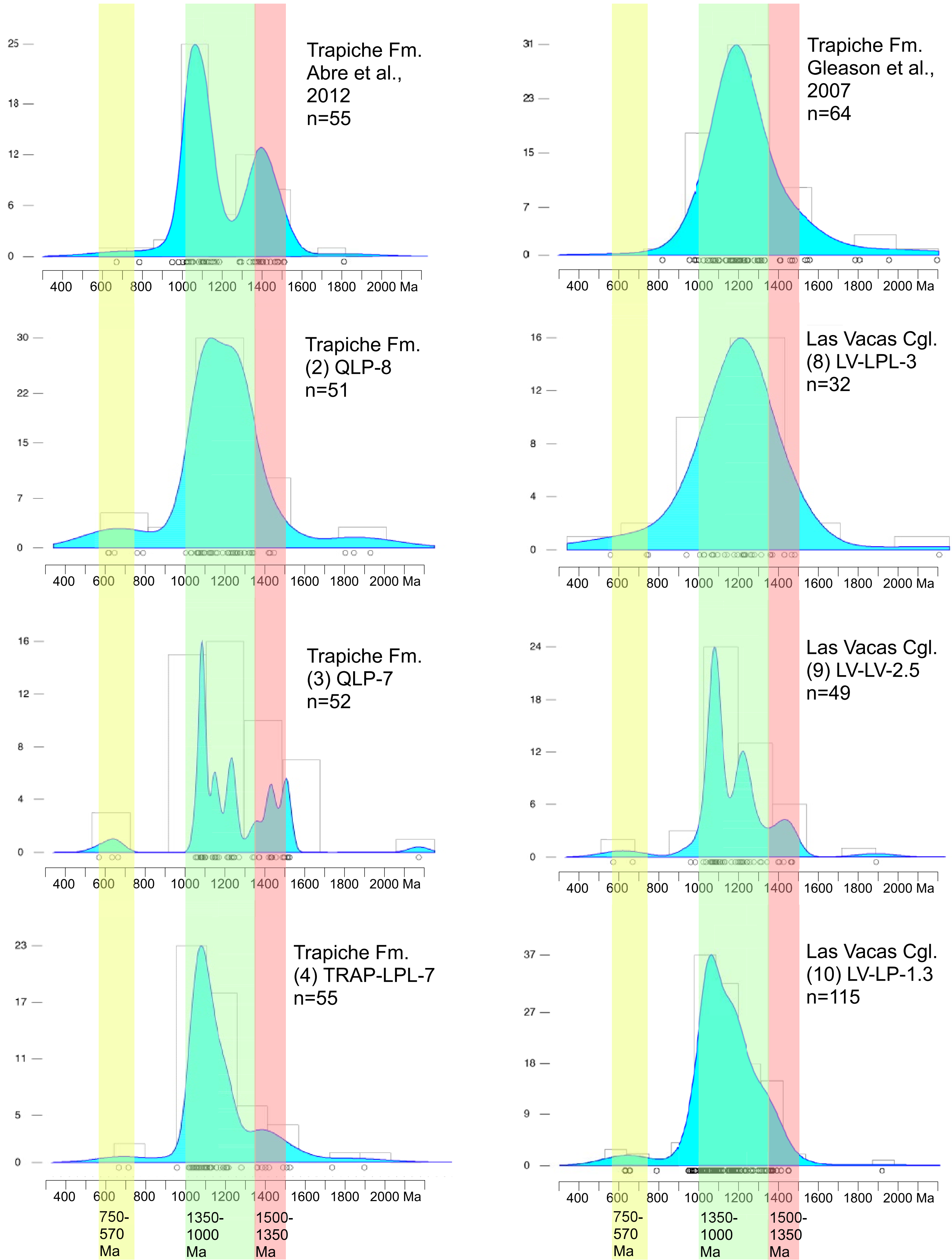

Figure 3. Kernel density estimator plots (Vermeesch, 2012) of samples from a vertical succession through the Las Vacas Conglomerate and Trapiche Formation in the northeastern Precordillera (sample locations shown in Figures 1 and 2, and documented in Supplemental Table 1; data listed in Supplemental Table 1 [see footnote 2]). In descending stratigraphic order, the top of the section is at the top of the left column, down the left column, to top of right column, and down the right column to the bottom of the section. Color bands highlight the most dominant mode (green), secondary mode (pink), and minor mode (yellow) of ages of detrital zircons to enhance comparisons through the complete vertical succession. Depositional ages of the Las Vacas–Trapiche succession span ~460 to ~450 Ma.

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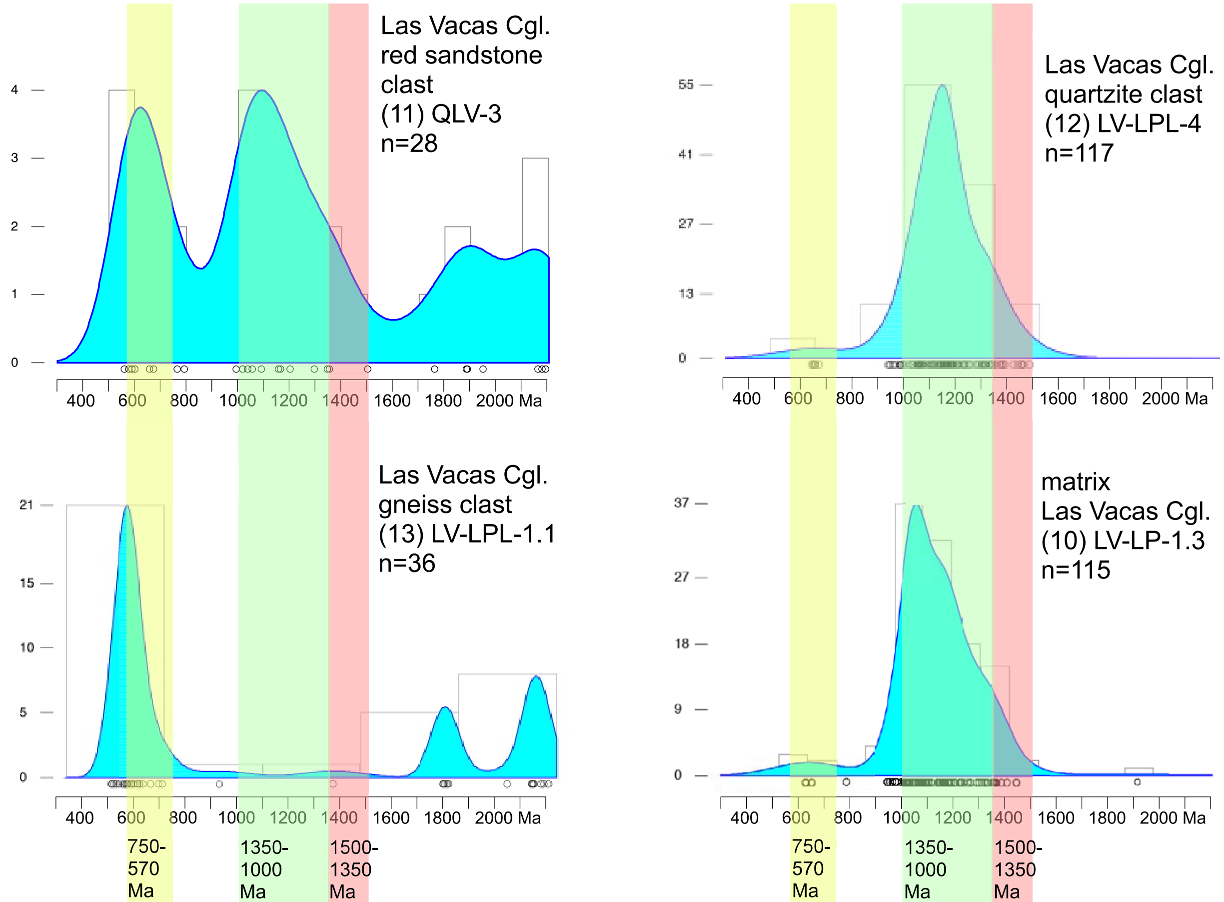

Figure 4. Kernel density estimator (KDE) plots of zircon analyses of a red sandstone clast (11.QLV-3), a quartzite clast (12.LV-LPL-4), and a gneiss clast (13.LV-LPL-1.1) in the Las Vacas Conglomerate (sample locations shown in Figures 1 and 2, and documented in Supplemental Table 1; data listed in Supplemental Table 1 [see footnote 2]); and a KDE plot of detrital zircons from the matrix sandstone (10.LV-LP-1.3, repeated from Figure 3). Color bands highlight the most dominant mode (green), secondary mode (pink), and minor mode (yellow) of ages of detrital zircons (from Figure 3).

Trapiche Formation

Above the coarse conglomerates and the local shale facies of the Las Vacas Conglomerate, the Trapiche Formation includes muddy and sandy turbidites that form the bulk of the clastic succession (Fig. 2). In the eastern Precordillera, the Trapiche consists of quartz arenites in classic turbidite sequences interlayered with muddy, finer grained turbidites. A mappable angular unconformity between the Trapiche and Las Vacas formations truncates a thin-skinned thrust fault and associated folds (Thomas and Astini, 2007). Along the angular unconformity, the lowermost Trapiche is a muddy turbidite. Unlike the underlying Las Vacas, the Trapiche in the eastern Precordillera contains no large intra-basinal olistoliths.

