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The Early Paleozoic history of the Cuyania (greater Precordillera) terrane of western Argentina: evidence from geochronology of detrital zircons from Middle Cambrian sandstones

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ABSTRACT

U-Pb geochronology of large detrital zircons populations is a powerful tool for interpreting sandstone provenance. Here, it is applied to three Middle Cambrian sandstones from the Precordillera of Argentina with the purpose of using the provenance interpretations to test paleogeographic and paleotectonic models proposed for the Cuyania or Precordillera terrane. Two samples from the La Laja Formation have distinctive detrital zircon age distributions. All zircon grains fall within unimodal populations of 1688-1200 Ma in one sample and 1559-1316 Ma in the other. Of these grains, 23% and 65%, respectively, are within the age range of the North American magmatic gap (1610-1490 Ma), indicating a non-Laurentian provenance. A very different sample was taken from a sandstone interval in a large olistolith within the Estancia San Isidro Formation. Its zircon population is dominated by a single, prominent 615-511 Ma age cluster, which is indicative of a provenance in a Brasiliano orogenic belt. The absence of zircons with Grenvillian ages (1200 to 950 Ma) is difficult to reconcile with paleogeographic and geotectonic models in which Cuyania rifted from Laurentia in Cambrian or Ordovician time. The data are most consistent with models in which Cuyania rifted from the southern margin of West Gondwana. Given a Cambrian association with Gondwana and a post-Ordovician arrival at its present position in Gondwana, the Cuyania terrane must have migrated along the southern and western margins of Gondwana during the Ordovician Period.

KEYWORDS **Argentina. Precordillera. Cuyania. Cambrian. Ordovician. Paleogeography.**

INTRODUCTION

The Precordillera of western Argentina contains extensive, well exposed, continuous outcrops of thick and varied Lower Paleozoic stratigraphic successions. Its Cambrian to Middle Ordovician carbonate succession with benthic faunas of strongly Laurentian character is unique to South America. The dramatic change to Middle and Upper Ordovician strata of largely siliciclastic facies with great vertical and lateral heterogeneity has been taken as a record of tectonic and paleogeographic upheaval. The Precordillera is part of a larger region in western Argentina that is referred to as the Cuyania (or Precordillera) terrane (Ramos, 1995; Ramos et al., 1998), which is allochthonous and did not arrive at its present geologic position, immediately outboard of the Famatinian magmatic belt, until Mid Ordovician time or later.

The origin of the Cuyania terrane and the mode and timing of its transfer to its present location are much debated topics. One hypothesis is that Cuyania is a crustal fragment that was derived from the southern (present coordinates) margin of West Gondwana and migrated along major strike-slip faults until reaching its present position in late Silurian to early Devonian time (Baldis et al., 1989; Aceñolaza and Toselli, 2000; Aceñolaza et al., 2002). Other models propose that Cuyania rifted from the Ouachita embayment of Laurentia (Dalla Salda et al., 1992b; Astini et al., 1995; Thomas and Astini, 1996; Dalziel, 1997; Keller, 1999). In one of these, the widely accepted Laurentian microcontinent model of Thomas and Astini (1996), this rifting occurred during the Early Cambrian, and subsequently Cuyania drifted across the Iapetus Ocean as a microcontinent before docking with the proto-Andean margin of Gondwana outboard of the Famatinian magmatic arc during Mid to Late Ordovician time.

The Laurentian affinity of Cuyania has been widely accepted on the bases of 1) its Grenvillian basement rocks, 2) its Middle Cambrian to Lower Ordovician carbonate platform succession, and 3) its Cambrian to Early Ordovician benthic faunas, especially Early and Mid Cambrian shallow-water trilobites. However appealing this evidence, it is not conclusive for a Laurentian connection in the Early Cambrian and an accretion to Gondwana in the Mid Ordovician.

Much more definitive evidence on paleogeographic relationships can be provided by U-Pb geochronology of detrital zircons. The age distributions in zircon populations are a key for determining the provenance of the sandstone from which the zircons were extracted. Finney et al. (2003a) were the first to use this technique to test paleogeographic models for the Cuyania terrane. They applied it to samples from sandstone beds from the upper Lower Cambrian Cerro Totora Formation and the lower Upper Ordovician Las Vacas Formation of the Precordillera terrane and, for comparison, to a sample from the Middle to Upper Cambrian La Cébila Formation of the Sierras Pampeanas, which represents the Gondwana continent. Unfortunately, their conclusions for a Gondwanan affinity of Cuyania were flawed. After publication and with their analyses of additional samples from the Cerro Totora Formation, they learned that results from the original Cerro Totora and La Cébila samples were inadvertently switched (Finney et al., 2004). Furthermore, they later learned that their "Cerro Totora" samples were mistakenly taken from sandstones of probable Paleogene age.

As part of this latter study of additional "Cerro Totora" samples, samples were also taken and analyzed from Middle Cambrian sandstone beds of the Precordillera. These sandstones are from the La Laja Formation at Marquesado Hill, San Juan Province and from the San Isidro olistolith at San Isidro, Mendoza Province. The U-Pb age distributions of detrital zircons from these Middle Cambrian samples are not consistent with a Laurentian provenance. In fact, they demonstrate a Gondwanan source area.

The purpose of this paper is to document the geochronology of detrital zircons from the Middle Cambrian sandstones and the petrography of the sandstones and, from this evidence, to interpret the provenance of the sandstones and to consider the paleogeographic implications. The data on the Middle Cambrian sandstones have not been published previously. Evidence from these sandstones indicates that Cuyania was part of Gondwana during the Cambrian Period. Furthermore, evidence from Upper Ordovician sandstones, presented in Finney et al. (2003a, 2003b, 2003c), indicates that Cuyania did not arrive at its present position relative to the rest of the Gondwana until after the Ordovician. This raises the question: Where was Cuyania during the Ordovician Period? The answer to that question is the goal of this paper.

GEOGRAPHIC LOCATION AND GEOLOGIC SETTING OF SAMPLES

The Argentine Precordillera

The Argentine Precordillera is a thin-skinned fold-thrust belt of late Cenozoic age, located in the Andean foreland of northwestern Argentina, and extending 400 kms north-south between latitude 29ºS and 33ºS. It is composed of a thick succession of Paleozoic strata, of which the Cambrian-Ordovician strata are particularly distinctive and display marked east-west changes in tectofacies (Astini et al., 1995; Thomas and Astini, 2003). In eastern and central belts of the Precordillera, the stratigraphic succession begins with a Lower Cambrian to upper Middle Ordovician carbonate succession that was deposited on a shallow marine platform. It is overlain locally by Middle Ordovician to Devonian age siliciclastic successions of variable thicknesses and of great vertical and lateral heterogeneity. This vertical facies change has been interpreted as a record of drowning, tectonic subsidence, and progradation of a synorogenic clastic wedge as Cuyania first approached and then collided with the proto-Andean margin of Gondwana (Astini, 1998; Thomas and Astini, 2003). Western belts are composed of shales and turbidites of Middle to Upper Ordovician age and possibly Devonian age. Locally, Middle Ordovician strata are olistostromes, in which the olistoliths are composed of strata from the carbonate platform succession. Accordingly, the depositional environment of the western tectofacies is interpreted as a steep shelf edge to deep marine slope along the margin of the carbonate platform (Keller, 1999; Thomas and Astini, 2003).

La Laja Formation Samples (LLFM1 and LLFM2)

Two samples (LLFM1 and LLFM2) were taken from a thin interval of sandstone within the upper part of the Soldano Member of the La Laja Formation at the northern end of the Sierra Chica de Zonda (Fig. 1).

The La Laja Formation is the oldest unit of the carbonate platform succession that is characteristic of the Precordillera. It occurs only in the San Juan Basin with outcrops in the eastern and central belts of the Precordillera. Its base is marked everywhere by active thrust faults. The formation is approximately 700 m thick and consists of a variety of shallow-water limestones, argillaceous limestones, and siltstones. Keller (1999) described it as a mixed carbonate-siliciclastic system that accumulated on a platform inboard of a carbonate belt that marked the platform margin and seaward of a near shore siliciclastic trap.

The La Laja Formation is subdivided into four members named, in ascending order, El Estero, Soldano, Rivadavia, and Juan Pobre (Baldis and Bordonaro, 1981; Bordonaro, 2003a, 2003b). On the basis of trilobite occurrences, the El Estero Member is correlated with the upper Lower Cambrian Series, and the Soldano, Rivadavia, and Juan Pobre with the Middle Cambrian Series. The depositional history of the formation was considered to be continuous until re-evaluation of the trilobite zonation indicated, instead, that there is major hiatus between the El Estero and Soldano members. This hiatus correlates with the lower Middle Cambrian and represents the global Hawke Bay regressive event (Bordonaro, 1999, 2003a, 2003b; Keller, 1999).

The Soldano Member, approximately 260 m thick, contains trilobites of the *Ehmaniella* Zone and thus correlates with the middle Middle Cambrian. At Marquesado Hill at the northernmost end of the Sierra Chica de Zonda (Fig. 1), Bordonaro (2003b) has collected trilobites from a fault-bounded section that extends from within the Soldano Member to the upper part of the Juan Pobre Member. Here the upper part of the Soldano Member includes a thin interval of quartz sandstone from which samples LLFM1 and LLFM2 were collected with sample LLFM1 being from a bed 3 m above that of LLFM2 (Fig. 1).

San Isidro Olistolith Sample (ISOS1)

A sample (ISOS1) was taken from a sandstone bed near the base of the well known San Isidro olistolith in the section on the south bank of Quebrada de San Isidro (Fig. 2). The San Isidro olistolith is one of several huge allochthonous blocks, composed mainly of carbonate rocks of Middle Cambrian, Upper Cambrian, or Upper Cambrian to Lower Ordovician age, that occur in the Middle to Upper Ordovician succession of the San Isidro area of the Precordillera of Mendoza. According to Keller (1999) and Thomas and Astini (2003), this succession was deposited on the slope or rise along the margin of the Precordillera platform.

The stratigraphic succession in the San Isidro region has a long history of study with repeated stratigraphic revisions since Harrington (in Harrington and Leanza, 1957) first defined the Ordovician strata as the Empozada Formation (see Heredia and Beresi, 2004). The olistoliths have on different occasions been identified as separate formations (e.g. Harrington, 1961; Borrello, 1971), included within the Empozada Formation (Heredia and Gallardo, 1996; Bordonaro et al., 1993), and included with the Ordovician strata but referred to as the Los Sombreros Formation (Keller, 1999; Thomas and Astini, 2003). Most recently, Heredia and Beresi (2004) redefined the stratigraphy, and their classification is followed here. The lower, predominately siliciclastic part of the succession, which includes the olistoliths, is defined by them as the Estancia San Isidro Formation. Graptolites of the *Paraglossograptus tentaculatus* Zone, collected from shales in the Estancia San Isidro Formation below the San Isidro olistolith, indicate a correlation with the upper Middle Ordovician Series (Llanvirn British series). This correlation also represents the time of deposition of the olistoliths in the Mendoza depositional basin. The Upper Ordovician (Caradoc-Ashgill) strata that overlie the Estancia San Isidro Fm compose the redefined, and restricted, Empozada Fm.

The San Isidro olistolith has a maximum thickness of 110 m and consists of five lithofacies, in ascending order: 1) sandstone, 2) oncolitic boundstone, 3) wackestone and shale, 4) packstone and interbedded sandstone, and 5) green shale (Heredia and Beresi, 2004). Our sandstone sample was collected from the sandstone lithofacies,

