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# The Putumayo Orogen of Amazonia and its implications for Rodinia reconstructions: New U–Pb geochronological insights into the Proterozoic tectonic evolution of northwestern South America

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ABSTRACT

Outcrops of late Meso- to early Neoproterozoic crust in northwestern South America are restricted to isolated exposures of basement inliers within the northern Andes of Colombia, Peru and Venezuela. However, evidence for the existence of an autochthonous Stenian–Tonian belt in northern Amazonia that is undisturbed by Andean orogenesis has not been recognized so far. Here we report ∼1200 new single-zircon U–Pb geochronological analyses from 19 Proterozoic rock samples of northwestern South America collected from the Garzón and Las Minas Andean cordilleran inliers, drill-core samples from the foreland basin basement, and outcrops of cratonic Amazonia in eastern Colombia (western Guyana shield). Our new geochronological results document the existence of a previously unrecognized Meso- to Neoproterozoic orogenic belt buried under the north Andean foreland basins, herein termed the Putumayo Orogen, which has implications for Proterozoic tectonic reconstructions of Amazonia during the assembly of the supercontinent Rodinia. Based on the interpretations of new and pre-existing data, we propose a three-stage tectonometamorphic evolution for this orogenic segment characterized by: (1) development of a pericratonic fringing-arc system outboard of Amazonia's leading margin during Mesoproterozoic time from ∼1.3 to 1.1 Ga, where the protoliths for metaigneous and metavolcanosedimentary units of the Colombian and Mexican inliers would have originated in a commonly evolving Colombian–Oaxaquian fringing-arc system; (2) amphibolite-grade metamorphism and migmatization between ca. 1.05 and 1.01 Ga by inferred amalgamation of these parautochtonous arc terranes onto the continental margin, and (3) granulite-grade metamorphism at ∼0.99 Ga during continent–continent collision related to Rodinia final assembly. Along with additional paleogeographic constraints, this new geochronological framework suggests that the final metamorphic phase of the Putumayo Orogen was likely the result of collisional interactions with the Sveconorwegian province of Baltica, in contrast to previously proposed models that place this margin of Amazonia as the conjugate of the Grenville province of Laurentia.


## 1. Introduction

Many reconstructions for the early Neoproterozoic supercontinent Rodinia predict interactions between a Laurentia–Baltica–Amazonia triple joint along internal collisional orogens (e.g. Hoffman, 1991 or Li et al., 2008 for a recent review). These different orogenic segments developed diachronously during late Mesoproterozoic to early Neoproterozoic times, and their timing defines the chronology for the collisional interactions that took place between different crustal blocks and microcontinents as Rodinia was assembled. In South America the Amazon Craton is the largest of the Precambrian blocks that constitute the continental platform (Tassinari and Macambira, 1999), and its role in the supercontinent cycle has for long been recognized (Cordani et al., 2009). Records of the participation of Amazonia in the supercontinent Rodinia are expressed as: (a) metamorphosed passive-margin and rift sequences of the Sunsás-Aguapei and Nova Brasilandia belts in western Brazil – eastern Bolivia (review by Teixeira et al., 2010), (b) scattered intracratonic magmatic events and shear-zones developed obliquely with respect to the colliding margin (review by Cordani et al., 2010), and (c) paleomagnetic evidences obtained from late Mesoproterozoic volcanic and sedimentary rocks of the Rondonia region in Brazil indicating proximity and interaction of this margin of Amazonia with respect to (modern) SE Laurentia

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(Tohver et al., 2002; D'Agrella-Filho et al., 2008). Although the involvement of Amazonia in Rodinia is in general a well-accepted hypothesis (e.g. Li et al., 2008), many details and questions regarding intercratonic orogen correlations and the evolution of Meso-Neoproterozoic collisional belts of the Amazon Craton are far from being resolved. An example of this issue is the observation that the Sunsás margin of Amazonia has been correlated by different authors with virtually every segment of the Grenville margin of Laurentia (see Tohver et al., 2004a, and references therein), in part due to the fact that the lack of geological and robust geochronological information from northwestern South America has left its role in many of these reconstructions mostly unconstrained.

As a result of dense vegetation cover, heavy tropical weathering, and the development of Phanerozoic sedimentary basins, there are still sizable areas in northern South America where its Precambrian basement remains poorly studied or even completely unknown. This is the case of the north Andean foreland basins, where a large portion of northern Venezuela, eastern Colombia, eastern Ecuador and eastern Peru (Fig. 1) comprise an area in excess of 800,000 km$^2$ of covered basement. However, with the exception of K–Ar and Rb–Sr ages from wells presented by Kovach et al. (1976) and Feo-Codecido et al. (1984) nothing else is known about the geochronology of this vast region.