In the more westerly Andean thrust sheets in the Precordillera (Fig. 1), the Trapiche Formation does contain carbonate-boulder megabeds and olistoliths interlayered with otherwise finer muddy turbidites and quartzose sandy turbidites (Fig. 2) (Astini, 1994b). Multiple zones of carbonate megabeds include clasts from the passive-margin stratigraphic succession from the Zonda Formation to San Juan Limestone (Fig. 2), contrasting with the more restricted

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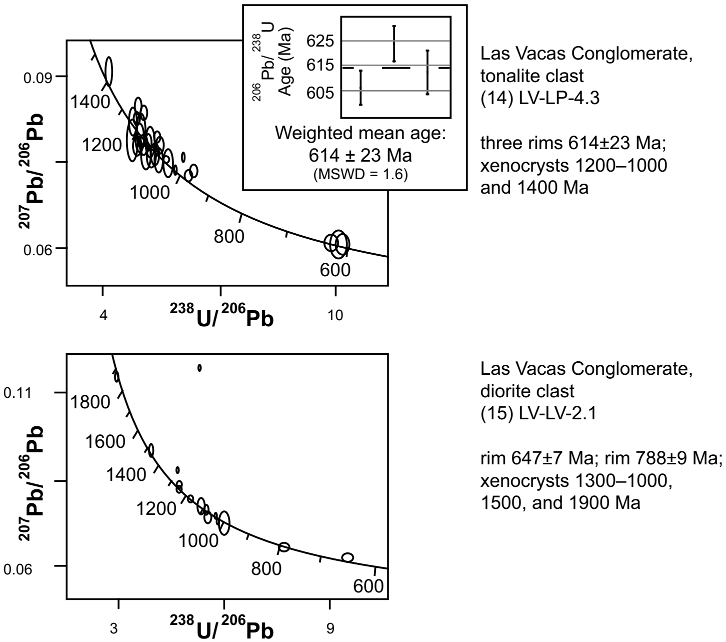

Figure 5. Tera-Wasserburg diagrams of U/Pb analyses of zircons from two igneous clasts (14.LV-LP-4.3, 15.LV-LV-2.1) in the Las Vacas Conglomerate (sample locations shown in Figures 1 and 2, and documented in Supplemental Table 2; data listed in Supplemental Table 2 [see footnote 3]).

stratigraphic range of olistoliths in the Las Vacas Conglomerate in the eastern Precordillera (Thomas and Astini, 2007). The contrast in olistoliths between the Las Vacas and Trapiche suggests a higher amplitude west-vergent frontal ramp with thin-skinned detachment in the Zonda Formation during Trapiche deposition (Thomas and Astini, 2007).

Along with southwestward progradation of the clastic facies and the distribution of clast sizes, west-directed paleocurrents in the northeastern Precordillera indicate sediment supply from the east (Astini, 1991, 1998b). In tracing the Trapiche Formation westward across strike of multiple Andean thrust sheets in the northern Precordillera, the prevailing westward paleocurrent patterns in the east progressively diverge northward and southward toward the west, consistent with transverse drainage across the proximal (eastern) part of the basin, diverging to more longitudinal currents within the more distal (western) part of the foredeep. The paleocurrent patterns are consistent with a single foreland basin.

The Trapiche Formation in the northeastern Precordillera, as well as the upper member of the La Cantera Formation and the La Pola Formation to the south along strike (Fig. 2), represent deep-water turbidite complexes as young as middle Late Ordovician (middle Katian) (Astini, 1991, 2003). The Trapiche Formation has a maximum thickness of ~1250 m, and is truncated unconformably beneath Carboniferous strata. In contrast, the equivalent units to the south are thinner (<300 m) and are truncated beneath late Late Ordovician Hirnantian glacial deposits (Don Braulio Formation, Fig. 2) (Astini, 2003; Astini et al., 2005). The La Pola Formation has many of the distinctive characteristics of the Trapiche Formation, including polymictic conglomerates with quartz-sand matrix and westerly directed paleocurrents (Astini, 2001b).

Samples were systematically collected through the stratigraphic succession in the eastern Precordillera and through two stratigraphic successions in the western thrust sheets (Figs. 1, 2, 3, 7). Three samples, as well as two previously published results (Gleason et al., 2007; Abre et al., 2012), represent the vertical succession of the Trapiche Formation in the east (Fig. 3), and three samples represent the succession in the west (Fig. 7). One of the previously analyzed samples was reported to be from the Las Vacas Conglomerate (Gleason et al., 2007); however, the lithologic description and location of the quartzose sandstone sample suggest that it is likely from the lower Trapiche Formation.

Don Braulio Formation

In the east-central Precordillera (Fig. 1), the Upper Ordovician (Hirnantian) Don Braulio Formation (Fig. 2) contains the record of Gondwanan glaciation (Buggisch and Astini, 1993; Astini, 2001a). In addition to classic glacial diamictites, the Don Braulio Formation includes interbeds of sandstone, one of which was analyzed for detrital-zircon ages (Fig. 6).

SUMMARY OF METHODS, DATA, AND RESULTS

Methods

Details of analytical procedures, U/Pb data, data presentations, and sample locations are described and listed in the supplemental material (Supplemental File[1], Supplemental Table 1[2], and Supplemental Table 2[3]). In brief, U/Pb systematics of zircons were determined at the sub-grain level by either SIMS (ion probe) following Barth and Wooden (2006), multi-collector ICP-MS (Mueller et al., 2008), or single collector ICP-MS (Chang et al., 2006), and were guided by cathodoluminescence images. Plots of age distributions of <5% discordant ^{206}Pb/^{238}U ages and <10% ^{207}Pb/^{206}Pb ages utilized the *density plotter* routine of Vermeesch (2012) to calculate a kernel density estimator (KDE) for each sample, both for data reported here and previously published data. Errors for all ages from all sources quoted in the text are at the 2-sigma level.

Zircons from Sandstones

Eight samples represent a vertical succession through the thick Middle–Upper Ordovician clastic wedge in the northeastern Precordillera: three from the Las Vacas Conglomerate, and five from the Trapiche Formation (Figs. 1,

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Supplemental File. Geochronologic Methods and Data

PRESENTATION

Zircons were separated from all samples by conventional density, size, and magnetic methods. Zircons were mounted in epoxy disks, polished to expose the grain interiors, and imaged using cathodoluminescense. These images were used to guide the analyses by either laser ablation inductively coupled plasma mass spectrometry or secondary ion mass spectrometry (SIMS: SHRIMP–RG, sensitive high resolution ion microprobe–reverse geometry). All ages mentioned in the text are listed in Supplemental Tables 1 and 2, and are reported at the 2σ level in the text. For ages <900 Ma, ages were calculated from the ratio of ^{206}Pb/^{238}U, and discordance was based on the difference between the ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ages. For ages >900 Ma, ages were calculated from the ratio of ^{207}Pb/^{206}Pb, and discordance was based on the difference between the ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U ages. For data plotted from published reports, the same criteria were applied. All ^{207}Pb/^{206}Pb ages reported or utilized in plots are <10% discordant, and ^{206}Pb/^{238}U ages are <5% discordant.

[1]Supplemental File: Geochronologic methods and data. Please visit http://dx.doi.org/10.1130/GES01212.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.

SUPPLEMENTAL TABLE 1. U/Pb ISOTOPIC DATA, AGES OF DETRITAL ZIRCONS, AND SAMPLE LOCATIONS

Sample Grain ID	All Ages in Ma ^{206}Pb/^{238}U	2 σ	^{207}Pb/^{235}U*	2 σ	^{207}Pb/^{206}Pb	2 σ	% D	^{204}Pb/^{206}Pb
1.DB-DB-3—Don Braulio Formation—31° 12' 57.0" S, 68° 29' 15.9" W								
DB-DB-3_17	513	13	523	12	570	25	-2.1	0.0028
DB-DB-3_29	614	18	615	15	617	24	-0.1	0.0008
DB-DB-3_26	618	20	619	16	624	18	-0.2	0.0012
DB-DB-3_47	676	27	683	22	707	32	-1.1	0.0018
DB-DB-3_35	1205	35	1137	23	1010	22	-19.4	0.0018
DB-DB-3_45	1004	32	1007	22	1014	15	0.9	0.0006
DB-DB-3_5	962	24	981	18	1023	17	5.9	0.0008
DB-DB-3_46	923	31	964	25	1059	40	12.8	0.0026
DB-DB-3_18	1004	26	1028	19	1080	14	7.0	0.0003
DB-DB-3_41	1113	36	1103	24	1084	19	-2.7	0.0019
DB-DB-3_2	1011	28	1037	20	1093	16	7.5	0.0005
DB-DB-3_37	1124	30	1121	20	1115	15	-0.8	0.0005
DB-DB-3_1	1027	29	1056	20	1118	17	8.1	0.0007
DB-DB-3_21	1099	31	1107	21	1121	16	1.9	0.0008
DB-DB-3_36	1176	32	1159	21	1128	15	-4.3	0.0003
DB-DB-3_24	500	15	630	52	1131	216	2.1	0.0010
DB-DB-3_30	1208	39	1182	25	1134	18	-6.5	0.0005
DB-DB-3_7	1002	26	1045	20	1135	23	11.6	0.0013
DB-DB-3_22	1123	39	1128	26	1136	16	1.1	0.0007
DB-DB-3_11	1081	25	1100	17	1137	14	4.9	0.0003
DB-DB-3_19	974	29	1029	36	1147	93	15.0	0.0075
DB-DB-3_6	1107	27	1131	18	1176	15	5.9	0.0005
DB-DB-3_10	1089	28	1121	20	1184	16	8.0	0.0007
DB-DB-3_3	1113	32	1140	22	1191	16	6.5	0.0012
DB-DB-3_23	1237	31	1222	20	1196	13	-3.5	0.0002

[2]Supplemental Table 1. U/Pb isotopic data, ages of detrital zircons, and sample locations. Please visit http://dx.doi.org/10.1130/GES01212.S2 or the full-text article on www.gsapubs.org to view Supplemental Table 1.