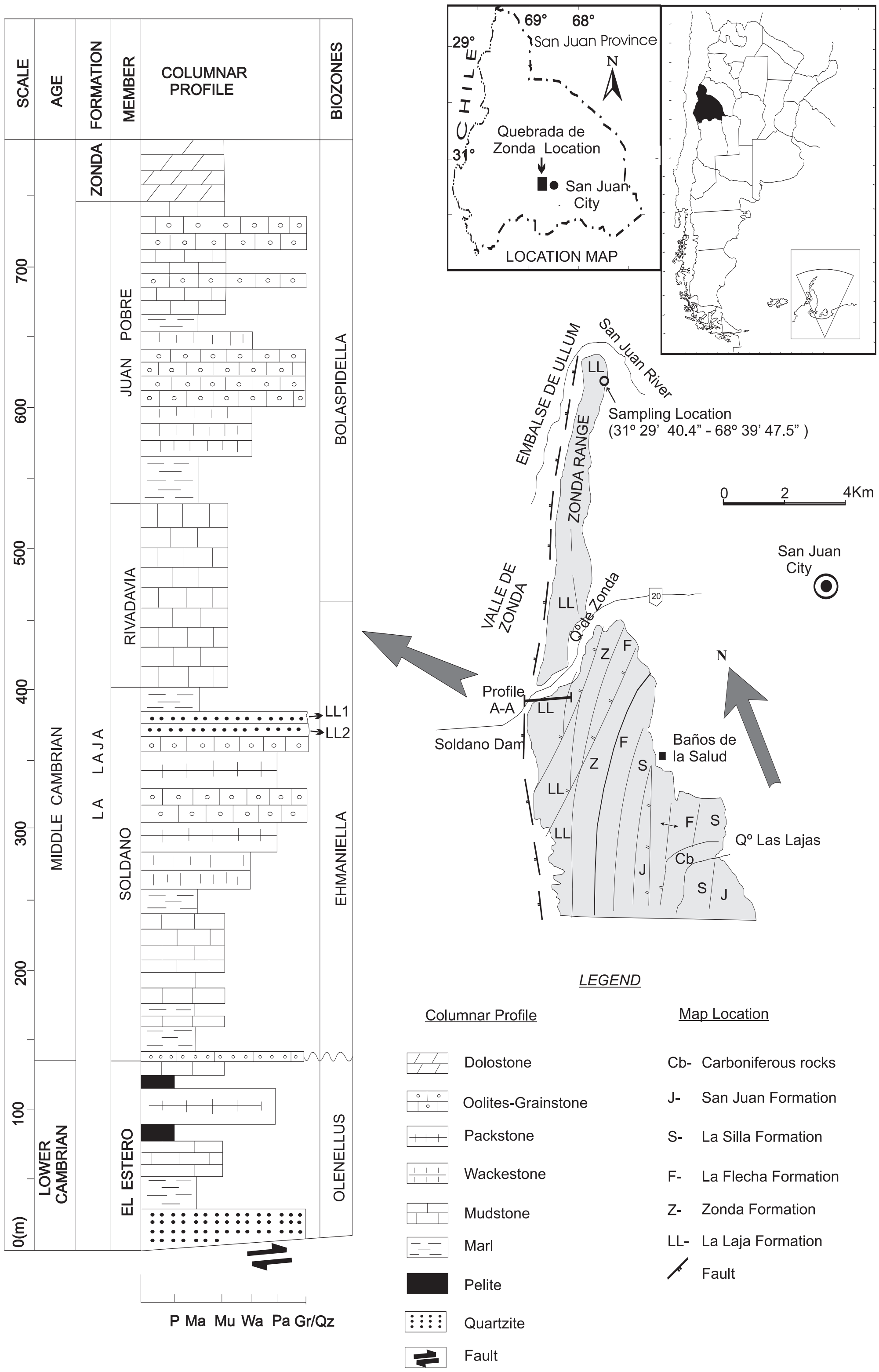

FIGURE 1 **Map showing the location of samples LLFM1 and LLFM2 at Marquesado Hill at the north end of the Sierra Chica de Zonda and a stratigraphic section of the La Laja Fm, generalized for entire mountain range, showing collections levels of LLFM1 and LLFM2 in upper part of Soldano Member. S31°29´40.4", W68°39´47,5"**

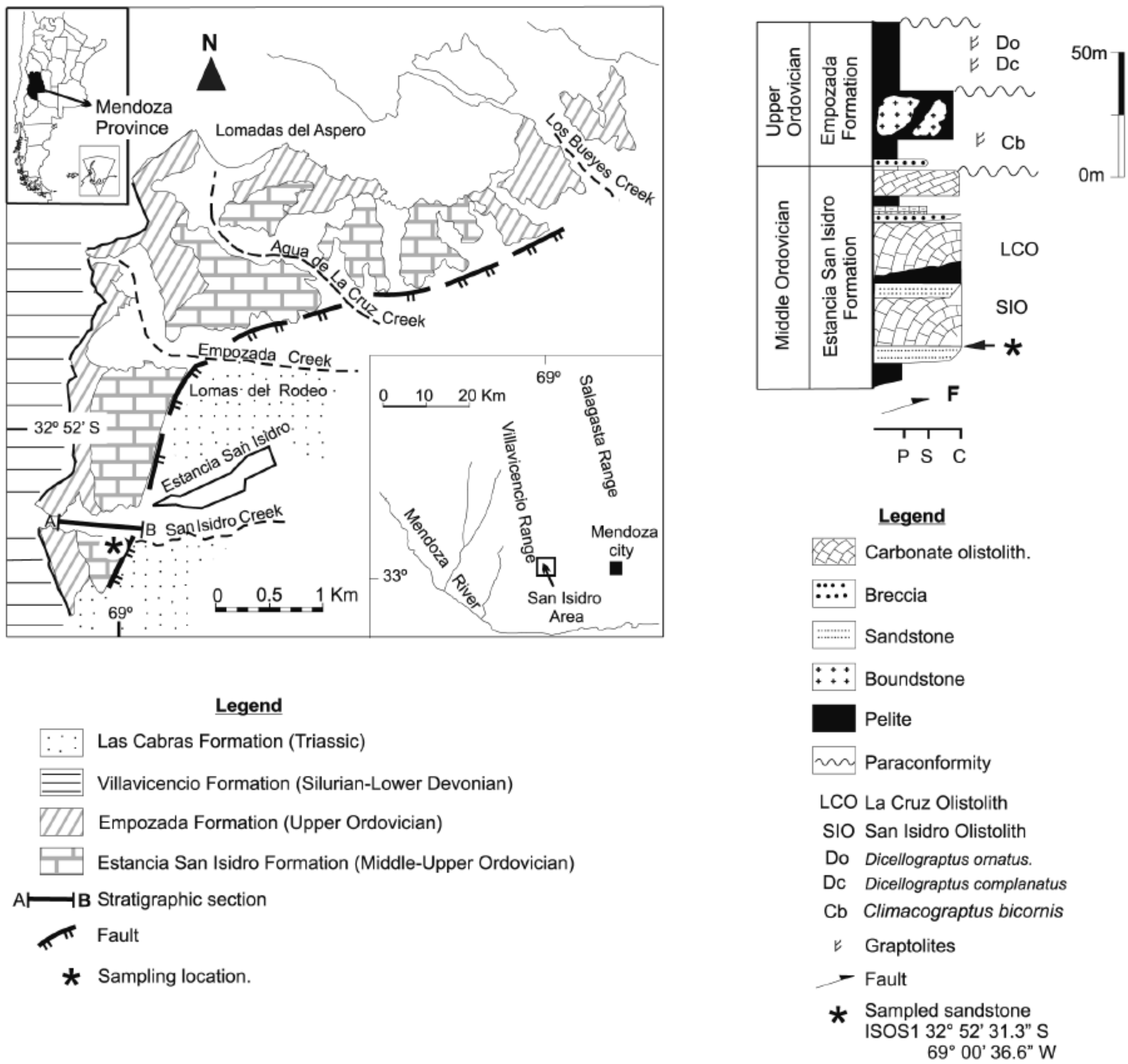

FIGURE 2 | **Map showing location of Quebrada de San Isidro and stratigraphic section for section along the southern margin of the Quebrada (modified from Heredia and Beresi, 2004). Stratigraphic column shows Estancia San Isidro and Empozada Fms, the position of the San Isidro olistolith in the stratigraphic section, the simplified stratigraphy within the olistolith, and the stratigraphic level of sample ISOS1. GPS coordinates for sample ISOS1 are S32º52'31.3" and W69º00'36.6".**

which is about 20 m thick, in the section along the south side of Quebrada de San Isidro (Fig. 2). The carbonate lithofacies have yielded important, diverse collections of trilobites described by Borrello (1971) and assigned to the Middle Cambrian Zone of *Glossopleura*. The succeeding Middle Cambrian Zone of *Oryctocephalus* has subsequently been recognized based on the discovery of *Tonkinella stephensis* (Heredia, 1994; Bordonaro, 2003b). Accordingly, we consider our sandstone sample to correlate with the Middle Cambrian Series.

The introduction of the Cambrian to Lower Ordovician olistoliths into the Mendoza depositional basin is attributed to gravity slide and rock fall mechanisms, resulting from collapse of the carbonate platform of the Precordillera (Heredia and Gallardo, 1996; Keller, 1999; Heredia and Beresi, 2004). Keller (1999; Keller et al., 1993) considered the rocks of the San Isidro olistolith to be identical and the trilobites almost identical to those of coeval (Middle Cambrian) strata of the La Laja Formation, which were deposited in an inner platform setting. Thus, the sandstone sampled for zircons must have also been deposited originally, as is the case of the La Laja Fm, in relatively shallow water on the carbonate platform of the Precordillera. However, with recent revisions of the trilobite zonation of the La Laja Fm, the lower part of the San Isidro olistolith, that part with trilobites of the *Glossopleura* Zone, is now correlated with the lower Middle Cambrian hiatus in the La Laja Fm (Bordonaro, 2003b). Accordingly, the sandstone sampled from the San Isidro olistolith likely was deposited on the outer carbonate platform during the time of the Hawke Bay regressive event.

METHODS OF GEOCHRONOLOGICAL AND PETROGRAPHIC ANALYSES

Zircons were analyzed with a Micromass Isoprobe equipped with 9 faraday collectors, an axial Daly detector, and 4 ion-counting channels. The Isoprobe is coupled to a New Wave DUV 193 laser ablation system, which has an emission wavelength of 193 nm. The analyses were conducted on 35 micron spots with an output energy of 60 mJ and a repetition rate of 8 hz. Each analysis consisted of one twenty-second background measurement (on peak centers with no laser firing) followed by twelve 1-second integrations on peaks with the laser firing. The depth of each ablation pit is ~12 microns. The collector configuration allows simultaneous measurement of ^{204}Pb in a secondary electron multiplier while ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, and ^{238}U are measured with Faraday detectors. All analyses were conducted in static mode.

Isotope ratios, calculated ages, and errors for all zircon grains analyzed are listed in the Appendix, which is located in the electronic version of this paper and available in the journal webpage (www.geologica-acta.com).

Inter-element fractionation during the analysis was monitored by analyzing fragments of a large concordant zircon crystal that has a known (ID-TIMS) age of 564 ± 4 Ma (2-sigma). This reference zircon was analyzed once for every five unknowns. The isotope ratios are also corrected for common Pb using the measured ^{204}Pb, assuming an initial Pb composition according to Stacey and Kramers (1975) and uncertainties of 1.0 and 0.3 (2-sigma), respectively, for ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb. The isotope ratios reported in the Appendix have been corrected for common Pb and for fractionation. Errors for the ratios and ages are reported at the 1-sigma level, and include uncertainties only from the isotopic measurements. Systematic errors arising from the fractionation correction, common Pb composition, decay constants, and standard age would yield an additional ~2-3% (2-sigma) to each calculated age.

Ages used for provenance interpretation, shown in bold in the Appendix, are based on ^{206}Pb/^{207}Pb ratios for >1.2 Ga grains and ^{206}Pb/^{238}U ratios for <1.2 Ga grains. Analyses that are interpreted to be unreliable are shown in italics. Unreliable ^{206}Pb/^{238}U ages are those with measurement errors >10%. ^{206}Pb/^{207}Pb ages are rejected if analyses display >10% reverse discordance, >30% normal discordance (based on comparison of ^{206}Pb/^{238}U and ^{206}Pb/^{207}Pb ages), or have >10% measurement errors.

Thin sections cut from sandstone samples were impregnated with blue epoxy and stained for feldspar recognition. Except for rare grains in LLFM2, etched feldspar grains in these samples did not take the potassium stain, but they also were not strongly stained for calcium, indicating albitic (Na) compositions. The samples were pointed-counted using the Gazzi-Dickinson method (Ingersoll et al., 1984) to minimize grain size effects on the detrital modes. A total of 300 points were counted for each thin section, including monomineralic grains, lithic fragments, and interstitial cements.

GEOCHRONOLOGICAL AND PETROGRAPHIC RESULTS

La Laja Formation Samples (LLFM1 and LLFM2)

Sample LLFM1 is a moderately well-sorted, coarse-grained quartz arenite composed predominately of very well rounded quartz grains (96%), a few unknown grains completely altered to carbonate (4%), and very rare grains of albite feldspar (observed but not counted) cemented by quartz and carbonate. Zircons were observed in this texturally and mineralogically mature sample as inclusions in quartz, but not as discrete detrital grains. Except for a trace of potassium feldspar, sample LLFM2 is similar in composition to that of LLFM1, but sample LLFM2 is matrix-dominated with too few grains to reliably point count.

Reliable ages were obtained for 95 zircon grains in sample LLFM1 and 86 in sample LLFM2 (Figs. 3 and 4; Appendix). All 181 grains fall within an age range of ~500 Ma within the late Paleoproterozoic to Mesoproterozoic. The grains in sample LLFM2 are confined to a narrow range (1559 -1316 Ma), and their age distribution forms a unimodal peak at 1518 Ma (Fig. 4). The grains of sample LLFM1 occupy a slightly wider range (1688-1200 Ma), and their age distribution defines peaks at 1457 and 1393 Ma (Fig. 4). The ages in LLFM2 are less scattered, less discordant, and therefore more robust than those of LLFM1 (Fig. 3). Of the 181 zircons in the two samples (see Appendix), 3 have U/Th ratios greater than 5, which indicates that they are metamorphic origin; the other 178 zircons have U/Th ratios of 5 or less, indicating that they are of igneous origin (Rubatto et al., 2001; Williams, 2001; Rubatto, 2002).

San Isidro Olistolith Sample (ISOS1)

Sample ISOS1 is a poorly sorted arkose composed of coarse, angular to rounded grains cemented mainly by clay minerals and lesser carbonate. Of the grains counted, 33% are quartz, 47% are feldspar (albitized plagioclase), 6% are mica (predominately biotite), 8% are lithic fragments (phyllite and siltstone), and 5% are indeterminant grains completely altered to carbonate or clay minerals.