SUPPLEMENTAL TABLE 2. SIMS U/Pb GEOCHRONOLOGIC DATA, APPARENT AGES FOR CLASTS OF IGNEOUS ROCKS, AND SAMPLE LOCATIONS

Spot[a]		U[b]	Th	Th/U	^{206}Pb*[b]	f^{206}Pb$_c$[b]	^{238}U/^{206}Pb[c]		^{207}Pb/^{206}Pb[c]		^{206}Pb/^{238}U[d]		^{207}Pb/^{206}Pb[d]	
15.LV-LV-2.1—Las Vacas Conglomerate (diorite clast)—29° 41' 25.7" S, 68° 39' 47.6" W														
8.1	om	415	242	0.6	38	0.16	9.4613	(1.1)	0.0625	(1.3)	647	(7)	679	(29)
14.1	om	276	163	0.6	31	<0.01	7.6908	(1.1)	0.0654	(1.4)	788	(9)	780	(30)
10.1	c	47	28	0.6	7	<0.01	5.9837	(1.7)	0.0724	(3.0)	996	(16)	960	(69)
4.1	r	908	56	0.1	134	<0.01	5.8133	(0.3)	0.0728	(0.7)			989	(15)
11.1	c	163	54	0.3	25	<0.01	5.5155	(1.2)	0.0741	(1.5)			1033	(30)
2.1	c	839	415	0.5	125	0.07	5.7426	(0.3)	0.0743	(0.6)			1040	(14)
5.1	c	194	150	0.8	30	0.08	5.4760	(0.7)	0.0761	(1.3)			1082	(27)
13.1	c	93	23	0.3	15	0.09	5.3306	(1.3)	0.0772	(2.1)			1106	(43)
12.1	c	442	80	0.2	75	0.07	5.0341	(1.1)	0.0794	(0.8)			1181	(16)
7.1	c	436	66	0.2	79	0.03	4.7126	(1.1)	0.0820	(0.8)			1232	(17)
9.1	c	392	62	0.2	71	0.21	4.7165	(1.1)	0.0834	(0.8)			1268	(16)
1.1	c	564	430	0.8	104	0.66	4.6703	(0.4)	0.0875	(0.7)			1363	(13)
15.1	c	144	45	0.3	32	0.15	3.9051	(1.3)	0.0933	(1.1)			1480	(22)
3.1	r	227	162	0.7	66	<0.01	2.9314	(0.6)	0.1141	(0.7)			1857	(14)
6.1	r	893	350	0.4	145	4.99	5.2958	(0.4)	0.1167	(0.6)			1877	(13)

[3]Supplemental Table 2. SIMS U/Pb geochronologic data, apparent ages for clasts of igneous rocks, and sample locations. Please visit http://dx.doi.org/10.1130/GES01212.S3 or the full-text article on www.gsapubs.org to view Supplemental Table 2.

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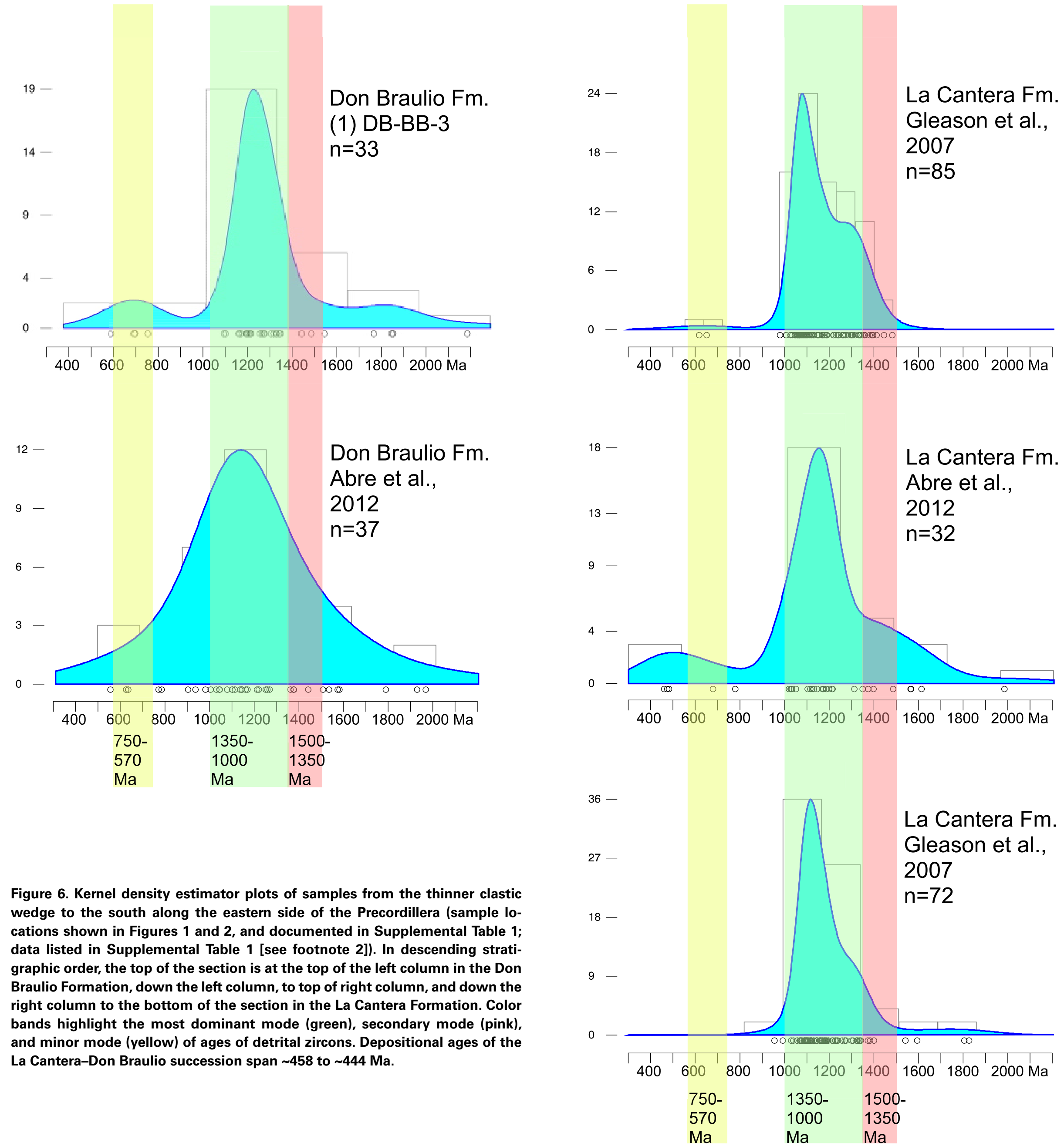

Figure 6. Kernel density estimator plots of samples from the thinner clastic wedge to the south along the eastern side of the Precordillera (sample locations shown in Figures 1 and 2, and documented in Supplemental Table 1; data listed in Supplemental Table 1 [see footnote 2]). In descending stratigraphic order, the top of the section is at the top of the left column in the Don Braulio Formation, down the left column, to top of right column, and down the right column to the bottom of the section in the La Cantera Formation. Color bands highlight the most dominant mode (green), secondary mode (pink), and minor mode (yellow) of ages of detrital zircons. Depositional ages of the La Cantera–Don Braulio succession span ~458 to ~444 Ma.

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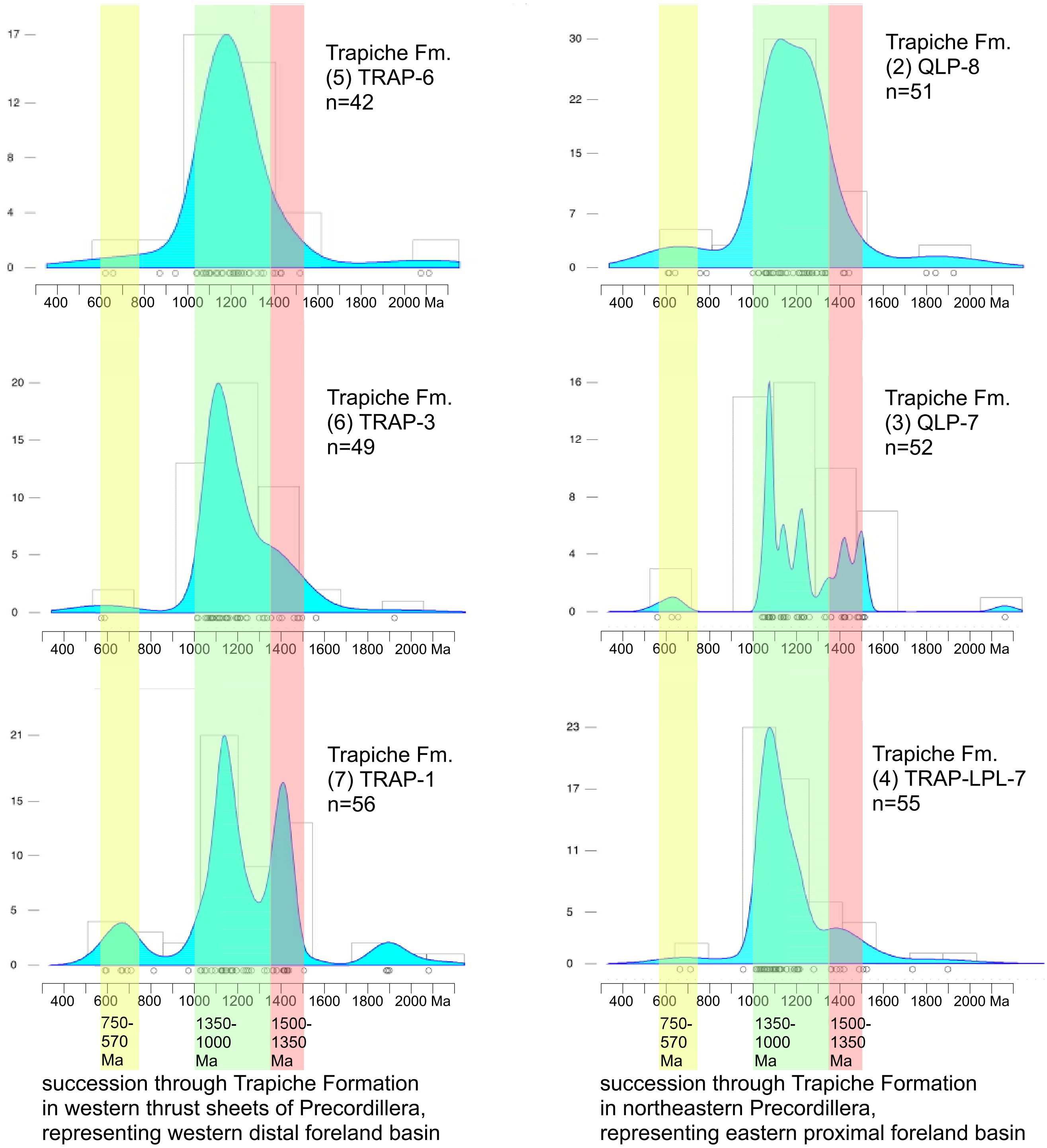

Figure 7. Kernel density estimator plots of samples from the Trapiche Formation, to compare a succession of three samples in the northeastern Precordillera (right column in stratigraphic order, also shown in Figure 3) with a succession of three samples farther to the west (left column in stratigraphic order) (sample locations shown in Figures 1 and 2, and documented in Supplemental Table 1; data listed in Supplemental Table 1 [see footnote 2]). Color bands highlight the most dominant mode (green), secondary mode (pink), and minor mode (yellow) of ages of detrital zircons.

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2, 3). Five samples represent a vertical succession through the thinner clastic succession to the south along the eastern side of the Precordillera (Figs. 1, 2, 6). The distributions of detrital-zircon ages define distinct populations that are remarkably consistent through all of the samples. The dominant mode is between 1350 and 1000 Ma; the most distinct concentration is at ~1150–1050 Ma in most of the samples (Figs. 3, 6). An important secondary mode is between 1500 and 1350 Ma (Figs. 3, 6). Younger ages are scattered sparsely between 1000 and 440 Ma (Figs. 3, 6); however, only two grains (440 ± 10 and 477–463 Ma in the La Cantera Formation; Abre et al., 2012) are younger than 507 Ma. A minor concentration of grains is between 750 and 570 Ma (Figs. 3, 6). Older, less concentrated age groupings are scattered between 2720 and 1500 Ma (Figs. 3, 6), but grains older than 1800 Ma are very rare. The distributions of ages of detrital zircons from the thinner clastic wedge to the south are indistinguishable from those from the thicker Las Vacas–Trapiche succession in the northeastern Precordillera (compare Fig. 3 and Fig. 6).

A group of six samples from the Trapiche Formation (Fig. 7) represents the east-to-west distribution across the Precordillera. Three samples are from the vertical set in the northeastern Precordillera illustrated in Figure 3, and three are from outcrops farther west in the Precordillera (Figs. 1, 2, 7). These samples, representing the more proximal and more distal components of the Trapiche, show no distinct differences in dominant and secondary age modes across the depositional system. The samples in the western Trapiche have a dominant mode of 1350–1000 Ma with the primary concentration at 1100–1010 Ma (Fig. 7). An important secondary mode is between 1500 and 1350 Ma (Fig. 7). Sparsely represented younger ages range from 970 to 531 Ma with a minor concentration at 750–570 Ma (Fig. 7). Older grains are less abundant and range from 2061 to 1516 Ma (Fig. 7).

Two conclusions can be drawn from these sample sets. First, dispersal of sediment from one composite source persisted through the Middle and Late Ordovician deposition of the succession from the lower Las Vacas Conglomerate through the Trapiche Formation in the northeastern Precordillera, and from the La Cantera Formation to the Don Braulio Formation in the south. Second, a consistent composite provenance supplied detritus for the Trapiche Formation across the width of the foreland basin. In summary, sediment from one regional provenance spread both north-to-south along the basin and east-to-west across the basin, indicating both a temporally persistent source and a unified dispersal system across a single basin.

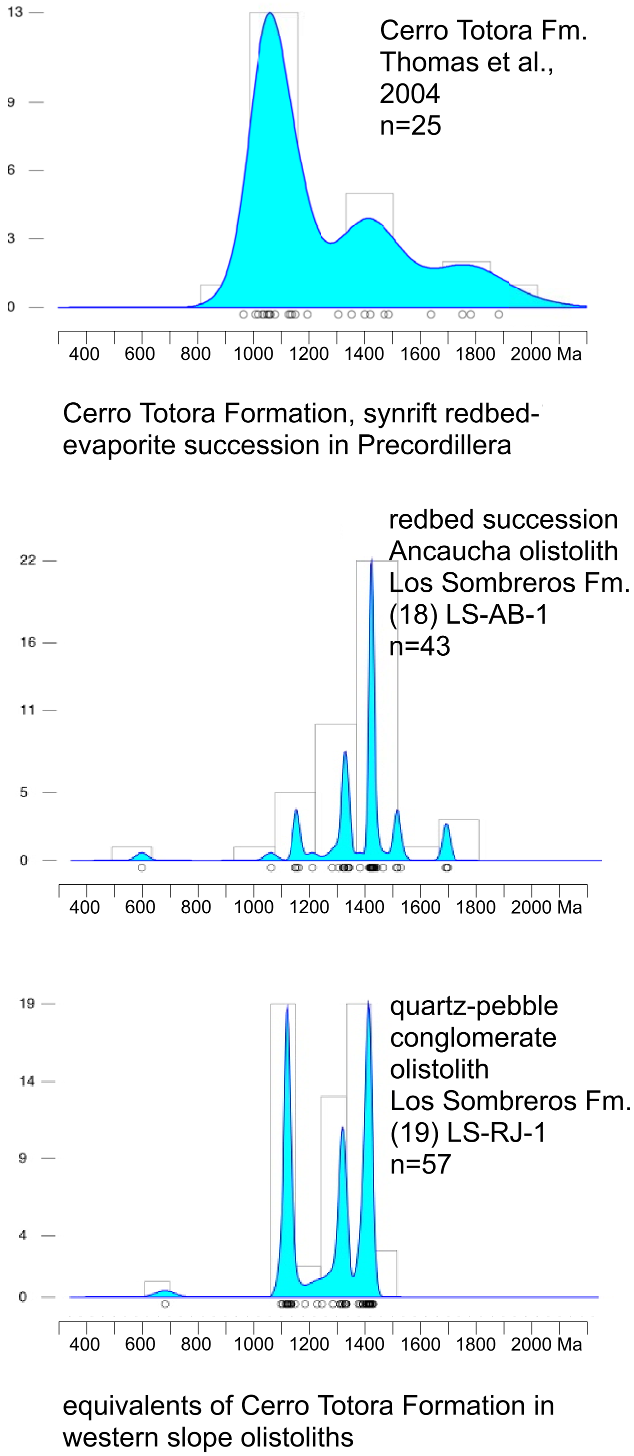
Zircons from Lithic Clasts in the Las Vacas Conglomerate

Two clasts of igneous rocks in the Las Vacas Conglomerate have numerous xenocrystic zircons that dominantly range in age between 1200 and 1000 Ma with a few older components (Fig. 5). These data indicate a Grenville-age source for the magmas. Rims (overgrowths) on the older zircons are distinctly younger. Three analyses of rims from a tonalite clast (14.LV-LP-4.3) have Th/U ratios >0.1, which is consistent with an igneous origin, and give a concordant $^{206}Pb/^{238}U$ age of 614 ± 23 Ma, which is interpreted to be the crystallization age. A diorite clast (15.LV-LV-2.1) yielded fewer zircons; the youngest $^{206}Pb/^{238}U$ age of 647 ± 7 Ma from a rim on one grain provides a maximum crystallization age. The xenocryst ages in both samples are consistent with the dominant detrital-zircon ages in the Las Vacas sandstones; the Neoproterozoic crystallization ages are represented less abundantly in the detrital populations.

Ages of detrital zircons from a quartzite clast (12.LV-LPL-4) mostly range from 1467 to 917 Ma with concentrations near 1440, 1320, 1140, 1060, and 940 Ma, and have a less prominent concentration at 656–628 Ma, consistent with the crystallization ages of the igneous clasts (Fig. 4). The quartzite includes single grains at 2704, 1733, and 1521 Ma. The maximum depositional age of the quartzite is younger than the youngest detrital grain (628 Ma), and the age of quartzite metamorphism is older than the Middle Ordovician depositional age of the Las Vacas Conglomerate. The quartzite clast in the Las Vacas may have been derived from the lower part of the Caucete Group (Fig. 2), which is in the footwall of the west-directed Las Pirquitas thrust fault along the western side of the Sierra de Pie de Palo (Fig. 1) east of the Ocloyic foreland basin. The Caucete Group is interpreted to have been deposited on Precordillera basement in a rift setting before separation of the Precordillera from Laurentia; the provenance is interpreted to have been primarily Laurentian Grenville and Granite-Rhyolite basement rocks along with a lesser contribution from Iapetan synrift rocks (Naipauer et al., 2010). Similarity to the distribution of ages of detrital zircons from sandstones in the Middle–Upper Ordovician clastic wedge (compare Fig. 4 with Figs. 3, 6, 7) suggests that reworking of the quartzite could have been an important contributor of the sand-sized detritus in the Ordovician sandstones.

Clasts of gneiss are rare in the Las Vacas Conglomerate; however, one clast was collected for zircon analysis. The gneiss clast (13.LV-LPL-1.1) has a spectrum of ages distinct from that of the sand-sized detritus in the Las Vacas (Fig. 4). The most dominant ages in the gneiss are 2194–2009, 1786–1759, and 672–472 Ma; other ages are sparse (Fig. 4). The younger age concentration (672–472 Ma) is similar to the youngest secondary mode in the ages of detrital grains in the Las Vacas Conglomerate (Fig. 3) and includes the crystallization age of the igneous clasts (Fig. 5).

A clast of red sandstone (11.QLV-3) has detrital-zircon ages with no distinct concentrations; instead ages are loosely clustered at 2200–2150, 1950–1880, 1350–1000, and 800–550 Ma (Fig. 4). The younger cluster is similar in age to minor components of the detrital population in the Las Vacas sandstones (Fig. 3), as well as a significant concentration in the gneiss clast (Fig. 4), a minor component of the quartzite clast (Fig. 4), and the crystallization age of the igneous clasts (Fig. 5). The ages between 1350 and 1000 Ma correspond to the primary concentration in the Las Vacas detrital grains (Fig. 3) and the dominant concentration in the quartzite clast (Fig. 4). Ages between 2200 and 1880 Ma correspond to minor components of the detrital grains and to a significant concentration in the gneiss clast (Fig. 4). The age spectrum of the red sandstone is distinctly different from the red sandstone in the Lower Cambrian Cerro Totora Formation (compare Figs. 4 and 8) (Thomas et al., 2004), which is the only known pre-Ordovician redbed unit in the Precordillera.