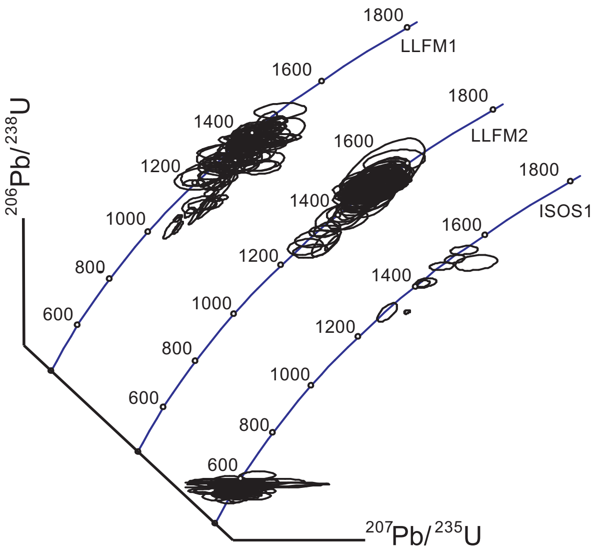

FIGURE 3 **Concordia plots for the La Laja (LLFM1, LLFM2) and San Isidro (ISOS1) samples. Errors are shown at the 1-sigma level. Isotope ratios, calculated ages, and errors for all zircon grains analyzed, including those used to construct the Concordia plots, are listed in the Appendix (see electronic version available in the journal webpage, www.geologica-acta.com).**

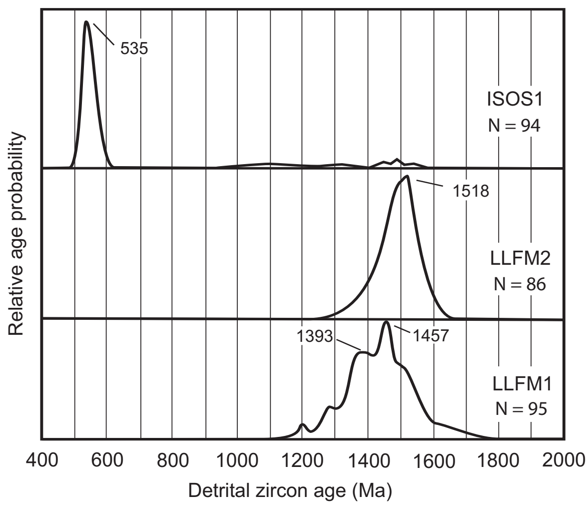

FIGURE 4 **Relative age-probability curves showing U-Pb individual detrital zircon age spectra for the two samples from the La Laja Formation (LLFM1 and LLFM2) and the sample from the San Isidro olistolith (ISOS1). N = number of grains providing reliable ages and thus plotted on curves. Each curve incorporates the age and analytical uncertainty for each grain as a normal probability distribution. Each curve is then normalized to the number of grains analyzed resulting in curves of equal area. Isotope ratios, calculated ages, and errors for all zircon grains analyzed are listed in the Appendix (see electronic version).**

Most of the quartz, feldspar, and mica occur as monomineralic grains, but some occur within coarse rock fragments (e.g. quartz and feldspar, or quartz and mica) counted, in accordance with the Gazzi-Dickinson method, as their sand-sized components. The feldspar appears to be albitized plagioclase, but it is unclear whether the albitization occurred in the source rock prior to erosion or as a product of burial diagenesis within the San Isidro olistolith. Zircons were observed as inclusions in quartz, but not as discrete detrital grains.

Reliable ages were obtained for 94 zircons from this texturally and mineralogically immature sample (Figs. 3 and 4, Appendix). Of these, 86 are within the very narrow range of 615-511 Ma, and the age distribution defines a unimodal peak at 535 Ma (Fig. 4). The other eight grains range in age from 1688 to 1318 Ma. Of particular interest, the age of the youngest grain in the sample (511±11 Ma) corresponds to the earliest Mid Cambrian Epoch (513 to 501 Ma) on the Geologic Time Scale of Gradstein et al. (2004), which is also the approximate time of deposition of the sandstone; 92 of the 94 zircons have U/Th ratios less than 5, indicating an igneous origin.

DISCUSSION

The Cuyania Terrane

As understanding of the suspect nature of the Precordillera evolved and expanded, the concept of the terrane changed as well. Although the term Precordillera terrane is widely used, Ramos (1995) created the term Cuyania to refer to a 1000 km long composite terrane that included not only the Precordillera in its northwestern part, but also small exposures of Ordovician carbonate rocks much farther to the south at Ponón Trehué and Cerro San Jorge, and Cambrian-Ordovician carbonate rocks in the subsurface of the Cuyo basin (Ramos et al., 1998: fig. 1). Miocene volcanic rocks of the Precordillera include xenoliths that are presumed to be representative of crystalline basement of the Precordillera and have been dated as Grenvillian age (Abbruzzi et al., 1993; Kay et al., 1996). For this reason, the occurrences of Grenvillian age crystalline rocks in Sierra de Pie de Palo, Ponón Trehué, and other localities are used to further characterize and delimit the Cuyania terrane (see fig. 1 in Sato et al., 2000), and Cuyania is considered to have a Grenvillian age basement (Thomas and Astini, 1996; Ramos et al., 1998).

Ramos et al. (1986) were the first to consider the region of the Precordillera as a possibly far-traveled, suspect or allochthonous terrane. However, on the basis of stratigraphic and structural patterns, Baldis et al. (1989) concluded that it was derived from a position that today would be in Patagonia and that beginning in the Mid Ordovician it migrated along major transform or strike-slip faults until reaching its present position in late Silurian to early Devonian time. In contrast, the stratigraphy and biogeographic affinities of benthic faunas in the Cambro-Ordovician stratigraphic succession led others to argue for a Laurentian origin for the Precordillera terrane.

This origin was first explained by Dalla Salda et al., (1992a, 1992b) with a tectonic model in which the Precordillera was transferred from Laurentia to Gondwana as the result of a continent-continent collision during the Mid to Late Ordovician. Soon thereafter, Astini et al. (1995) and Thomas and Astini (1996) concluded that the Precordillera terrane rifted from the Ouachita embayment of Laurentia in the Early Cambrian, drifted across the Iapetus Ocean as a microcontinent, and accreted to the proto-Andean margin of Gondwana in the Mid Ordovician. In a somewhat similar model but with different timing, Keller (1999) proposed that the Early Cambrian rifting did not result in the complete separation of the Precordillera terrane from Laurentia. Instead, Keller (1999) argued that complete separation occurred in the Mid to Late Ordovician and accretion to Gondwana in the Late Silurian to Early Carboniferous. In another version, Dalziel (1997) proposed that the Precordillera formed the tip of the Texas Plateau that extended from Laurentia, and that following the Mid Ordovician collision of this plateau with Gondwana the Precordillera terrane detached as Laurentia rifted away. More recently, Aceñolaza and Toselli (2000) and Aceñolaza et al. (2002) have proposed a modified version of the hypothesis of Baldis et al. (1989). In their interpretation, the Cuyania (or greater Precordillera) terrane originated as a platform between South America, Africa, and Antarctica.

Proponents of a Laurentian affinity for Cuyania have several strong arguments. These include 1) similarities in the carbonate platform successions and benthic faunas of the Precordillera and eastern Laurentia, and 2) the Grenvillian age and Laurentian character of the basement rocks of Cuyania. The stratigraphic and faunal similarities can be explained by Cuyania having been at a low paleolatitude in the early Paleozoic, as was Laurentia, without necessarily a direct connection to Laurentia (Finney et al., 2003a). The Laurentian character of the basement rocks is based on distinctive Pb isotopic ratios in the Grenvillian basement rocks of Cuyania that are considered to be characteristic of basement rocks in the North American Grenville province (Kay et al., 1996). However, Wareham et al. (1998) demonstrated that Grenvillian-age rocks in other parts of Gondwana have similar Pb isotopic ratios. The detrital zircon data from our samples of Middle Cambrian sandstones in the Precordillera provide compelling evidence that the basement of Cuyania may include rocks that are not of Grenvillian age and are not of Laurentian character.

Interpretation of Provenance

La Laja Formation Samples (LLFM1 and LLFM2)

On a QFL diagram (Fig. 5), sample LLFM1 plots in the Continental Interior field (Dickinson et al., 1983). Given its textural and mineralogical maturity, it is likely a multi-cycle sediment, extensively reworked in the shallow interior sea of the Precordillera platform. No reworked quartz overgrowths are present on the grains, however; thus, it is uncertain whether or not the sand was derived from significantly older sandstone units, even though the detrital zircon age populations in the two La Laja samples are unimodal and restricted to an age range that is substantially older (by more than 700 my) than the depositional age of the sandstone. Multiple cycles of erosion, transportation and deposition would have provided multiple opportunities for introduction into the sediment supply of zircons from a variety of sources and of a variety of ages. However, it appears that this was not the case for the La Laja sandstone, in contrast to similar Paleozoic sandstones, such as the Eureka Quartzite of western North America, that are multi-cyclical and were deposited on carbonate platforms yet include multi-modal zircon age populations (Gehrels and Dickinson, 1995; Gehrels and Stewart, 1998).

The zircon age populations of the La Laja samples are evidence that 1) the area of their ultimate provenance was very restricted, including igneous rocks with crystallization ages, within the interval of 1688-1200 Ma, and concentrated in the range of 1600-1400 Ma, and 2) the zircon populations in sandstones that may have served as more intermediate source areas were restricted also to the same crystalline sources. The sandstone of the upper Lower Cambrian Cerro Totora Formation is thus excluded as a potential intermediate source. Its zircon age population is multi-modal and lacks zircons with ages in the range of 1640-1490 Ma (Thomas et al., 2004), which are abundant in the La Laja samples.

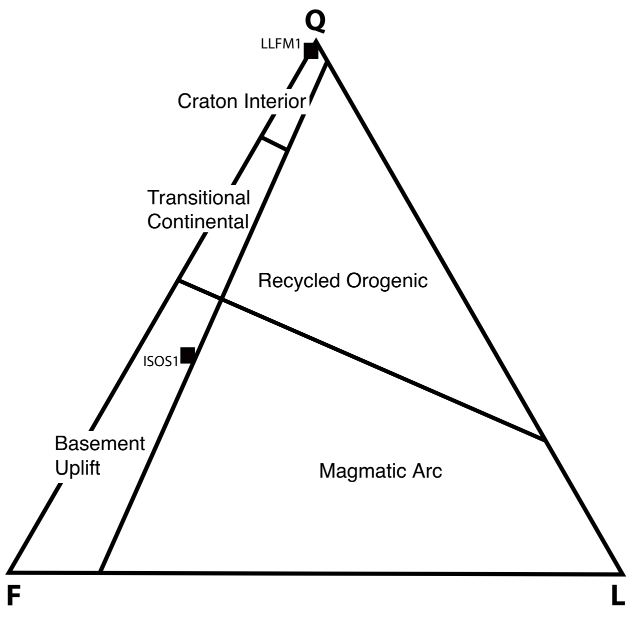

FIGURE 5 **QFL diagram for framework grains in sandstone samples from the La Laja Fm (LLFM1) and the San Isidro olistolith (ISOS1). Grain types and provenance fields are from Dickinson et al. (1983).**

Perhaps the basement rocks of Cuyania served as the ultimate provenance for zircons of the La Laja sandstone. However, the detrital zircon age populations of the La Laja samples are difficult to reconcile with the widely held assumption that the basement rocks are solely of Grenvillian age. Most of the La Laja zircons (1700-1200 Ma) are older than rocks of the Grenvillian orogen (1300-1000 Ma), and the few U-Pb zircon ages of 1100 to 1000 Ma available for basement rocks in Cuyania (Kay et al., 1996; Sato et al., 2000) are significantly younger than the La Laja zircons. Perhaps, the basement of Cuyania includes older rocks rifted from the Granite-Rhyolite province of the Laurentian mid-continent. This province with plutons as old as 1470 Ma (Van Schmus et al., 1993) is at the northern margin of the Ouachita embayment. Nevertheless, the abundance of La Laja zircons in the age range of 1610-1490 Ma (22.6% of those in sample LLFM1 and 65% of those in sample LLFM2) argues against a Laurentian mid-continent provenance because this age range corresponds to the North American magmatic gap, a time of tectonic stability and magmatic quiescence (Ross and Villeneuve, 2003; Karlstrom et al., 2001). Few rocks are known from North America that fall within this age range (Van Schmus et al., 1993), and those rocks that do fall within this range occur in Labrador and are younger than 1500 Ma (Tucker and Gower, 1994). In fact, other than Labrador, rocks corresponding to the North American magmatic gap are known only from Baltica (Ahall et al., 2000), eastern Australia (Blewett et al., 1998; Fanning et al., 1988), and the Amazonian craton (Tassinari and Macambira, 1999). Accordingly, either the ultimate provenance of the La Laja zircons was the basement of Cuyania, and that basement probably was not of Laurentian affinity. Or, the ultimate provenance was external to Cuyania, and it was not the region around the Ouachita embayment of Laurentia. In fact, it could have been the southwestern part of the Amazonian craton where the full age range (1700-1200 Ma) of zircons in the La Laja samples, including the span of the North American magmatic gap, is well represented by widespread granitic intrusions (Bettencourt et al., 1999; Geraldes et al., 2001; Payolla et al., 2002).

San Isidro Olistolith Sample (ISOS1)

Sample ISOS1 is interpreted as a first-cycle sandstone because it is texturally and mineralogically immature and includes detrital zircons with ages nearly contemporaneous with the time of deposition of the sandstone. On a QFL diagram (Fig. 5), the composition of sample ISOS1 plots in the Basement Uplift field of Dickinson et al. (1983). It likely was derived from plutonic basement rocks of tonalitic composition.

From the detrital-zircon age distribution, it is evident that the sand of the San Isidro sample was derived primarily from igneous rocks with crystalline ages of 615-511 Ma with minor introduction of sediment from another source represented by the zircons in the 1688-1318 Ma age group. The latter could have been the host rocks for the younger intrusions. We conclude that this primary crystalline source was exposed basement rocks of Cuyania for the following reasons. Stratigraphic relations in the San Isidro olistolith and stratigraphic similarities to the La Laja Formation indicate that the San Isidro sandstone was deposited on the shallow-water platform of the Cuyania terrane, possibly in an outer platform setting. The texture and mineralogy of the sandstone and the age of its zircons indicate that, following erosion, the sediment was transported a relatively short distance and for a very short time before deposition. In the Mid Cambrian, Cuyania was experiencing rapid post-rift thermal subsidence and accumulating its thick carbonate platform succession (Bond et al., 1984; Thomas and Astini, 1999). Accordingly, in prevailing geotectonic models involving rifting, e.g. the Laurentian microcontinent model of Astini et al. (1995) and Thomas and Astini (1996), Cuyania was separated by open ocean from a larger continent, and thus it was not in a position to receive sediment dispersed from an external source area. The older group of zircons has the same age range (1688-1318 Ma) as the zircons from the slightly younger sandstone of the La Laja Formation, and 25% of these older zircons, i.e. 2 of 8, have ages that fall within the North American magmatic gap. This indicates that this secondary sediment source was the same as that of the sampled La Laja sandstone and also was not Laurentian.

Worthy of consideration is a possible connection between the 615-511 Ma group of San Isidro zircons and the Wichita igneous province of the Southern Oklahoma aulacogen. The Wichita igneous province (Gilbert and Denison *in* Van Schmus et al., 1993) formed close to the margin of the Ouachita embayment contemporaneous with development of the rifted margin of the embayment (Thomas and Astini, 1999). It includes a bimodal igneous suite of gabbro/basalt and granite/rhyolite with the mafic and felsic magmatism possibly contemporaneous at 528 ±29 Ma during early rifting of the aulacogen (Lambert et al., 1988). Perhaps, similar rocks intruded into the basement of what would become the Cuyania terrane and are the provenance of the 615-511 Ma group. However, the compositional and textural evidence for tonalite as the source rock of the San Isidro sandstone, i.e., abundant coarse-grained quartz and plagioclase (now albitized) and little to no potassium feldspar, is not consistent with an origin from either the mafic or the potassium-rich igneous rocks of the Wichita igneous province. This is reflected in the great lithologic differences between the San Isidro sandstone and the Upper Cambrian Reagan Sandstone of Oklahoma. In the Wichita Mountains, the Reagan Sandstone is a first-cycle sandstone that was eroded directly from the Wichita igneous province and includes orthoclase and microcline as well as abundant glauconite and hematite and clasts of rhyolite (Tsegay, 1983). Thomas et al. (2000) reported U-Pb zircon ages of 536 ±5 Ma and 539 ±5 Ma for the rhyolite of the Wichita igneous suite, and M. Charles Gilbert (pers. comm. 2004) provided a U-Pb zircon age of 534 ±1.5 Ma for the Mount Scott Granite. In addition, Riggs et al., (1996) interpreted zircons from the Triassic Dockum Group with ages of 525-515 Ma as being derived from the Amarillo-Wichita uplift. In contrast, two-thirds of the San Isidro zircons in the 615-511 Ma group are older than the 539 Ma maximum age of the Wichita igneous province reported by Thomas et al. (2004). Furthermore, the ~100 my, more-or-less continuous age span of the 615-511 Ma group (Appendix) is indicative of a major orogenic belt rather than a small, isolated igneous province that represents a single geologic event, i.e., the formation of the Southern Oklahoma aulacogen (Gilbert and McConnell, 1991).

The 615-511 Ma group of zircons is strongly indicative of a Gondwanan provenance, and the Brasiliano orogen in particular. The Brasiliano orogen and the contemporaneous Pan-African orogen, composed of numerous orogenic belts and recorded by zircons of 650-500 Ma age, were produced during the final assembly of West Gondwana and the closing of the Mozambique Ocean between West and East Gondwana (Meert and Van der Voo, 1997; Unrug, 1997; Brito Neves et al., 1999; Veevers, 2003, Jacobs and Thomas, 2004). Between 600 Ma and 500 Ma, tectonic activity and emplacement of granitoids, such as the Cape granites in the Saldania belt of southwest Africa, were concentrated along the southern and western margins of West Gondwana (Veevers, 2003), and culminated with the 535-520 Ma Pampean orogeny of the Paraguay-Cordoba belt along the west side of the Rio de la Plata craton (Rapela et al., 1998). Thus, one needs to look no further than the southern margin of West Gondwana to find the source area for the 615-511 Ma zircons in the San Isidro sandstone.

Paleogeographic Implications

The detrital zircon age populations of the La Laja and San Isidro samples are distinctive. Each is dominated by a unimodal population. Those of the La Laja samples contain abundant grains with ages that correspond to the North American magmatic gap, indicating a provenance that was not Laurentia, whether the ultimate provenance was basement rocks of Cuyania or crystalline rocks external to Cuyania, possibly the Amazonian craton. The prominent, unimodal 615-511 Ma age cluster in the San Isidro sample is distinctive of a provenance in a Brasiliano orogenic belt, which must have been actively eroding and in close proximity to the site of deposition during Mid Cambrian time. The nearly complete absence of typical Grenvillian-age (1200-1000 Ma) zircons from the La Laja and San Isidro samples is unexpected, given that detritus of this age has dominated sedimentary systems of eastern Laurentia/North America for the past 1.0 billion years (Eriksson et al., 2003). It challenges widely held assumptions regarding the nature of basement rocks of Cuyania and the affinity of Cuyania with Laurentia. Together, the La Laja and San Isidro samples cannot be reconciled with models in which the basement rocks of Cuyania are entirely of Grenvillian age and Laurentian affinity and in which Cuyania rifted from the Ouachita embayment of Laurentia. Instead, they are most compatible with a model in which the basement rocks of Cuyania are of Gondwanan affinity, indicating that the Cuyania terrane was derived from, or rifted from, a margin of Gondwana.

Detrital zircon evidence from the Cerro Totora Formation has been used recently to support the Laurentian microcontinent model. The upper Lower Cambrian Cerro Totora Formation, exposed in the northern Precordillera, is composed of evaporates and silicilastics and has been interpreted as a syn-rift deposit that accumulated in a graben as Cuyania rifted from the Ouachita embayment of Laurentia (Thomas and Astini, 1999; Thomas et al., 2001). It is correlative with the upper Lower Cambrian El Estero Member of the La Laja Formation, and it is overlain stratigraphically by carbonate strata that correlate with the upper part of the La Laja Formation. Thomas et al., (2004) compared detrital zircon age populations from a sandstone sample taken from the Cerro Totora Formation with a sandstone sample from the Lower Cambrian Rome Formation of Alabama, regarded as a contemporaneous syn-rift deposit of southern Laurentia. On the basis of the distribution and similarity of age clusters, Thomas et al., (2004) concluded that 1) none of the zircons in the Cerro Totora sample correspond to a distinctive Gondwanan age, 2) the age populations of the Rome and Cerro Totora samples are similar and "correspond to ages of crystalline provinces of the Laurentian craton," and 3) the detrital zircons "link the Cerro Totora to Laurentian provenances and support . . . . transfer of the Precordillera from the Ouachita embayment of the Laurentian margin to Gondwana." We note, however, 1) that all of the zircon age populations of the Cerro Totora sample correspond to U-Pb zircon ages from granites in the Sunsás, Rondonian-San Ignácio, and Rio Negro-Juruena provinces in the southwestern part of the Amazonian craton (Tassinari and Macambira, 1999; Bettencourt et al., 1999), 2) that the Cerro Totora sample is dominated by detrital zircon age groups of Mesoproterozoic or Grenvillian age, which are represented by crystalline rocks in many other parts of Gondwana as well, and 3) that the Cerro Totora sample lacks the distinctly Laurentian Superior province cluster (2.7-2.5 Ga) of the Rome sample. Therefore, just as the Cerro Totora age groups do not correspond to a "distinctive" Gondwanan age, they also do not correspond to a "distinctive" Laurentian age. In light of the relatively small number of zircons in the Cerro Totora sample (n=25), we raise the question of whether or not the similarity of age clusters in the Rome and Cerro Totora formations merely represents derivation from crystalline rocks of similar age on separate cratons.

The similarity of the Cerro Totora and Rome zircon populations may be fortuitous, and thus not definitive of a Laurentian affinity of Cuyania. In contrast, the strongly unimodal distributions and distinctive zircon-age groups of the La Laja and San Isidro sandstones and the absence of typical Grenvillian-age zircons are, we believe, conclusive evidence that the provenance of these sandstones was not Laurentian but instead was Gondwanan. Although all dated exposures of crystalline basement rocks in Cuyania are of Grenvillian age, only a very small part of that basement is exposed. Therefore, we consider the possibility that the basement of Cuyania includes rocks of a Brasiliano orogenic belt and possibly even the 1688-1200 Ma crystalline source rocks of the La Laja samples. Alternatively, the Cuyania terrane may have included these rocks during the Mid Cambrian, but subsequently they were structurally largely removed during migration of the terrane. On the other hand, the distinctive La Laja and San Isidro sands may have been dispersed to the carbonate platform of Cuyania from an external source area, namely another area in Gondwana. This would have required a connection to the Gondwanan continent, but that connection may have been tenuous and even broken, following the rifting event that formed and isolated the Cuyania terrane and allowed for its thermal subsidence. However, the early Mid Cambrian Hawke Bay regressive event may have temporarily reestablished the connection and thus facilitated the dispersal of sediment to Cuyania from Gondwana.

The Hawke Bay regression and the subsequent flooding of the carbonate platform could explain the very different detrital zircon age populations in the La Laja and San Isidro samples. The San Isidro sandstone was deposited during the regressive event that exposed the platform or during an early stage of the subsequent transgression. The La Laja sandstone was deposited substantially later after the platform was flooded. This flooding may have drowned the source area of the San Isidro sands, preventing them from reentering the sedimentary system. The small population of older zircons in the San Isidro sample fall within the age range of the zircons in the La Laja samples, which includes the North American magmatic gap. This indicates that this distinctive sediment was dispersed onto the carbonate platform over a period of time represented by at least two trilobite zones in the Middle Cambrian.

Geotectonic Considerations

In our opinion, the paleogeographic affinity of Cuyania in Early to Mid Cambrian time must have been with Gondwana to account for the geochronology of detrital zircons in sandstones of the San Isidro olistolith and the La Laja Formation. As proposed by Finney et al. (2003a), a location of Cuyania along the southern margin of West Gondwana (present coordinates) would have placed it at a low paleolatitude within the tropical belt and in the path of equatorial oceanic currents flowing directly from Laurentia (Fig. 6A). This paleogeographic position would have resulted in Cuyania having a warm-water carbonate succession with faunas of Laurentian character. The occurrence of shallow-water benthic trilobites of Laurentian affinity in the Cambrian strata of the Precordillera is invoked as the strongest evidence supporting the Laurentian microcontinent model. However, in that model, Cuyania was separated from Laurentia and undergoing thermal subsidence during the late Early Cambrian to Late Cambrian while the trilobites dispersed across the intervening and rapidly widening ocean. Therefore, rather than a direct connection of Cuyania to Laurentia, trilobite paleobiogeography can reflect instead the proximity of the southwest margin of Gondwana and Cuyania to Laurentia.

The stratigraphic succession of the Precordillera is best explained by an early Cambrian rifting event that separated Cuyania as a terrane or microcontinent from the margin of Gondwana and initiated thermal subsidence. Rapela et al. (2003) have identified such a rifting event on the southern margin of West Gondwana. It is represented in the Neoproterozoic and early Paleozoic rocks in the Sierra de la Ventana belt, the Cape Fold Belt, the Falkland/Malvinas microplate, and the Ellsworth microplate. They proposed that this rifting event produced the microcontinents and terranes with Grenvillian basement that later collided with the proto-Andean margin. Their model is similar that of Aceñolaza et al. (2002) in the location proposed for the origin of Cuyania. In addition, the lateral-escape tectonic model recently proposed by Jacobs and Thomas (2004) offers an alternative mechanism for producing the Cuyania terrane from a similar location.