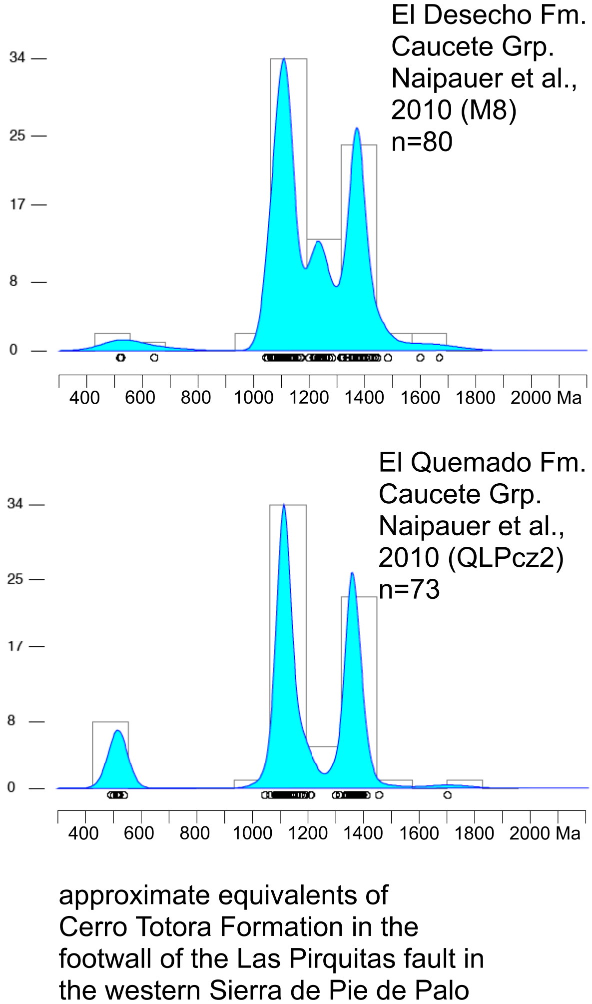


Figure 8. Kernel density estimator plots of detrital-zircon populations in late synrift sandstones of the Precordillera: Cerro Totora Formation synrift redbeds of the Precordillera cover succession; two samples from olistoliths in the Los Sombreros Formation of the western slope facies of the Precordillera (sample locations shown in Figures 1 and 2, and documented in Supplemental Table 1; data listed in Supplemental Table 1 [see footnote 2]); and samples from the El Desecho and El Quemado Formations (Caucete Group) in the footwall of the Las Pirquitas fault in the western part of the Sierra de Pie de Palo (stratigraphic units shown in Figure 2).

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POSSIBLE SEDIMENT SOURCES

Sedimentological data and interpretations indicate westward dispersal of clastic sediment from a source east of the Precordillera. Detrital-zircon age populations characterize the ages of potential source rocks and strongly indicate a consistent source of sediment both along and across strike of the Precordillera and throughout the Middle to Late Ordovician time span of deposition of the clastic wedge. Potential sediment sources to the east of the Precordillera clastic wedge include an alignment of basement massifs (Sierras de Maz, Espinal, Umango, Pie de Palo, and Valle Fértil; Fig. 1). Farther east, the Famatina magmatic arc (Fig. 1) is an Ordovician continental-margin arc associated with the subduction of the leading edge of the Precordillera terrane. Basement rocks of the Precordillera may constitute part of the forearc accretionary complex. Synrift and passive-margin strata of the Precordillera cover, deformed and uplifted within the accretionary complex of the eastern Precordillera, may have supplied recycled detritus to the clastic wedge.

Basement Massifs East of the Precordillera

Zircons from basement orthogneisses in the Sierra de Pie de Palo (Figs. 1, 9) have U/Pb ages ranging from 1282 to 938 Ma (McDonough et al., 1993; Casquet et al., 2001; Vujovich et al., 2004; Rapela et al., 2010; Mulcahy et al., 2011; Garber et al., 2014). A granite orthogneiss has a zircon age of 774 ± 6 Ma, which is interpreted to be from an early phase of Iapetan rifting (Baldo et al., 2006). A metadacite/rhyolite exposed within a structural window above sedimentary rocks of the Caucete Group in the Sierra de Pie de Palo has a crystallization age of 669 ± 6 Ma; xenocrystic grains have ages of ~1200–1020 Ma (Mulcahy et al., 2011). A metasedimentary garnet-mica schist has detrital zircons dominantly with Mesoproterozoic ages less than 1160 Ma, but the youngest detrital grain has an age of ~665 Ma (Vujovich et al., 2004). Within the Sierra de Pie de Palo, Ocloyic metamorphism peaked at ~470–465 Ma (Ramos et al., 1998; Casquet et al., 2001; Vujovich et al., 2004; Mulcahy et al., 2011; Garber et al., 2014); small plutons, dikes, and sills have ages of 480–440 Ma (Pankhurst et al., 1998; Baldo

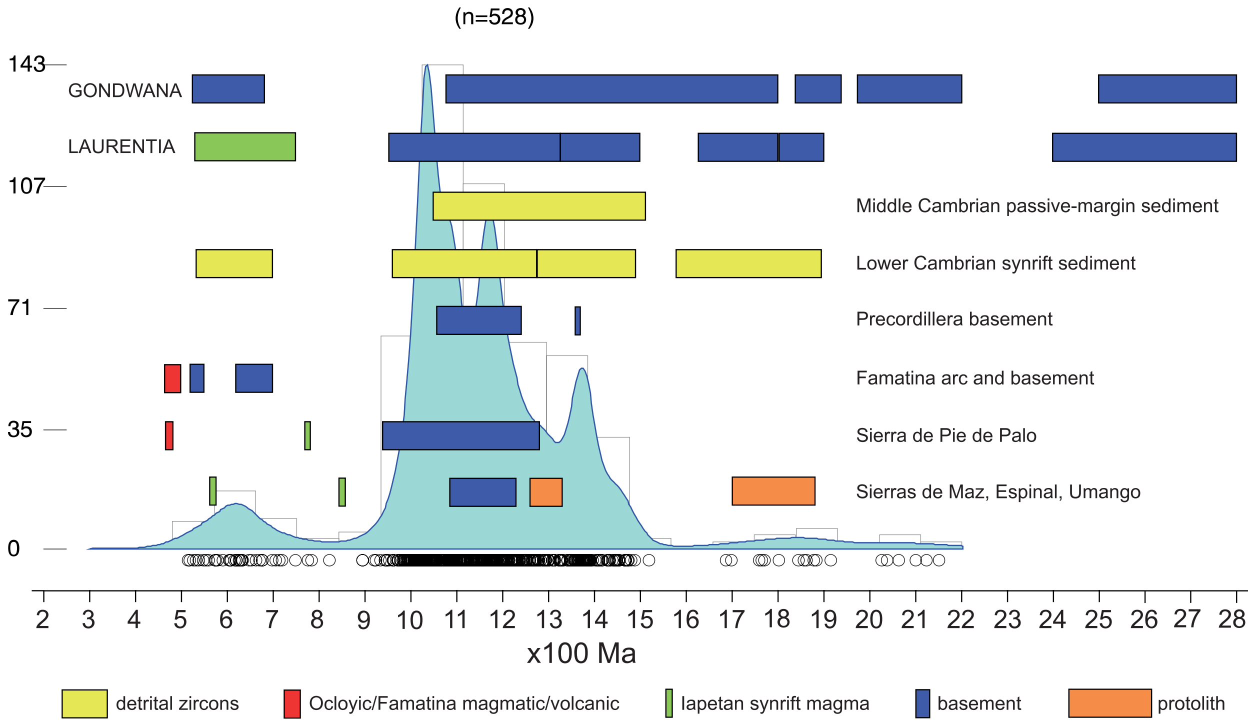

Figure 9. Comparison of detrital-zircon age populations (composite kernel density estimator [KDE] plot of detrital zircons in samples 1 through 10, n = 528) in the Middle–Upper Ordovician clastic wedge in the Ocloyic foreland basin on the Precordillera with the ages of rocks in possible components of the provenance, and a general comparison with ages of basement rocks in Laurentia and Gondwana. For potential provenance of basement rocks and igneous rocks, the color bars represent the ranges of all reported ages. For potential provenance of recycled detrital zircons from Precordillera sedimentary cover rocks, the color bars summarize the ranges of ages, which are shown in KDE plots in Figures 8 and 10.

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et al., 2005; Mulcahy et al., 2011). Thermo-barometric data (Dalla Salda and Varela, 1984; Casquet et al., 2001; Mulcahy et al., 2011; Garber et al., 2014) document as much as 40–45 km of unroofing of the Pie de Palo basement since the Ordovician (Ramos, 2004).

Zircons from a metasedimentary garnet schist in the Sierra de Maz (Figs. 1, 9) have cores with U/Pb ages of 1880–1700 Ma and overgrowths with ages of 1230–1180 (weighted mean 1208 ± 28) Ma, indicating a Paleoproterozoic provenance of metasedimentary rocks and Mesoproterozoic high-grade metamorphism (Casquet et al., 2006). Orthogneisses have igneous crystallization ages of 1092 ± 6 to 1086 ± 10 Ma; older orthogneisses have protolith ages of 1330–1260 Ma and metamorphic ages of 1175–1095 Ma (Rapela et al., 2010). A granitic orthogneiss in the Sierra de Umango (Figs. 1, 9) has a U/Pb zircon age of 1108 ± 13 Ma (Varela et al., 2003). Younger rocks interpreted to be rift related include mylonitic orthogneisses in Sierra del Espinal (Figs. 1, 9) with an age of 845 Ma (Baldo et al., 2008; Colombo et al., 2009), and carbonatites and syenites in Sierra de Maz with ages of ~570 Ma (Casquet et al., 2008).

Mesoproterozoic rocks of the Sierras de Maz, Espinal, Umango, and Pie de Palo (Fig. 1) may be parts of the basement of a single larger terrane (e.g., Ramos et al., 1986; Ramos, 2004; Naipauer et al., 2010). Mesoproterozoic amalgamation of the Pie de Palo and Precordillera terranes formed the Cuyania composite terrane (Ramos, 2009). Following Mesoproterozoic amalgamation and accretion to Amazonia, Neoproterozoic breakup of Rodinia separated the composite terrane(s) from Amazonia (Ramos, 2009). Either the amalgamated terrane or a collection of separate small terranes along the leading edge of the Precordillera terrane was subducted under western Gondwana during the Ordovician Ocloyic collision (Chernicoff et al., 2009; Ramos, 2009; van Staal et al., 2011). If the basement massifs are part of the Precordillera basement, they are footwall horses in the Ocloyic accretionary complex. Alternatively, the Sierras de Maz, Espinal, Umango, and Pie de Palo may be part of a Mesoproterozoic mobile belt, extending northwest to Arequipa/Antofalla (Casquet et al., 2006, 2010), which was accreted initially to Amazonia during the Sunsas orogeny at 1200–1000 Ma (e.g., Loewy et al., 2004). If the basement terrane(s) were accreted during the Mesoproterozoic and remained attached to Amazonia, the basement massifs are hanging-wall horses in the Ocloyic accretionary complex. In either scenario, the Mesoproterozoic rocks were overprinted by Ocloyic metamorphism, shortened by top-to-west thrusting, and ultimately exposed in the proximal hinterland of the Ocloyic foreland basin on the Precordillera.