In the Laurentian microcontinent model of Thomas and Astini (1996, 2003), Astini et al. (1995), and Astini (1998), the Precordillera terrane or Cuyania docked with the proto-Andean margin of Gondwana outboard of the Famatinian magmatic belt during late Mid Ordovician time, and the Upper Ordovician siliciclastic strata of the Precordillera represent a clastic wedge that formed in response to that collision. Because zircons of Famatinian age (490-470 Ma) have not been detected in sandstone samples from the Upper Ordovician strata, Finney et al. (2003a, 2003b, 2003c) concluded that Cuyania was not

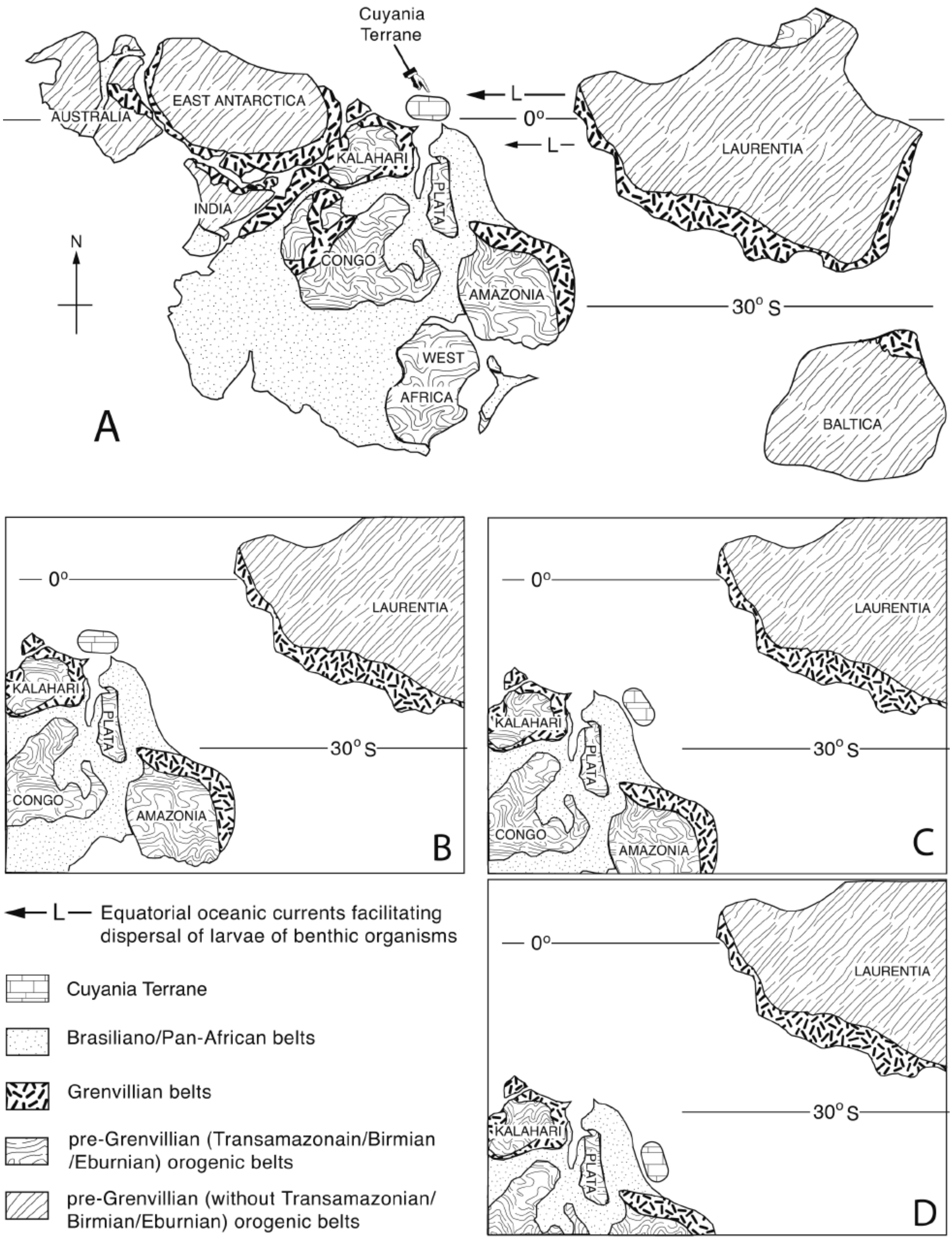

FIGURE 6 | **Paleogeographic reconstruction with Cuyania (A) located on the southern margin of West Gondwana (present coordinates) during the Cambrian, (B) migrating to higher paleolatitude along with Gondwana during the Early to Mid Ordovician Epochs, (C) beginning its transcurrent movement along the Iapetus margin of West Gondwana during the Mid to Late Ordovician Epochs, and (D) arriving at its present position in Gondwana during late Silurian to Devonian time. Modified from Hoffman (1991).**

outboard of the Famatinian magmatic belt and did not dock with the proto-Andean margin of Gondwana in the Mid Ordovician. In fact, Baldis e al. (1989), Rapela et al. (1998) and Keller (1999) have argued on the basis of stratigraphic and faunal relations and on other geologic evidence that Cuyania did not arrive at its present position until late Silurian or early Devonian time. The question that remains is "Where was Cuyania during the Ordovician?"

We propose that, after rifting from the southern margin of West Gondwana in the Early Cambrian, Cuyania remained relatively close to Gondwana, possibly with enough of a connection to allow for the dispersal of sediment from Gondwana during the early Mid Cambrian regressive event, while still allowing for thermal subsidence. Warm water benthic faunas in the stratigraphic succession of the Precordillera indicate that Cuyania maintained its position at a low paleolatitude until Mid Ordovician time (Benedetto, 1998). Subsequent appearances of cooler water faunas may reflect the general migration of Cuyania along with Gondwana to progressively higher paleolatitude during the Mid and Late Ordovician (Fig. 6B to 6D). The dramatic stratigraphic replacement of the relatively homogenous, Cambrian to lower Middle Ordovician carbonate platform succession by Middle and Upper Ordovician strata of largely siliciclastic facies with great vertical and lateral heterogeneity records a tectonic upheaval. That upheaval could be the initiation of transcurrent motion of Cuyania along the southwestern margin of Gondwana as proposed by Aceñolaza et al. (2002) with the sporadic subsidence of pull-apart basins in which Upper Ordovician and Silurian strata rapidly accumulated.

CONCLUSIONS

Detrital zircons in the La Laja and San Isidro samples have distinctive U-Pb age populations indicating that their ultimate provenances were crystalline rocks that were not of Grenvillian age and were not of Laurentian affinity. Given that they occur in Middle Cambrian sandstones deposited on the carbonate platform of Cuyania, these zircons were eroded either from basement rocks of Cuyania or from rocks external to Cuyania. Both situations are difficult to reconcile with Cuyania having rifted from the Ouachita embayment of Laurentia in the Early Cambrian. On the other hand, potential source rocks do exist in West Gondwana in Proterozoic orogenic belts on the southwestern margin of the Amazonian craton and in Brasiliano-Pan African orogenic belts throughout the southern part of West Gondwana.

Our interpretation of a Gondwanan affinity of Cuyania in the Mid Cambrian and a post-Ordovician arrival at its present position outboard of the Famatinian magmatic arc requires that Cuyania migrated along the southern margin of West Gondwana during the Ordovician Period, with initiation of this migration recorded in marked facies change at the top of the carbonate platform succession in the Precordillera.

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APPENDIX

U-Pb GEOCHRONOLOGIC ANALYSES

			Isotopic ratios					Apparent ages (Ma)							
U (ppm)	$^{206}Pb/^{204}Pb$	U/Th	$^{207}Pb^*/^{235}U$	± (%)	$^{206}Pb^*/^{238}U$	± (%)	error corr.	$^{206}Pb^*/^{238}U$	±(Ma)	$^{207}Pb^*/^{235}U$	± (Ma)	$^{206}Pb^*/^{207}Pb^*$	±(Ma)	**Preferred age**	**± (Ma)**
LLFM1															
94	4957	2	2.24224	3.91	0.20474	0.77	0.20	**1200.8**	**10.2**	**1194**	**85**	1183	38	**1201**	**10**
24	*1234*	*2*	*2.13585*	*13.79*	*0.19193*	*3.04*	*0.22*	*1131.8*	*37.5*	*1161*	*262*	*1214*	*132*		
37	3340	2	2.35385	7.44	0.21133	2.81	0.38	1235.9	38.1	1229	164	**1216**	**68**	**1216**	**68**
30	1059	3	2.35605	9.88	0.20810	2.73	0.28	1218.7	36.5	1229	213	**1248**	**93**	**1248**	**93**
136	4782	2	2.53262	2.36	0.22201	1.18	0.50	1292.5	16.9	1282	59	**1263**	**20**	**1263**	**20**
318	4015	2	2.04609	1.59	0.17800	0.97	0.61	1056.1	11.1	1131	33	**1278**	**12**	**1278**	**12**
225	1386	2	1.97706	3.72	0.17075	3.16	0.85	1016.2	34.7	1108	72	**1292**	**19**	**1292**	**19**
40	2931	2	2.55104	6.14	0.21986	1.57	0.26	1281.1	22.3	1287	148	**1296**	**58**	**1296**	**58**
76	2956	3	2.44719	4.12	0.20996	2.46	0.60	1228.6	33.2	1257	98	**1305**	**32**	**1305**	**32**
67	2655	3	2.60742	6.38	0.22236	1.59	0.25	1294.3	22.8	1303	156	**1317**	**60**	**1317**	**60**
37	2126	2	2.67983	9.71	0.22825	1.60	0.17	1325.3	23.6	1323	235	**1319**	**93**	**1319**	**93**
56	2288	3	2.48891	5.03	0.21103	1.16	0.23	1234.3	15.8	1269	120	**1328**	**47**	**1328**	**47**
81	3014	1	2.56939	5.26	0.21694	1.11	0.21	1265.7	15.4	1292	129	**1336**	**50**	**1336**	**50**
58	3531	2	2.76003	3.90	0.23298	0.89	0.23	1350.1	13.4	1345	104	**1336**	**37**	**1336**	**37**
38	1985	2	2.67411	9.74	0.22551	2.77	0.28	1310.9	40.2	1321	235	**1338**	**90**	**1338**	**90**
78	2878	1	2.77434	2.71	0.23338	0.64	0.24	1352.2	9.7	1349	74	**1343**	**25**	**1343**	**25**
201	4300	2	2.04326	2.11	0.17108	1.81	0.86	1018.1	19.9	1130	43	**1352**	**11**	**1352**	**11**
42	2124	2	2.65493	3.85	0.22200	1.38	0.36	1292.5	19.7	1316	99	**1355**	**35**	**1355**	**35**
136	6110	14	2.73844	2.53	0.22866	1.72	0.68	1327.5	25.3	1339	68	**1357**	**18**	**1357**	**18**
72	3761	1	2.81392	4.00	0.23471	1.11	0.28	1359.1	16.8	1359	108	**1359**	**37**	**1359**	**37**
244	4108	2	2.19157	1.96	0.18259	1.39	0.71	1081.1	16.3	1178	43	**1362**	**13**	**1362**	**13**
65	3083	3	2.90246	4.04	0.24117	1.65	0.41	1392.8	25.6	1383	113	**1367**	**36**	**1367**	**36**
88	1860	1	2.79846	2.30	0.23236	1.38	0.60	1346.9	20.6	1355	63	**1368**	**18**	**1368**	**18**
121	18571	1	2.84351	2.29	0.23600	0.93	0.41	1365.9	14.1	1367	64	**1369**	**20**	**1369**	**20**
66	3092	2	2.91544	4.01	0.24157	0.81	0.20	1394.9	12.6	1386	112	**1372**	**38**	**1372**	**38**
38	1605	2	2.92668	5.09	0.24229	1.85	0.36	1398.6	28.9	1389	141	**1374**	**46**	**1374**	**46**
46	2205	1	2.88391	6.15	0.23848	0.48	0.08	1378.8	7.3	1378	166	**1376**	**59**	**1376**	**59**
65	3290	1	2.91262	3.12	0.24024	1.47	0.47	1388.0	22.8	1385	88	**1381**	**26**	**1381**	**26**
47	1822	1	2.70156	5.16	0.22256	1.41	0.27	1295.4	20.2	1329	133	**1383**	**48**	**1383**	**48**
73	2763	1	2.29017	5.50	0.18821	2.24	0.41	1111.7	27.1	1209	121	**1388**	**48**	**1388**	**48**
141	4749	1	2.47804	2.96	0.20318	1.21	0.41	1192.4	15.8	1266	72	**1392**	**26**	**1392**	**26**
77	6242	4	2.97683	2.18	0.24388	1.25	0.57	1406.8	19.6	1402	64	**1394**	**17**	**1394**	**17**
84	3760	3	2.65990	3.60	0.21776	1.81	0.50	1270.0	25.4	1317	93	**1395**	**30**	**1395**	**30**
92	3765	2	2.82921	2.35	0.23147	1.47	0.62	1342.2	21.9	1363	66	**1397**	**18**	**1397**	**18**
75	7333	1	2.96033	3.47	0.24212	1.30	0.38	1397.7	20.3	1398	99	**1397**	**31**	**1397**	**31**
112	5396	1	2.94616	2.15	0.24073	0.92	0.43	1390.5	14.3	1394	62	**1399**	**19**	**1399**	**19**
29	2161	1	2.67133	9.35	0.21757	2.08	0.22	1269.0	29.1	1321	227	**1405**	**87**	**1405**	**87**
67	4402	1	2.84671	3.81	0.23165	0.73	0.19	1343.2	10.9	1368	105	**1407**	**36**	**1407**	**36**
79	4790	2	2.86757	4.86	0.23219	1.19	0.25	1346.0	17.8	1373	133	**1416**	**45**	**1416**	**45**
42	2918	1	2.96114	6.76	0.23904	0.78	0.11	1381.7	12.0	1398	185	**1422**	**64**	**1422**	**64**
101	3208	3	2.69419	3.31	0.21714	1.77	0.53	1266.7	24.7	1327	87	**1425**	**27**	**1425**	**27**
42	1849	2	2.86764	7.44	0.23086	1.60	0.21	1339.0	23.7	1374	196	**1427**	**69**	**1427**	**69**
36	2723	1	2.95805	5.23	0.23759	1.62	0.31	1374.2	24.8	1397	146	**1432**	**47**	**1432**	**47**
35	1469	1	2.96413	4.54	0.23802	1.36	0.30	1376.4	20.9	1399	128	**1432**	**41**	**1432**	**41**
88	5835	2	2.79665	4.42	0.22454	1.84	0.42	1305.8	26.6	1355	118	**1433**	**38**	**1433**	**38**
196	8145	2	2.46167	2.29	0.19745	0.95	0.42	1161.6	12.1	1261	56	**1434**	**20**	**1434**	**20**
69	3231	2	2.55266	3.58	0.20479	1.13	0.32	1201.0	14.9	1287	89	**1434**	**32**	**1434**	**32**
60	4481	1	3.03945	5.77	0.24383	0.81	0.14	1406.6	12.8	1418	164	**1434**	**55**	**1434**	**55**
168	3204	2	2.77302	3.28	0.22238	0.52	0.16	1294.4	7.5	1348	88	**1435**	**31**	**1435**	**31**
95	3130	2	2.87838	2.93	0.23075	1.55	0.53	1338.4	23.0	1376	82	**1435**	**24**	**1435**	**24**

			Isotopic ratios					Apparent ages (Ma)							
U (ppm)	^{206}Pb/^{204}Pb	U/Th	$^{207}Pb^*$/^{235}U	± (%)	$^{206}Pb^*$/^{238}U	± (%)	error corr.	$^{206}Pb^*$/^{238}U	±(Ma)	$^{207}Pb^*$/^{235}U	± (Ma)	$^{206}Pb^*$/$^{207}Pb^*$	±(Ma)	**Preferred age**	**± (Ma)**
LLFM1															
104	7542	2	3.14208	2.78	0.25181	1.72	0.62	1447.8	27.9	1443	85	**1436**	**21**	**1436**	**21**
86	3810	1	2.34866	4.90	0.18813	1.24	0.25	1111.2	15.1	1227	111	**1437**	**45**	**1437**	**45**
249	9846	2	2.56668	2.22	0.20531	1.92	0.87	1203.8	25.4	1291	56	**1440**	**11**	**1440**	**11**
15	2663	1	2.92411	6.34	0.23371	2.51	0.40	1353.9	37.7	1388	173	**1441**	**55**	**1441**	**55**
59	11802	1	3.09398	6.19	0.24676	1.12	0.18	1421.7	17.8	1431	178	**1445**	**58**	**1445**	**58**
221	16787	2	2.54984	2.01	0.20242	1.06	0.53	1188.3	13.8	1286	51	**1454**	**16**	**1454**	**16**
140	4557	2	2.68030	2.04	0.21280	1.24	0.61	1243.7	17.0	1323	54	**1454**	**15**	**1454**	**15**
61	2691	2	2.80871	4.09	0.22272	0.60	0.15	1296.2	8.6	1358	110	**1456**	**38**	**1456**	**38**
119	1799	2	3.10446	1.80	0.24606	0.75	0.42	1418.1	11.9	1434	55	**1457**	**15**	**1457**	**15**
11	*2187*	*2*	*2.24532*	*19.91*	*0.17793*	*5.58*	*0.28*	*1055.7*	*63.7*	*1195*	*375*	*1457*	*182*		
261	8833	2	2.33801	4.37	0.18522	4.22	0.97	1095.4	50.2	1224	99	**1458**	**11**	**1458**	**11**
81	4892	2	2.88458	2.59	0.22847	1.05	0.41	1326.5	15.5	1378	73	**1459**	**22**	**1459**	**22**
215	14259	1	3.08070	1.84	0.24366	1.30	0.71	1405.7	20.4	1428	56	**1461**	**12**	**1461**	**12**
66	2367	2	3.09227	2.90	0.24404	1.82	0.63	1407.7	28.6	1431	87	**1465**	**21**	**1465**	**21**
222	14652	2	3.04343	1.09	0.24010	0.59	0.54	1387.2	9.1	1419	33	**1466**	**9**	**1466**	**9**
34	1895	2	2.88197	8.72	0.22690	2.70	0.31	1318.2	39.4	1377	228	**1470**	**79**	**1470**	**79**
95	6126	1	2.97121	3.31	0.23358	0.80	0.24	1353.2	12.1	1400	95	**1473**	**30**	**1473**	**30**
118	3055	5	3.15718	3.14	0.24779	0.76	0.24	1427.1	12.1	1447	96	**1476**	**29**	**1476**	**29**
44	1896	2	3.01066	7.69	0.23610	1.38	0.18	1366.4	21.0	1410	211	**1477**	**72**	**1477**	**72**
27	2702	2	3.03472	10.50	0.23780	1.29	0.12	1375.3	19.8	1416	281	**1479**	**99**	**1479**	**99**
113	1834	1	3.31504	6.34	0.25912	1.45	0.23	1485.3	24.2	1485	194	**1484**	**58**	**1484**	**58**
67	1618	1	3.02203	5.06	0.23584	1.86	0.37	1365.0	28.3	1413	145	**1487**	**45**	**1487**	**45**
15	*1932*	*2*	*3.04691*	*26.14*	*0.23745*	*4.93*	*0.19*	*1373.4*	*75.0*	*1420*	*595*	*1489*	*243*		
128	8376	2	3.00908	1.62	0.23415	1.07	0.66	1356.2	16.1	1410	48	**1492**	**12**	**1492**	**12**
136	3935	7	2.68052	2.64	0.20850	1.04	0.39	1220.8	14.0	1323	70	**1493**	**23**	**1493**	**23**
59	2670	1	3.11898	4.31	0.24209	1.21	0.28	1397.6	18.9	1437	128	**1497**	**39**	**1497**	**39**
69	3373	2	3.24072	2.96	0.25137	0.72	0.24	1445.5	11.6	1467	93	**1498**	**27**	**1498**	**27**
123	3307	1	2.52181	6.31	0.19542	6.04	0.96	1150.7	75.7	1278	150	**1500**	**17**	**1500**	**17**
68	3700	1	2.93285	3.44	0.22580	1.12	0.33	1312.5	16.3	1390	98	**1512**	**31**	**1512**	**31**
90	2938	2	3.27554	2.17	0.25150	0.94	0.44	1446.2	15.3	1475	70	**1517**	**18**	**1517**	**18**
87	4377	2	2.46390	3.69	0.18915	1.45	0.39	1116.7	17.7	1262	88	**1518**	**32**	**1518**	**32**
76	8729	2	3.27259	2.62	0.25102	0.68	0.26	1443.7	11.0	1475	84	**1519**	**24**	**1519**	**24**
96	14450	1	3.22494	2.10	0.24731	1.02	0.49	1424.6	16.2	1463	67	**1520**	**17**	**1520**	**17**
29	4602	1	2.88219	4.74	0.22059	2.22	0.47	1285.0	31.5	1377	130	**1523**	**39**	**1523**	**39**
77	3766	1	3.09369	4.73	0.23652	0.99	0.21	1368.6	15.1	1431	139	**1525**	**44**	**1525**	**44**
120	6444	2	2.92154	2.47	0.22258	1.19	0.48	1295.5	17.1	1388	71	**1532**	**20**	**1532**	**20**
151	5121	2	2.86612	3.06	0.21783	1.07	0.35	1270.4	15.0	1373	86	**1537**	**27**	**1537**	**27**
47	2820	2	3.24526	2.49	0.24461	1.28	0.51	1410.6	20.1	1468	79	**1552**	**20**	**1552**	**20**
190	8458	2	2.57371	2.27	0.19355	0.72	0.32	1140.6	9.0	1293	58	**1556**	**20**	**1556**	**20**
44	2020	2	3.20969	4.69	0.24081	1.59	0.34	1390.9	24.7	1460	142	**1561**	**41**	**1561**	**41**
53	2689	2	3.17299	4.98	0.23555	1.17	0.24	1363.5	17.8	1451	149	**1581**	**45**	**1581**	**45**
66	3068	1	3.01561	3.78	0.22370	1.33	0.35	1301.4	19.2	1412	110	**1582**	**33**	**1582**	**33**
26	1474	2	3.29208	6.53	0.24391	2.73	0.42	1407.0	42.8	1479	198	**1584**	**55**	**1584**	**55**
45	3260	2	3.15296	5.04	0.23347	1.13	0.22	1352.7	17.0	1446	150	**1585**	**46**	**1585**	**46**
31	1426	1	3.08745	5.97	0.22108	2.14	0.36	1287.6	30.4	1430	172	**1648**	**52**	**1648**	**52**
51	2050	1	3.05831	4.27	0.21791	1.29	0.30	1270.8	18.1	1422	125	**1657**	**38**	**1657**	**38**
50	3292	2	3.36094	4.14	0.23915	0.64	0.16	1382.3	9.9	1495	132	**1659**	**38**	**1659**	**38**
29	2166	2	3.08670	4.90	0.21629	1.48	0.30	1262.3	20.6	1429	143	**1688**	**43**	**1688**	**43**
LLFM2															
27	*1064*	*1*	*2.32845*	*41.46*	*0.26809*	*3.41*	*0.08*	*1531.1*	*58.7*	*1221*	*686*	*708*	*439*		
28	*846*	*2*	*2.30444*	*24.56*	*0.23501*	*5.25*	*0.21*	*1360.7*	*79.1*	*1214*	*455*	*961*	*245*		
64	*352*	*1*	*2.55538*	*17.83*	*0.25569*	*5.12*	*0.29*	*1467.8*	*83.9*	*1288*	*381*	*1000*	*173*		
28	*584*	*1*	*2.64971*	*20.98*	*0.25676*	*11.47*	*0.55*	*1473.3*	*187.1*	*1315*	*449*	*1064*	*177*		
64	*2426*	*2*	*2.94317*	*14.40*	*0.25705*	*3.46*	*0.24*	*1474.7*	*57.1*	*1393*	*359*	*1270*	*136*		
164	5004	8	2.56303	5.69	0.21865	1.78	0.31	1274.7	25.1	1290	138	**1316**	**52**	**1316**	**52**