Famatina Continental-Margin Arc and Related Basement Sierras

The Ordovician Famatina volcanic/magmatic continental-margin arc (Fig. 1) formed on the western margin of Gondwana during subduction of the leading edge of the Precordillera terrane (e.g., Astini et al., 1995; Thomas and Astini, 2003; Ramos, 2004). Remnants of the arc are now exposed east of the alignment of basement massifs (Sierras de Maz, Espinal, Umango, and Pie de Palo). The evolution of the western margin of Gondwana includes: 700–640 Ma, Brasiliano orogeny imprinted on Mesoproterozoic basement; 640–600 Ma, rifting and opening of the Puncoviscana basin, and deposition of trench-fill and foreland-basin sediment, partly contemporaneous with opening of Iapetus; 550–520 Ma, Pampean orogeny, including deformation of Puncoviscana sedimentary rocks during subduction beneath a magmatic continental-margin arc; and 515–460 Ma, Famatina subduction (Collo et al., 2009; Escayola et al., 2011; Mulcahy et al., 2014). Detrital-zircon populations in post-Pampean sedimentary cover deposited on the western margin of Gondwana include dominant concentrations of 791–519 Ma (Brasiliano and Pampean) and 1294–996 Ma (Grenville), and few grains as old as ~2100 Ma (Collo et al., 2009; Adams et al., 2011). The Famatina arc complex includes a marine sedimentary and volcanic succession of Early and Middle Ordovician (Tremadocian to Darriwilian) age (Astini, 1999, 2003). Arc plutons range in age from ~499 to 468 Ma (Fig. 9) (Pankhurst et al., 2000). In the Precordillera, the succession from the upper part of the passive-margin carbonate (San Juan Formation) to the early synorogenic black shale (Gualcamayo Shale) includes numerous beds of volcanic ash (bentonites), which are temporally and geochemically linked to Famatina (Huff et al., 1997, 1998; Astini, 1998a; Astini et al., 2007). Zircons from the bentonites have ages between 473 and 464 Ma (Huff et al., 1997; Fanning et al., 2004; Thompson et al., 2012). Detrital zircons in Famatina sedimentary rocks range in age from 2097 to 473 Ma with the dominant concentration at ~641–519 Ma and a lesser concentration at 1215–996 Ma (Collo et al., 2009).

Southeastward along strike of the Famatina arc system, deeper exhumation has exposed metaplutonic and metasedimentary basement rocks of the Sierra de Valle Fértil (Fig. 1) (Otamendi et al., 2009). The central part of the range is dominated by 485–465 Ma magmatism of the Famatina arc (Ducea et al., 2010). Detrital zircons from metasedimentary rocks within the Sierra de Valle Fértil are dominated by 1050, 600, and 520 Ma ages, suggesting Cambrian sediment deposited along the Gondwana margin (Cristofolini et al., 2012). Along the western margin of the Sierra de Valle Fértil, plutonic rocks within the informally named Resina complex give ages of 1099–1062 and ~840 Ma (McClelland et al., 2005). Detrital zircons from quartzites at Las Chacras at the western margin of Sierra de Valle Fértil include ages of 1400–1000 Ma with minor concentrations at 2900 and 2680 Ma; detrital zircons from metagraywackes include ages of 650–600 and 540–515 Ma, as well as 2080, 2030, and 1180 Ma (McClelland et al., 2005). At Las Chacras, metamorphism at 461–456 Ma followed granite emplacement at 472 Ma (Casquet et al., 2012; Mulcahy et al., 2014). These data support an interpretation of a forearc/accretionary complex on the Gondwanan upper plate near the suture (Ramos, 2004; Astini and Dávila, 2004).

Basement Rocks of the Precordillera

Some, or all, of the basement massifs (Sierras de Maz, Espinal, Umango, and Pie de Palo; Fig. 1) east of the Precordillera sedimentary thrust belt may be the basement of the composite Cuyania/Precordillera terrane (e.g., Ramos et al., 1986; Astini et al., 1995; Ramos, 2004) or alternatively may represent a separate terrane or terranes (e.g., Ramos et al., 1986; Ramos, 2004, 2010; Casquet et al., 2010). In contrast, some other basement rocks are directly tied to the Precordillera.

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At the probable northern boundary of the Precordillera terrane, the northwest-trending Jagüé shear zone along the Rio Bonete (Fig. 1) includes mylonitic granite and marble (Martina and Astini, 2009). The granite is interpreted to be part of the Precordillera basement, and the associated calcitic and dolomitic marbles are consistent with a passive-margin transgression similar to that documented for the characteristic carbonate succession in the Precordillera (Martina et al., 2005; Martina and Astini, 2009). Zircons from the mylonitic granite have a weighted mean age (U/Pb LA-ICP-MS) of 1118 ± 17 Ma (Martina et al., 2005).

More than 150 km south of the primary outcrops of the Precordillera platform rocks, basement granite at Ponón Trehue in the San Rafael block (Fig. 1) underlies a basal conglomerate and overlying carbonate (Astini et al., 1995; Bordonaro et al., 1996; Cingolani and Varela, 1999; Astini, 2002; Cingolani et al., 2003). U/Pb zircon ages (weighted mean $^{207}Pb/^{206}Pb$) for granite samples are 1205 ± 1 and 1204 ± 2 Ma (Thomas et al., 2012). Basement rocks associated with metasedimentary carbonates farther south in the Las Matras block (Fig. 1) have a U/Pb zircon age of 1244 ± 42 Ma (Sato et al., 2004).

Tertiary dacitic to andesitic plutons in the Precordillera sedimentary succession at Ullún (Fig. 1) contain xenoliths of basement rocks. The xenoliths yield zircon ages of 1102 ± 6 and 1099 ± 3 Ma for mafic gneisses and 1118 ± 54 and 1096 ± 50 Ma for acidic gneisses (Kay et al., 1996). Additional U/Pb zircon data yielded a crystallization age of ~1165 Ma and a metamorphic overprint at ~1060 Ma (Rapela et al., 2010).

A conglomerate olistolith in the Los Ratones olistostrome within the Middle Ordovician off-shelf slope facies (Los Sombreros Formation) on the western margin of the Precordillera (Fig. 1) contains rounded clasts of granodiorite, granitic gneiss, and granodioritic gneiss (Thomas et al., 2012). The conglomerate is interpreted to reflect synrift erosion of continental basement rocks along fault scarps and deposition in alluvial fans within a graben system at the rifted continental margin (Astini et al., 1995; Thomas and Astini, 1999, 2003; Thomas et al., 2012). Subsequently, the synrift conglomerate was displaced by slope-collapse faults and/or submarine canyons into the Los Sombreros muddy slope facies, which contains a mixture of olistoliths from the platform, slope, and basement (Astini et al., 1995; Keller, 1999). U/Pb zircon ages of 1370 ± 2 and 1367 ± 5 Ma for two separate basement clasts within the single conglomerate olistolith are distinctly older than other known basement rocks in and around the Precordillera (Thomas et al., 2012). The basement clasts are similar in age to the Granite-Rhyolite province of southern Laurentia, suggesting that the Iapetan rift cut across the boundary between the Grenville and Granite-Rhyolite provinces and incorporated part of the Granite-Rhyolite province into the Precordillera terrane.

In summary, the zircon ages of basement rocks of the Precordillera are mostly within the range of 1244–1060 Ma, similar to ages from the basement massifs east of the Precordillera (Fig. 9). These ages indicate that most of the Precordillera basement is coeval with the Grenville orogeny of eastern Laurentia. The ages of 1370–1367 Ma for basement clasts in the Los Ratones synrift conglomerate, however, indicate that the Precordillera basement includes part of the Laurentian Granite-Rhyolite province.

Recycled Lower Cambrian Precordillera Synrift Sedimentary Rocks

The Lower Cambrian Cerro Totora Formation (Fig. 2), a succession of redbeds and evaporites, is interpreted to be the sedimentary fill of synrift grabens along the opening Iapetan rift between the Texas promontory of Laurentia and the Precordillera microcontinent terrane (Thomas and Astini, 1999). Detrital zircons from a sandstone within the redbed succession have ages in three dominant groups: 1890–1640, 1490–1300, and 1160–970 Ma (Fig. 8) (Thomas et al., 2004). The zircon ages reflect sources on the Laurentian craton (Mazatzal, Yavapai, Central Plains, and Trans-Hudson provinces; Granite-Rhyolite province; and Grenville province; respectively), indicating sediment dispersal from the Laurentian craton to the opening rift before the Precordillera completely separated from Laurentia.

In addition to the olistolith of synrift conglomerate that contains clasts of Granite-Rhyolite basement rocks, the variety of olistoliths in the Los Sombreros Formation includes a quartz-pebble conglomerate and a succession of redbeds. Detrital-zircon ages from the quartz-pebble conglomerate (19.LS-RJ-1), with the exception of a single grain at 644 Ma, are all between 1391 and 1059 Ma with prominent concentrations at 1380, 1290, and 1090 Ma (Fig. 8). A separate olistolith (18.LS-AB-1, Ancaucha block, Fig. 1) contains a succession of redbeds with carbonate interbeds; and, with the exception of a single grain at 557 Ma, a sandstone has a spread of zircon ages between 1668 and 1016 Ma with concentrations at 1650, 1490, 1390, 1280, and 1110 Ma (Fig. 8).

Along the western Sierra de Pie de Palo, marbles and quartzites of the Caucete Group in the footwall of the top-to-west Las Pirquitas thrust fault (Fig. 1) are interpreted to include metamorphosed synrift deposits of the Precordillera (Astini and Dávila, 2004; Naipauer et al., 2005, 2010; van Staal et al., 2011). Quartzites (El Quemado Formation, Fig. 2) that are stratigraphically older than the Cerro Totora Formation have detrital-zircon ages in clusters of 1449–1295, 1207–1042, and 537–492 Ma, and rare older grains (Fig. 8) (McClelland et al., 2005; Naipauer et al., 2005, 2010). Quartzites (El Desecho Formation, Fig. 2) that are approximately equivalent in depositional age to the Cerro Totora Formation have detrital-zircon ages in clusters of 1443–1315, 1281–1043, and 641–517 Ma, similar to those of the El Quemado Formation, and have an older component at 1667–1596 Ma (Fig. 8) (Naipauer et al., 2010). The detrital-zircon ages suggest that the Caucete Group includes equivalents of the Cerro Totora Formation (Naipauer et al., 2010).

Recycled Cambrian Passive-Margin Platform Rocks of the Precordillera

The Middle Cambrian La Laja Formation is the lowest part of the passive-margin carbonate succession on the Precordillera platform (Fig. 2) (Astini et al., 1995; Gomez and Astini, 2015). The dominantly limestone formation contains thin interbeds of quartzose sandstone and sandy limestone in the lower part, as well as a massive quartzose sandstone unit ~15 m thick. New

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U/Pb zircon ages from the thicker sandstone unit (sample 17.03-346, Fig. 1) are clustered dominantly at 1512–1248 Ma with the primary concentration at 1355 Ma and include a few younger (1078 Ma) and older (maximum 1581 Ma) grains (Fig. 10). Two published analyses of the same sandstone by Naipauer et al. (2008) have ages strongly clustered between 1478 and 1100 Ma with primary concentrations at 1364 and 1360 Ma, very similar to the new analyses of sample 17.03-346 (Fig. 10). Earlier published analyses by Finney et al. (2005) are slightly different in detail, ranging from 1688 to 1200 Ma with clusters at 1518, 1457, and 1343 Ma. Taking the very similar results from Naipauer et al. (2008) and sample 17.03-346 (Fig. 10), most of the zircon grains are in the age range of the Granite-Rhyolite province of Laurentia; the distribution is compatible with derivation from a component of Granite-Rhyolite basement in the Precordillera, as indicated by the basement clasts (1370–1367 Ma; Thomas et al., 2012) in the conglomerate olistolith. Similar results were obtained from a sample of a thinner sandstone interbed in the lower La Laja Formation (sample 16.LL-LL-1, Fig. 10).

An olistolith of Middle Cambrian carbonate within the Los Ratones olistostrome in slope facies of the western Precordillera (Fig. 1) is the approximate correlative of the La Laja Formation of the shelf facies (Naipauer et al., 2008). Detrital zircons from the carbonate olistolith have ages clustered between 1647 and 1220 Ma with a concentration between 1377 and 1340 Ma (Fig. 10) (Naipauer et al., 2008).

The Angacos Formation (upper Caucete Group, Fig. 2), in the footwall of the Las Pirquitas thrust fault along the western Sierra de Pie de Palo (Fig. 1), is interpreted to be equivalent to the La Laja Formation (Naipauer et al., 2010). Detrital zircons from the Angacos Formation are primarily in two age groups: 1450–1313 and 1148–1070 Ma with some ages scattered between (Fig. 10) (Naipauer et al., 2010). The older age group is consistent with a Granite-Rhyolite source and with correlation to the La Laja Formation; the younger age group suggests sediment from the Grenville-equivalent parts of the Precordillera basement.

DISCUSSION AND INTERPRETATIONS

Both the new and previously published age populations of detrital zircons from sandstones (Figs. 3, 6, 7) are remarkably consistent throughout the foreland succession from Las Vacas Conglomerate through Trapiche Formation in the northeastern Precordillera and equivalent La Cantera Formation to the south, as well as from the glaciogenic Don Braulio Formation. The consistent distribution of detrital-zircon ages strongly supports a single composite provenance along the eastern side of the Precordillera, both along strike of the peripheral foreland basin and throughout the time of filling of the basin (extending from latest Floian to Hirnantian time). The stratigraphic succession, southwestward progradation of the clastic facies, southwestward thinning of the clastic wedge, and west-directed paleocurrent indicators (Spalletti et al., 1989; Astini, 1991; Astini et al., 1995; Cingolani et al., 2003) all support generally westward dispersal of clastic sediment from a source east of the Precordillera. The ages of detrital zircons define the age characteristics of the rocks in the provenance and may be correlated with specific age provinces (Fig. 9).

The dominant group in the age spectrum of the detrital zircons is ~1350–1000 Ma (Figs. 3, 6, 7), corresponding in age to the Grenville/Sunsas orogenic events and assembly of supercontinent Rodinia. These ages are common for basement rocks throughout the Western Sierras Pampeanas (Sierras de Maz, Espinal, Umango, and Pie de Palo; Figs. 1, 9) along the eastern side of the Precordillera, suggesting a proximal and consistent source of detritus to the foreland basin. Some of these grains may have been recycled from the Cambrian sedimentary cover of the Precordillera and/or metamorphosed equivalent sedimentary rocks along the western Sierra de Pie de Palo, which is possibly represented by the quartzite clast in the Las Vacas Conglomerate.

A lesser, but substantial, concentration of detrital-zircon ages in the range of 1500–1350 Ma indicates a component of the provenance that is not represented in the known ages from basement rocks of the sierras. A conglomerate olistolith, however, provides evidence that the Precordillera basement rocks included a component of the Granite-Rhyolite province of Laurentia (Thomas et al., 2012). Detrital zircons with ages of 1500–1350 Ma in late synrift (Cerro Totora Formation, Fig. 8) and passive-margin (La Laja Formation, Fig. 10) strata of the Precordillera, as well as metamorphosed equivalents along the western Sierra de Pie de Palo (Caucete Group, Figs. 8, 10), indicate sediment supply from the Granite-Rhyolite component of the Precordillera basement or directly from the Laurentian Granite-Rhyolite province before the Precordillera was separated from Laurentia (Naipauer et al., 2010). These sands possibly were recycled on the passive-margin shelf from the synrift Cerro Totora Formation and equivalents in the Caucete Group; alternatively, basement rocks may have been exposed during passive-margin transgression on the shelf (Thomas, 1991; Thomas and Astini, 1996). These data suggest that recycling from Cambrian synrift and passive-margin deposits, incorporated into the accretionary complex of the Ocloyic orogen, may have been an important contributor of detritus to the Ocloyic foreland basin.

A less prominent group of detrital-zircon ages at ~750–570 Ma (Figs. 3, 6, 7) has a probable source in the same provenance as that of the igneous clasts (Fig. 5) in the Las Vacas Conglomerate. One indication of the possible source is the metadacite/rhyolite with a crystallization age of 669 Ma (Mulcahy et al., 2011) in the western Sierra de Pie de Palo, suggesting magmatism associated with either Iapetan rifting or a Brasiliano arc. Other igneous rocks in the Western Sierras Pampeanas, interpreted as Iapetan synrift, have ages of 845, 774, and 570 Ma (Baldo et al., 2006, 2008; Casquet et al., 2008; Colombo et al., 2009). Iapetan synrift igneous rocks along the Laurentian margin range in age from 765 to 530 Ma (summary in Thomas, 2014). Metasedimentary rocks in the Sierra de Pie de Palo and the Sierra de Valle Fértil contain detrital zircons with ages between 665 and 515 Ma (Vujovich et al., 2004; McClelland et al., 2005), which may be a source of recycled sediment. Quartzites in the Caucete Group have a minor group of younger (640–490 Ma) detrital zircons (Fig. 8) (Naipauer et al., 2010), similar in age to detrital zircons (656–628 Ma) in the