U (ppm)	$^{206}Pb/^{204}Pb$	U/Th	Isotopic ratios $^{207}Pb^*/^{235}U$	± (%)	$^{206}Pb^*/^{238}U$	± (%)	error corr.	Apparent ages (Ma) $^{206}Pb^*/^{238}U$	±(Ma)	$^{207}Pb^*/^{235}U$	± (Ma)	$^{206}Pb^*/^{207}Pb^*$	±(Ma)	**Preferred age**	**± (Ma)**
LLFM2															
99	6114	1	2.70098	6.51	0.22447	1.87	0.29	1305.5	26.9	1329	164	**1366**	**60**	**1366**	**60**
173	7948	2	2.79676	4.46	0.23058	1.18	0.26	1337.5	17.5	1355	119	**1382**	**41**	**1382**	**41**
73	*3368*	*2*	*3.37457*	*14.27*	*0.27799*	*2.42*	*0.17*	*1581.2*	*43.3*	*1499*	*399*	*1383*	*135*		
165	11918	3	2.62455	5.47	0.21531	1.54	0.28	1257.1	21.3	1308	136	**1391**	**50**	**1391**	**50**
293	3122	1	2.83397	3.83	0.23181	1.62	0.42	1344.0	24.2	1365	105	**1397**	**33**	**1397**	**33**
42	2134	3	2.98177	6.48	0.24060	2.78	0.43	1389.8	43.0	1403	180	**1423**	**56**	**1423**	**56**
126	4964	1	3.30083	6.30	0.26609	1.74	0.28	1520.9	29.8	1481	192	**1425**	**58**	**1425**	**58**
90	2374	2	3.24291	4.24	0.26066	2.08	0.49	1493.2	34.8	1468	131	**1430**	**35**	**1430**	**35**
273	14060	3	3.26525	7.30	0.26234	1.46	0.20	1501.8	24.7	1473	217	**1431**	**68**	**1431**	**68**
356	18306	3	3.19798	4.22	0.25567	1.22	0.29	1467.6	20.0	1457	129	**1441**	**39**	**1441**	**39**
161	8788	2	3.24230	6.42	0.25792	1.41	0.22	1479.2	23.4	1467	192	**1450**	**60**	**1450**	**60**
492	15056	2	3.21355	6.31	0.25536	1.64	0.26	1466.0	26.9	1460	188	**1452**	**58**	**1452**	**58**
194	22668	2	3.33528	6.25	0.26494	1.95	0.31	1515.1	33.2	1489	192	**1453**	**56**	**1453**	**56**
264	9936	2	3.08137	5.43	0.24474	1.96	0.36	1411.3	30.8	1428	157	**1453**	**48**	**1453**	**48**
27	1712	2	3.24972	5.68	0.25782	1.44	0.25	1478.7	23.9	1469	172	**1455**	**52**	**1455**	**52**
97	4854	4	3.27236	6.15	0.25962	2.03	0.33	1487.9	33.9	1475	186	**1455**	**55**	**1455**	**55**
96	3928	1	3.30952	5.58	0.26267	2.73	0.49	1503.5	46.0	1483	172	**1455**	**46**	**1455**	**46**
49	4876	2	3.39609	7.31	0.26877	1.82	0.25	1534.6	31.4	1504	225	**1460**	**67**	**1460**	**67**
115	4850	4	3.31008	4.13	0.26188	2.62	0.63	1499.4	44.1	1483	130	**1461**	**30**	**1461**	**30**
286	14434	3	3.46992	4.36	0.27410	1.18	0.27	1561.6	20.7	1520	143	**1464**	**40**	**1464**	**40**
157	6588	1	3.43098	5.46	0.27090	2.89	0.53	1545.4	50.3	1512	175	**1464**	**44**	**1464**	**44**
273	5236	2	3.13970	3.76	0.24711	2.15	0.57	1423.5	34.2	1443	113	**1470**	**29**	**1470**	**29**
336	33350	2	3.37366	4.95	0.26551	1.31	0.27	1517.9	22.5	1498	157	**1471**	**45**	**1471**	**45**
340	6908	2	3.13853	5.00	0.24699	3.28	0.65	1423.0	52.0	1442	148	**1471**	**36**	**1471**	**36**
668	6968	3	2.82096	4.24	0.22183	3.17	0.75	1291.5	45.1	1361	115	**1472**	**27**	**1472**	**27**
154	7774	2	3.36902	5.79	0.26416	2.67	0.46	1511.1	45.3	1497	181	**1478**	**49**	**1478**	**49**
153	25546	2	3.34867	5.37	0.26174	1.21	0.22	1498.7	20.3	1493	168	**1484**	**50**	**1484**	**50**
81	3128	2	3.34948	3.60	0.26176	2.65	0.74	1498.8	44.5	1493	116	**1484**	**23**	**1484**	**23**
175	9570	3	3.39151	5.14	0.26495	2.06	0.40	1515.1	35.2	1502	163	**1485**	**45**	**1485**	**45**
56	3010	1	3.51289	9.87	0.27443	6.22	0.63	1563.3	109.0	1530	302	**1485**	**73**	**1485**	**73**
63	4244	1	3.27778	5.36	0.25540	2.03	0.38	1466.3	33.3	1476	164	**1490**	**47**	**1490**	**47**
115	10414	2	3.19838	5.23	0.24885	1.66	0.32	1432.6	26.5	1457	157	**1492**	**47**	**1492**	**47**
85	6458	2	3.44437	6.93	0.26805	3.85	0.56	1530.9	66.2	1515	217	**1492**	**55**	**1492**	**55**
108	2820	2	3.41331	5.94	0.26516	1.83	0.31	1516.2	31.1	1508	187	**1495**	**53**	**1495**	**53**
138	8214	2	3.45176	6.49	0.26771	2.82	0.43	1529.2	48.5	1516	205	**1498**	**55**	**1498**	**55**
79	4668	3	3.31675	5.32	0.25717	3.21	0.60	1475.4	53.0	1485	165	**1499**	**40**	**1499**	**40**
111	11678	1	3.43542	6.91	0.26622	3.41	0.49	1521.6	58.2	1513	216	**1500**	**57**	**1500**	**57**
84	3782	2	3.08172	5.36	0.23879	1.97	0.37	1380.4	30.3	1428	155	**1500**	**47**	**1500**	**47**
68	3372	1	3.50653	6.62	0.27149	3.34	0.50	1548.4	58.2	1529	212	**1502**	**54**	**1502**	**54**
62	7552	1	3.43789	5.19	0.26594	1.78	0.34	1520.2	30.5	1513	167	**1503**	**46**	**1503**	**46**
228	21178	1	3.40151	5.01	0.26309	1.98	0.40	1505.6	33.5	1505	160	**1503**	**43**	**1503**	**43**
113	6184	2	3.32265	6.07	0.25686	1.33	0.22	1473.8	22.0	1486	187	**1504**	**56**	**1504**	**56**
104	5248	2	3.40887	5.70	0.26351	2.62	0.46	1507.8	44.3	1506	180	**1505**	**48**	**1505**	**48**
54	4096	1	3.45580	7.19	0.26697	2.81	0.39	1525.4	48.1	1517	225	**1506**	**62**	**1506**	**62**
124	2654	1	3.31698	5.46	0.25613	2.33	0.43	1470.0	38.4	1485	169	**1507**	**47**	**1507**	**47**
78	3598	3	3.55191	5.36	0.27413	2.88	0.54	1561.7	50.7	1539	177	**1508**	**43**	**1508**	**43**
132	4462	2	3.42865	6.33	0.26435	2.95	0.47	1512.1	50.1	1511	200	**1509**	**53**	**1509**	**53**
87	6504	2	3.41990	4.93	0.26373	1.88	0.38	1508.9	32.0	1509	158	**1509**	**43**	**1509**	**43**
134	6546	2	3.66906	6.81	0.28282	2.08	0.31	1605.6	37.7	1565	226	**1510**	**61**	**1510**	**61**
138	4966	2	3.44440	7.32	0.26547	2.08	0.28	1517.8	35.5	1515	228	**1510**	**66**	**1510**	**66**
61	3352	2	3.46365	5.24	0.26703	1.92	0.37	1525.7	33.0	1519	169	**1510**	**46**	**1510**	**46**
52	2804	2	3.45487	2.71	0.26598	1.01	0.37	1520.4	17.2	1517	91	**1512**	**24**	**1512**	**24**
225	12566	2	3.33055	4.25	0.25647	0.91	0.21	1471.8	15.1	1488	135	**1512**	**39**	**1512**	**39**
196	16492	2	3.46323	5.72	0.26651	1.88	0.33	1523.0	32.2	1519	184	**1513**	**51**	**1513**	**51**
78	7060	2	3.41201	3.80	0.26252	1.31	0.34	1502.7	22.1	1507	124	**1513**	**34**	**1513**	**34**

U (ppm)	$^{206}Pb/^{204}Pb$	U/Th	Isotopic ratios $^{207}Pb^*/^{235}U$	± (%)	$^{206}Pb^*/^{238}U$	± (%)	error corr.	Apparent ages (Ma) $^{206}Pb^*/^{238}U$	±(Ma)	$^{207}Pb^*/^{235}U$	± (Ma)	$^{206}Pb^*/^{207}Pb^*$	±(Ma)	**Preferred age**	**± (Ma)**
LLFM2															
70	4086	2	3.48995	6.05	0.26857	1.59	0.26	1533.6	27.5	1525	194	**1513**	**55**	**1513**	**55**
133	9992	2	3.48688	7.43	0.26813	1.16	0.16	1531.3	20.1	1524	234	**1514**	**69**	**1514**	**69**
248	15716	3	3.27652	4.05	0.25193	1.71	0.42	1448.4	27.7	1476	127	**1515**	**35**	**1515**	**35**
36	1714	1	3.37067	4.38	0.25898	1.41	0.32	1484.6	23.4	1498	140	**1516**	**39**	**1516**	**39**
79	4704	2	3.48377	4.44	0.26747	2.93	0.66	1527.9	50.4	1524	146	**1517**	**31**	**1517**	**31**
183	9234	1	3.48165	4.68	0.26727	2.29	0.49	1526.9	39.3	1523	153	**1518**	**38**	**1518**	**38**
142	7392	2	3.44699	4.89	0.26457	2.59	0.53	1513.2	44.0	1515	158	**1518**	**39**	**1518**	**39**
103	1958	2	3.37319	4.18	0.25894	1.79	0.43	1484.4	29.9	1498	134	**1518**	**36**	**1518**	**36**
149	9140	5	3.46287	6.66	0.26561	1.72	0.26	1518.5	29.4	1519	211	**1519**	**61**	**1519**	**61**
70	6022	7	3.48105	4.44	0.26705	1.96	0.44	1525.8	33.6	1523	146	**1519**	**38**	**1519**	**38**
61	2510	1	3.44846	7.24	0.26444	1.61	0.22	1512.5	27.4	1516	226	**1520**	**67**	**1520**	**67**
87	3328	1	3.37878	2.72	0.25907	1.33	0.49	1485.1	22.2	1500	89	**1520**	**22**	**1520**	**22**
118	6260	2	3.34973	6.66	0.25658	3.18	0.48	1472.3	52.4	1493	205	**1522**	**55**	**1522**	**55**
202	13276	2	3.38155	5.86	0.25895	2.14	0.37	1484.5	35.7	1500	184	**1522**	**51**	**1522**	**51**
101	4802	2	3.48445	7.13	0.26670	3.49	0.49	1524.0	59.7	1524	225	**1523**	**59**	**1523**	**59**
163	9678	3	3.52789	4.40	0.27012	1.54	0.35	1541.4	26.7	1534	147	**1523**	**39**	**1523**	**39**
717	2250	1	2.89220	1.88	0.22144	1.67	0.89	1289.5	23.9	1380	54	**1523**	**8**	**1523**	**8**
185	11252	2	3.51693	6.61	0.26886	1.39	0.21	1535.0	24.1	1531	212	**1525**	**61**	**1525**	**61**
100	2006	3	3.32256	6.29	0.25388	2.20	0.35	1458.5	36.0	1486	193	**1526**	**55**	**1526**	**55**
50	2728	2	3.52581	4.58	0.26921	2.22	0.48	1536.8	38.4	1533	152	**1528**	**38**	**1528**	**38**
99	8590	1	3.47710	6.46	0.26551	2.77	0.43	1518.0	47.2	1522	206	**1528**	**55**	**1528**	**55**
84	4864	2	3.55206	6.70	0.27100	2.41	0.36	1545.9	42.0	1539	217	**1529**	**59**	**1529**	**59**
76	2934	1	3.43024	3.62	0.26128	2.06	0.57	1496.4	34.6	1511	119	**1532**	**28**	**1532**	**28**
101	4530	2	3.44446	4.91	0.26199	1.82	0.37	1500.0	30.7	1515	159	**1535**	**43**	**1535**	**43**
78	5630	1	3.53244	6.16	0.26821	3.56	0.58	1531.7	61.3	1535	200	**1538**	**47**	**1538**	**47**
144	6066	2	3.46550	5.68	0.26304	2.15	0.38	1505.4	36.3	1519	182	**1539**	**49**	**1539**	**49**
54	3080	1	3.38188	5.98	0.25650	2.91	0.49	1471.9	47.9	1500	187	**1540**	**49**	**1540**	**49**
168	16286	2	3.51560	4.64	0.26646	1.93	0.42	1522.8	33.0	1531	153	**1542**	**40**	**1542**	**40**
98	3662	5	3.31397	6.08	0.25093	2.93	0.48	1443.3	47.2	1484	186	**1544**	**50**	**1544**	**50**
142	2178	1	3.57356	2.94	0.26915	2.08	0.71	1536.5	36.0	1544	101	**1554**	**19**	**1554**	**19**
60	4578	2	3.58641	5.58	0.26936	2.35	0.42	1537.6	40.6	1547	185	**1559**	**47**	**1559**	**47**
29	*1782*	*2*	*3.68949*	*18.17*	*0.26257*	*2.18*	*0.12*	*1503.0*	*36.8*	*1569*	*521*	*1659*	*167*		
ISOS1															
56	1386	1	0.76981	9.82	0.08252	2.02	0.21	**511.1**	**10.8**	580	74	858	100	**511**	**11**
30	1694	2	0.68065	18.11	0.08257	2.58	0.14	**511.4**	**13.7**	527	118	596	194	**511**	**14**
53	2396	4	0.67167	9.73	0.08438	1.24	0.13	**522.2**	**6.7**	522	64	520	106	**522**	**7**
56	2237	1	0.77349	8.38	0.08444	1.90	0.23	**522.6**	**10.4**	582	64	820	85	**523**	**10**
49	20425	2	0.90385	8.91	0.08450	1.66	0.19	**522.9**	**9.0**	654	79	1136	87	**523**	**9**
13	2478	2	0.98622	12.37	0.08449	2.03	0.16	**522.9**	**11.0**	697	117	1308	118	**523**	**11**
19	1085	2	0.53116	25.58	0.08457	2.44	0.10	**523.3**	**13.3**	433	129	-26	308	**523**	**13**
47	16417	2	0.71654	20.02	0.08492	0.50	0.02	**525.4**	**2.7**	549	136	646	215	**525**	**3**
46	2896	1	0.70600	8.39	0.08513	1.14	0.14	**526.7**	**6.3**	542	58	609	90	**527**	**6**
79	5165	2	0.61924	9.13	0.08521	0.74	0.08	**527.2**	**4.1**	489	56	316	103	**527**	**4**
134	2996	1	0.59097	4.67	0.08525	0.56	0.12	**527.4**	**3.1**	472	28	208	54	**527**	**3**
29	6827	2	0.80047	21.15	0.08532	1.09	0.05	**527.8**	**6.0**	597	159	870	219	**528**	**6**
57	12344	1	0.76925	10.72	0.08533	1.22	0.11	**527.8**	**6.7**	579	81	787	112	**528**	**7**
39	1559	1	0.62539	9.42	0.08543	1.76	0.19	**528.5**	**9.7**	493	58	333	105	**529**	**10**
24	1567	1	0.72862	14.76	0.08550	2.27	0.15	**528.9**	**12.5**	556	104	667	156	**529**	**13**
55	1620	2	0.69443	5.05	0.08553	1.31	0.26	**529.1**	**7.2**	536	35	563	53	**529**	**7**
23	2523	2	0.64524	12.47	0.08564	2.31	0.19	**529.7**	**12.7**	506	79	398	137	**530**	**13**
39	1099	1	0.63571	19.61	0.08584	2.01	0.10	**530.9**	**11.1**	500	119	359	220	**531**	**11**
125	4069	2	0.66294	5.94	0.08608	0.61	0.10	**532.3**	**3.4**	516	39	447	66	**532**	**3**
64	3347	1	0.64399	11.10	0.08617	0.92	0.08	**532.8**	**5.1**	505	70	380	124	**533**	**5**
41	10084	2	0.66999	11.84	0.08630	2.10	0.18	**533.6**	**11.7**	521	78	465	129	**534**	**12**
90	2755	1	0.60239	7.27	0.08635	2.25	0.31	**533.9**	**12.5**	479	44	222	80	**534**	**13**