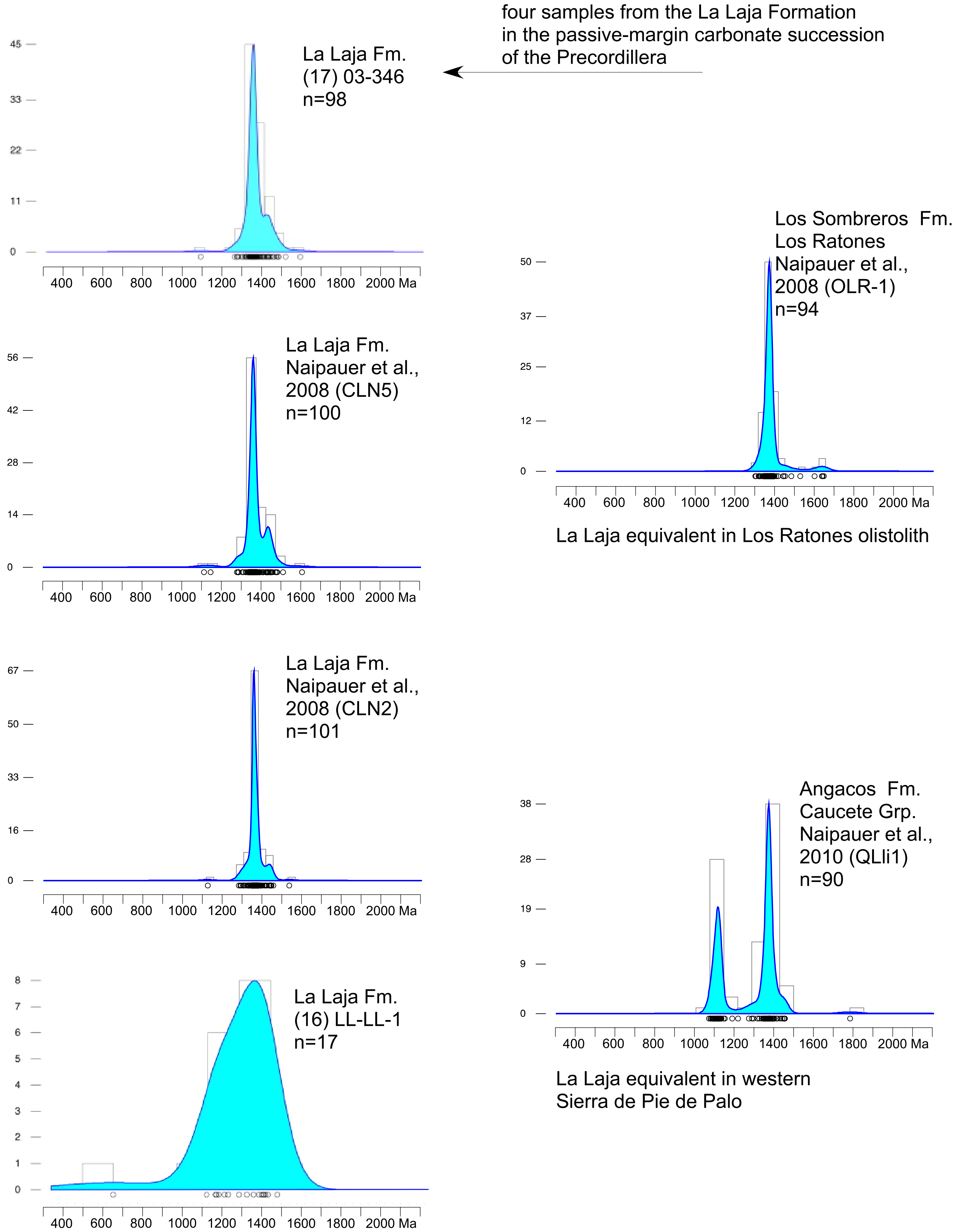

Figure 10. Kernel density estimator plots of detrital-zircon populations in sandstones within the Cambrian–Ordovician passive-margin carbonate succession in the Precordillera: four samples from La Laja Formation in the Precordillera passive-margin cover succession (sample locations 16.LL-LL-1 and 17.03-346 shown in Figures 1 and 2, and documented in Supplemental Table 1; data listed in Supplemental Table 1 [see footnote 2]); a sample from an olistolith in the Los Sombreros Formation of the western slope facies of the Precordillera; and a sample from the Angacos Formation (Caucete Group) in the footwall of the Las Pirquitas fault in the western part of the Sierra de Pie de Palo (stratigraphic units shown in Figure 2).

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quartzite clast in the Las Vacas Conglomerate (Fig. 4), suggesting an original supply from synrift igneous rocks, as well as a source for recycling sediment into the Ordovician clastic wedge. The relative abundance of igneous clasts in the Las Vacas Conglomerate may indicate a substantial magmatic component in the provenance that was more extensive than represented in the present outcrop geology. The interpreted depth of unroofing of the Western Sierras Pampeanas suggests that the igneous provenance may have been almost completely removed by post-Ordovician erosion.

The detrital-zircon age populations contain relatively few grains older than 1500 Ma (Figs. 3, 6, 7). The older grains possibly represent minor contributions of detritus from older Laurentian provinces recycled from the Cambrian synrift sandstones or from the Caucete Group, from xenocrysts of older protoliths in metamorphic rocks in the Western Sierras Pampeanas, or from distant Gondwanan provinces.

The general lack of detrital zircons with ages <500 Ma suggests that the Middle–Upper Ordovician clastic wedge in the Precordillera did not receive a significant volume of sediment from the Famatina arc complex. Ocloyic metamorphic and plutonic rocks are represented by only two detrital grains (440 ± 10 and 477–463 Ma in the La Cantera Formation; Abre et al., 2012), suggesting that most of these rocks remained deeply buried during the deposition of the clastic wedge. Lack of detritus from the Famatina arc suggests that sediment was trapped in a forearc basin east of the basement thrust sheets (now in the sierras along the east side of the Precordillera) and did not reach the foreland basin.

Among the rounded clasts of extra-basinal rocks in conglomerates of the Las Vacas Conglomerate in the northeastern Precordillera, the igneous rocks and the quartzite have affinities for the provenance of the detrital grains in the Ordovician clastic wedge; however, two other lithic clasts are more problematic. Zircons from the gneiss clast have ages of 2194–2009, 1786–1759, and 672–472 Ma (Fig. 4). The younger ages (672–472 Ma) correspond partly to a minor concentration of detrital zircons in the clastic wedge (Figs. 3, 6, 7) and include the age of the igneous clasts (Fig. 5), corresponding to the age of Iapetan rifting and to the span of Brasiliano and Pampean orogenic events. Zircons of 2194–2009 Ma match the age of the TransAmazonian event in Gondwana (including the Río de la Plata craton, southeast of the Eastern Sierras Pampeanas, east of the map area of Fig. 1B); the other zircon ages are diverse and not distinctive. The ages of zircons from the gneiss clast suggest a possible exotic thrust sheet of Gondwanan affinity within the Ocloyic hinterland; however, no direct evidence matches the clast to any particular outcrop. The unique signature of the gneiss clast suggests that this country rock did not supply a significant component of the sand-sized detritus. Zircons in the red sandstone clast have a diverse assortment of ages, including ranges of 2200–2150 (TransAmazonian), 1350–1000 (Grenville), and 800–550 (Iapetan rifting or Brasiliano) Ma (Fig. 4). The zircon population in the red sandstone differs from those in both the Lower Cambrian Cerro Totora Formation (synrift rocks on Precordillera, Fig. 8) and the Caucete Group (metamorphosed Precordillera strata in the Sierra de Pie de Palo, Fig. 8). Although the red sandstone lithologically resembles those in the Cerro Totora, the zircon populations indicate that the sandstones are not part of the same depositional system. One sandstone in the El Desecho Formation (Caucete Group), which contains some red strata, does include the ~600 Ma zircon-age group and is dominated by ages of 1500–1000 Ma, but lacks the 2100 Ma component. No source for the red sandstone is obvious.

The large olistoliths of exclusively San Juan Limestone and Gualcamayo Shale in the Las Vacas Conglomerate and the carbonate boulder beds and olistoliths in the Trapiche Formation have proximal local sources within the foreland basin from the leading edges of synsedimentary west-directed thin-skinned thrust sheets in the proximal part of the basin (Thomas and Astini, 2007). The synsedimentary thrust faults within the fill of the foreland basin indicate a break-forward sequence of thrusting of the leading part of the orogenic belt into the proximal part of the foreland basin in the footwall of the system of basement-rooted top-to-west thrust faults in the accretionary complex (Fig. 11).

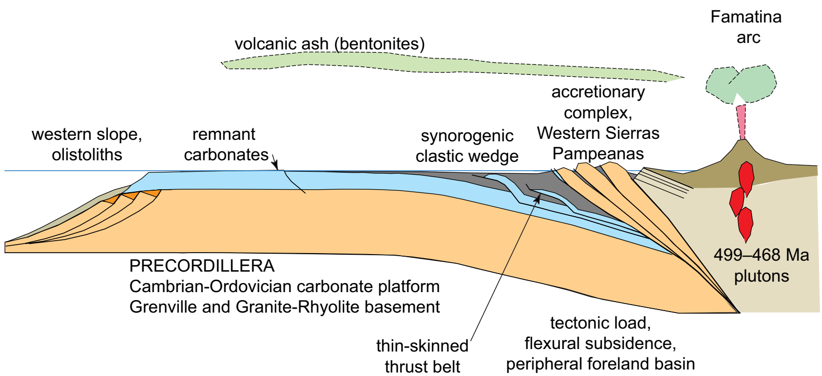

Figure 11. Diagrammatic cross section of tectonic model for the Middle–Late Ordovician foreland basin and clastic wedge in the context of accretion of the Precordillera to Gondwana and the Ocloyic orogeny.

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CONCLUSIONS

The Middle–Upper Ordovician (mainly Dapingian to Sandbian) succession of Gualcamayo Shale, Las Vacas Conglomerate, and Trapiche Formation, as well as equivalent units (La Cantera Formation and La Pola Formation) to the south, constitute an Ocloyic synorogenic clastic wedge that prograded westward and southwestward over the Cambrian–Ordovician passive-margin carbonate succession in the Precordillera (Fig. 2). The stratigraphic succession, thickness and facies distribution, and west-directed paleocurrents all document a synorogenic clastic wedge filling a peripheral foreland basin that subsided in response to tectonic loading as the Precordillera was subducted beneath western Gondwana and the Famatina continental-margin magmatic arc. A forearc accretionary complex along the east side of the peripheral foreland basin includes the basement massifs of the Western Sierras Pampeanas. Within the accretionary complex, including the basement and cover of the original eastern margin of the Precordillera, the Ocloyic orogen is expressed in metamorphic overprints, top-to-west thrusting, and minor plutonism. The Famatina continental-margin magmatic arc gave rise to volcanic ash beds deposited within the upper part of the passive-margin carbonates and lower part of the synorogenic clastic wedge on the Precordillera. Timing of events suggests that subduction stopped shortly after the continental crust of the Precordillera terrane entered the subduction zone. Late Ordovician (Hirnantian) glacial deposits (Don Braulio Formation), which extend widely over Gondwana, overlie the synorogenic clastic wedge in the Ocloyic foreland basin, indicating accretion of the Precordillera to Gondwana before the end of the Ordovician.

Detrital-zircon age populations in the sandstones of the Middle–Upper Ordovician clastic wedge in the Precordillera indicate sediment supplied primarily from the basement massifs of the Western Sierras Pampeanas along the east side of the Precordillera (Fig. 11). The dominant mode (~1350–1000 Ma) of the detrital-zircon ages corresponds to the ages of basement rocks in the Western Sierras Pampeanas (Fig. 9). A prominent secondary mode (1500–1350 Ma) corresponds to the age of the Granite-Rhyolite province of Laurentia, which is not represented in the basement rocks of the Western Sierras Pampeanas (Fig. 9). Granite-Rhyolite rocks constitute part of the basement of the Precordillera (Thomas et al., 2012), and zircons were available through recycling from synrift and passive-margin cover strata. A quartzite clast, as well as parts of the population of detrital zircons, indicates the importance of a source in the metasedimentary cover of the leading edge of the Precordillera, now in the footwall of the top-to-west basement-rooted Las Pirquitas thrust fault along the western side of the Sierra de Pie de Palo. Igneous clasts have ages (647–614 Ma) that are represented also in a minor mode (~750–570 Ma) of detrital-zircon ages; possible sources are in synrift igneous rocks in the basement massifs. No detrital zircons have ages that correspond to Famatina arc magmatism, indicating that sedimentary detritus from the arc may have been trapped in a forearc basin and did not reach the foreland. Indications of sediment provenance are consistent with subsidence of the foreland basin beneath a subduction complex, including top-to-west basement-rooted thrust sheets, which constitute the dominant source of sediment.

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Detrital-zircon geochronology and provenance of the Ocloyic synorogenic clastic wedge, and Ordovician accretion of the Argentine Precordillera terrane

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