			Isotopic ratios					Apparent ages (Ma)							
U (ppm)	$^{206}Pb/^{204}Pb$	U/Th	$^{207}Pb^*/^{235}U$	± (%)	$^{206}Pb^*/^{238}U$	± (%)	error corr.	$^{206}Pb^*/^{238}U$	±(Ma)	$^{207}Pb^*/^{235}U$	± (Ma)	$^{206}Pb^*/^{207}Pb^*$	±(Ma)	Preferred age	± (Ma)
ISOS1															
41	2383	1	0.77595	19.35	0.08637	1.96	0.10	534.0	10.9	583	142	779	202	534	11
89	2762	2	0.76939	5.95	0.08650	1.60	0.27	534.8	8.9	579	46	759	60	535	9
76	7343	4	0.71466	12.03	0.08652	1.06	0.09	534.9	5.9	548	84	600	130	535	6
47	2459	1	0.60681	18.21	0.08660	1.90	0.10	535.4	10.6	482	106	233	209	535	11
52	1731	2	0.73758	13.84	0.08668	0.80	0.06	535.9	4.5	561	99	664	148	536	5
84	2898	2	0.78254	7.03	0.08679	0.64	0.09	536.5	3.6	587	54	787	73	537	4
38	1616	2	0.70190	22.30	0.08697	1.54	0.07	537.6	8.7	540	148	550	243	538	9
59	1733	1	0.75442	12.09	0.08739	1.60	0.13	540.1	9.0	571	89	695	128	540	9
236	5862	2	0.74487	1.70	0.08751	0.62	0.36	540.8	3.5	565	13	665	17	541	4
58	3349	1	0.71768	4.79	0.08753	1.33	0.28	540.9	7.5	549	34	584	50	541	8
48	2124	1	0.94638	11.73	0.08761	1.72	0.15	541.4	9.7	676	107	1156	115	541	10
72	2559	1	0.69356	8.03	0.08770	1.34	0.17	541.9	7.6	535	55	505	87	542	8
49	1626	2	0.63611	6.74	0.08795	0.86	0.13	543.4	4.9	500	43	305	76	543	5
42	1146668	2	0.69193	3.30	0.08805	1.42	0.43	544.0	8.1	534	23	491	33	544	8
83	1343	15	0.92565	5.06	0.08807	0.63	0.12	544.1	3.5	665	47	1101	50	544	4
62	1867	1	0.58698	6.76	0.08831	0.87	0.13	545.5	4.9	469	40	110	79	546	5
20	4725	2	0.69665	51.47	0.08836	1.76	0.03	545.8	10.0	537	311	499	567	546	10
63	5565	2	0.80315	6.35	0.08843	1.95	0.31	546.3	11.1	599	51	802	63	546	11
40	1937	2	0.65881	17.92	0.08861	1.15	0.06	547.3	6.5	514	113	368	202	547	7
44	2349	2	0.69867	10.24	0.08871	1.34	0.13	547.9	7.7	538	70	496	112	548	8
22	1671	2	0.54011	39.29	0.08871	1.16	0.03	547.9	6.6	439	195	-102	483	548	7
92	4042	1	0.78684	7.42	0.08872	1.10	0.15	547.9	6.3	589	58	752	77	548	6
71	25675	2	0.83145	6.52	0.08882	0.89	0.14	548.5	5.1	614	54	865	67	549	5
37	1444	1	0.79109	8.62	0.08907	0.91	0.10	550.0	5.2	592	67	755	91	550	5
39	1732	1	0.68266	6.76	0.08912	1.54	0.23	550.3	8.8	528	46	435	73	550	9
30	9512	1	0.79681	8.55	0.08955	2.24	0.26	552.9	12.9	595	67	759	87	553	13
67	2509	1	0.67048	5.58	0.08964	1.00	0.18	553.4	5.8	521	37	381	62	553	6
43	112770	1	0.68990	16.60	0.09003	1.54	0.09	555.7	8.9	533	110	435	184	556	9
49	2539	1	0.63277	11.99	0.09021	1.08	0.09	556.8	6.3	498	74	235	138	557	6
79	56379	1	0.68755	5.32	0.09024	0.94	0.18	557.0	5.5	531	37	423	58	557	6
115	5995	1	0.74561	5.68	0.09029	1.26	0.22	557.3	7.3	566	42	600	60	557	7
29	16069	1	0.89577	16.71	0.09055	2.09	0.13	558.8	12.2	650	142	979	169	559	12
18	1940	2	0.71179	12.51	0.09059	1.64	0.13	559.0	9.6	546	87	491	137	559	10
50	24715	2	0.61822	7.34	0.09058	0.91	0.12	559.0	5.3	489	45	172	85	559	5
85	1690	0	0.71084	6.04	0.09062	0.56	0.09	559.2	3.3	545	43	487	66	559	3
15	6379	2	0.72522	21.92	0.09062	2.13	0.10	559.2	12.4	554	150	531	239	559	12
32	2012	1	0.79189	12.85	0.09104	1.76	0.14	561.7	10.3	592	98	711	135	562	10
22	1770	2	0.79277	15.19	0.09132	2.94	0.19	563.3	17.3	593	116	707	159	563	17
154	6897	2	0.71155	3.78	0.09134	0.99	0.26	563.4	5.8	546	27	472	40	563	6
60	2663	1	0.65268	6.89	0.09146	0.79	0.12	564.2	4.7	510	45	275	78	564	5
47	30143	2	0.97755	8.33	0.09209	1.33	0.16	567.9	7.9	692	80	1121	82	568	8
34	1929	1	0.99858	11.61	0.09221	2.04	0.18	568.6	12.1	703	111	1161	113	569	12
28	6556	2	0.86089	16.74	0.09236	3.49	0.21	569.5	20.7	631	137	856	170	570	21
39	3890	1	0.65269	6.54	0.09281	0.84	0.13	572.1	5.0	510	43	241	75	572	5
31	7445	1	0.78573	16.78	0.09283	1.38	0.08	572.2	8.3	589	126	653	179	572	8
22	15716	1	0.87502	13.61	0.09298	1.80	0.13	573.1	10.8	638	114	876	140	573	11
30	1533	2	0.61606	128.33	0.09303	1.52	0.01	573.4	9.1	487	592	101	1517	573	9
39	1716	1	0.89058	7.86	0.09309	1.16	0.15	573.8	6.9	647	69	910	80	574	7
35	1381	2	0.59492	21.93	0.09320	0.97	0.04	574.4	5.8	474	125	13	263	574	6
41	1283	1	1.07287	12.46	0.09325	3.31	0.27	574.7	19.8	740	127	1280	117	575	20
21	3661	2	0.77059	13.20	0.09325	2.05	0.16	574.8	12.3	580	98	601	141	575	12
27	1925	1	0.71580	22.15	0.09331	0.85	0.04	575.1	5.1	548	149	438	246	575	5
32	29059	2	1.01778	57.03	0.09348	1.13	0.02	576.1	6.8	713	465	1171	564	576	7
38	4647	2	0.64366	21.32	0.09362	1.56	0.07	576.9	9.4	505	131	189	247	577	9
40	2313	3	0.60844	11.60	0.09369	1.80	0.15	577.3	10.8	483	69	54	137	577	11

U (ppm)	$^{206}Pb/^{204}Pb$	U/Th	Isotopic ratios $^{207}Pb^*/^{235}U$	± (%)	$^{206}Pb^*/^{238}U$	± (%)	error corr.	Apparent ages (Ma) $^{206}Pb^*/^{238}U$	±(Ma)	$^{207}Pb^*/^{235}U$	± (Ma)	$^{206}Pb^*/^{207}Pb^*$	±(Ma)	**Preferred age**	**± (Ma)**
ISOS1															
93	4248	1	0.67358	3.96	0.09372	0.72	0.18	**577.5**	**4.4**	523	27	291	44	**578**	**4**
16	2781	2	0.81152	12.21	0.09399	2.09	0.17	**579.1**	**12.7**	603	96	695	128	**579**	**13**
52	22507	2	0.95836	5.99	0.09412	0.67	0.11	**579.9**	**4.1**	682	57	1037	60	**580**	**4**
21	1023	2	0.60478	20.55	0.09419	1.44	0.07	**580.3**	**8.7**	480	119	27	246	**580**	**9**
24	13572	2	0.73545	47.73	0.09547	1.31	0.03	**587.8**	**8.1**	560	306	447	530	**588**	**8**
20	3519	2	0.87907	53.74	0.09565	1.52	0.03	**588.9**	**9.4**	641	393	827	560	**589**	**9**
20	4540	2	0.63486	20.68	0.09612	2.43	0.12	**591.7**	**15.1**	499	125	94	243	**592**	**15**
34	2340	2	0.86714	21.02	0.09687	0.64	0.03	**596.0**	**4.0**	634	170	772	221	**596**	**4**
18	830	1	1.00479	14.79	0.10015	2.01	0.14	**615.3**	**12.9**	706	141	1007	149	**615**	**13**
65	5851	3	2.61740	3.10	0.22309	2.06	0.66	1298.2	29.6	1306	79	**1318**	**22**	**1318**	**22**
478	*4830*	*0*	*1.37581*	*1.26*	*0.11429*	*1.12*	*0.89*	*697.6*	*8.2*	*879*	*18*	*1367*	*6*		
106	7778	12	3.06577	1.67	0.24466	0.65	0.39	1410.9	10.2	1424	51	**1444**	**15**	**1444**	**15**
42	23922	3	3.09686	2.84	0.24536	0.99	0.35	1414.5	15.6	1432	86	**1458**	**25**	**1458**	**25**
27	15823	3	3.29557	3.02	0.25784	0.74	0.24	1478.8	12.3	1480	96	**1482**	**28**	**1482**	**28**
150	8914	1	2.86633	0.92	0.22353	0.42	0.46	1300.5	6.1	1373	27	**1488**	**8**	**1488**	**8**
44	4001	2	3.45548	2.38	0.26333	0.77	0.32	1506.8	13.1	1517	80	**1532**	**21**	**1532**	**21**
32	4594	1	3.57215	3.11	0.26995	0.81	0.26	1540.5	14.0	1543	107	**1547**	**28**	**1547**	**28**
18	16129	1	3.71848	4.64	0.26049	1.47	0.32	1492.4	24.6	1575	162	**1688**	**41**	**1688**	**41**

$^{206}Pb/^{204}Pb$ is measured ratio.
All uncertainties are at the 1-sigma level, and include only mearurement errors.
Preferred age (shown in bold) based on $^{206}Pb/^{238}U$ if $^{206}Pb/^{238}U$ age is <1.2 Ga.
Preferred age (shown in bold) based on $^{206}Pb/^{207}Pb$ if $^{206}Pb/^{238}U$ age is >1.2 Ga.
Preferred age is not considered further if uncertainty is>10%.
$^{206}Pb/^{207}Pb$ age is not considered further if analysis is >30% discordant or >10% reversse discordant.
Analyses that are not considered further are shown in italics. U concentration andU/Th have uncertainties of ~25%.
Decay constants: $^{235}U=9.8485x10^{-10.}$ $^{238}U=1.55125x10^{-10}$, $^{238}U/^{235}U=137.88$.
Isotope ratios are corrected for Pb/U fractionation by comparison with standard zircon with an age of 564 ±4 Ma.
Initial Pb composition from Stacey and Kramers (1975), with uncertainties of 1.0 for $^{206}Pb/^{204}Pb$ and 0.3 for $^{207}Pb/^{204}Pb$.