Paleogeographic models that juxtapose the Sunsás margin of Amazonia against southeastern Laurentia implicitly predict that the Meso-Neoproterozoic orogen of the Amazon Craton should extend north of the Sunsás-Aguapei orogen, partly as a conjugate margin to the Laurentian Grenville province under the Amazon River basin, and possibly by interaction with a third continental mass even further north (e.g. Hoffman, 1991; Tohver et al., 2002, 2006; Fuck et al., 2008; Li et al., 2008; Cardona et al., 2010). This interpretation has benefited from the occurrence of high-grade metamorphic inliers included within the north Andean orogen in Colombia such as the Garzón and Santa Marta massifs, among others (Restrepo-Pace et al., 1997; Cordani et al., 2005; Ordonez-Carmona et al., 2006; Cardona et al., 2010). However, given the complex deformational history of the northern Andes (Aleman and Ramos, 2000), in particular its strong Meso-Cenozoic margin-parallel strike-slip transport component (Bayona et al., 2006, 2010) and possible involvement in later terrane collision event after the amalgamation of Pangea (Vinasco et al., 2006), the relationship between the cordilleran inliers and the non-exposed basement of the adjacent foreland basins remains uncertain.

The main objective of this paper is to present new zircon U–Pb geochronological results from Proterozoic basement rocks of northwestern South America, in an attempt to clarify many of these long-standing questions and provide a geochronological framework that can shed light on paleogeographic correlations involving the northwestern margin of the Amazon Craton. Samples reported in this contribution lie along a broadly NW–SE transect that covers most of the width of southern Colombia, ranging from exposures of cratonic Amazonia (W Guyana shield), to samples from Precambrian cordilleran inliers included within the Andean orogen (Fig. 2). In addition to refining the geochronology for various magmatic and metamorphic episodes in the north Andean cordilleran blocks and the western Guyana shield area, we present the first zircon U–Pb ages obtained from basement drill-core samples of the north Andean foreland basins as well as detrital zircon (DZ) analyses from high-grade metasedimentary units in the area. Our results comprise the first geochronological evidence for the existence of a previously unrecognized segment of an Ectasian to Tonian orogenic belt underlying the modern foreland cover, herein termed the Putumayo Orogen, which has a distinct geological evolution with respect to its Amazonian analog the Sunsás-Aguapei orogen. As will be discussed below, recognition of this new belt provides a better cratonic reference for linking the Andean cordilleran inliers with autochthonous Amazonia basement, improves our knowledge about the evolution of the Proterozoic orogens of South America and provides an additional piercing point in Amazonia for establishing intercratonic correlations with other late Meso- to early Neoproterozoic orogens worldwide.

## 2. Geological setting – known provinces of the Amazon Craton

The Amazon Craton has been broadly subdivided in six different Precambrian provinces (Fig. 1) and its evolution spans over 2 Ga of Earth's history. A detailed discussion about the general crustal configuration of the Amazon Craton is beyond the scope of this paper and only a brief summary of most relevant events are presented below. The interested reader is referred to the works of Teixeira et al. (1989), Tassinari and Macambira (1999), Santos et al. (2000), Cordani and Teixeira (2007), and Santos et al. (2008) for a more in depth discussion on this subject. In general, it is thought that after the amalgamation of Archean microcontinents along the Maroni-Itacaiunas (MI) province during the Transamazonian orogeny, the Ventuari-Tapajos (VT) and Rio Negro-Juruena (RNJ) belts evolved through the continuous accretion of intraoceanic arcs to this proto-Amazonia nucleus. The two marginal provinces located towards the southwestern portion of the craton, the Rondonia-San Ignacio (RSI) and the Sunsás-Aguapei (SA), are the result of accretionary and collisional tectonics that took place throughout the Mesoproterozoic (Sadowski and Bettencourt, 1996; Cordani and Teixeira, 2007).

The RSI orogeny, which took place during the time interval from ca. 1.56 to 1.30 Ga, is characterized by the accretion of early Mesoproterozoic arc terranes overprinted by high-grade metamorphism during the mid Mesoproterozoic by inferred collision of a microcontinent – the Paragua block – against the RNJ continental margin (Bettencourt et al., 2010). Collision of the Paragua block against Amazonia resulted in high-grade metamorphism of the Chiquitania gneisses and the Lomas Manechis granulites at about 1.33 Ga (Bettencourt et al., 2010; Santos et al., 2008), also coinciding with cessation of arc magmatism in the Pensamiento granitic complex (Matos et al., 2009).

Following the 1.33 Ga accretion event, a passive margin developed in the area and a long-lasting period of tectonic quiescence with localized intraplate extension followed, resulting in the deposition of the Sunsás/Vibosi groups (Litherland and Bloomfield, 1981; Litherland et al., 1989) and the Nova Brasilândia aulacogen sedimentary sequences (Tohver et al., 2004b), respectively. These basins were later inverted and metamorphosed during the Sunsás orogeny ca. 1.1 Ga (Teixeira et al., 2010), synchronous with deformation occurring along the Llano segment of the Grenville margin of Laurentia (Mosher et al., 2004). Collisional interactions affecting this portion of SW Amazonia during the late Mesoproterozoic have been used as evidence for the participation of the Amazon Craton during the amalgamation of Rodinia.

## 3. The Proterozoic of NW South America (Colombia–Venezuela–Peru–Ecuador)

### *3.1. Cratonic Amazonia*

The northwestern-most outcrops of the Amazon Craton in South America are found in the Orinoco and Amazonas regions of eastern Colombia, western Venezuela and northwestern Brazil (Figs. 1 and 2). Most of the geological mapping in Colombia, along with the only geochronological study available from this area, was conducted during the PRORADAM project (Galvis et al., 1979; Proradam, 1979; Priem et al., 1982). The craton in this region

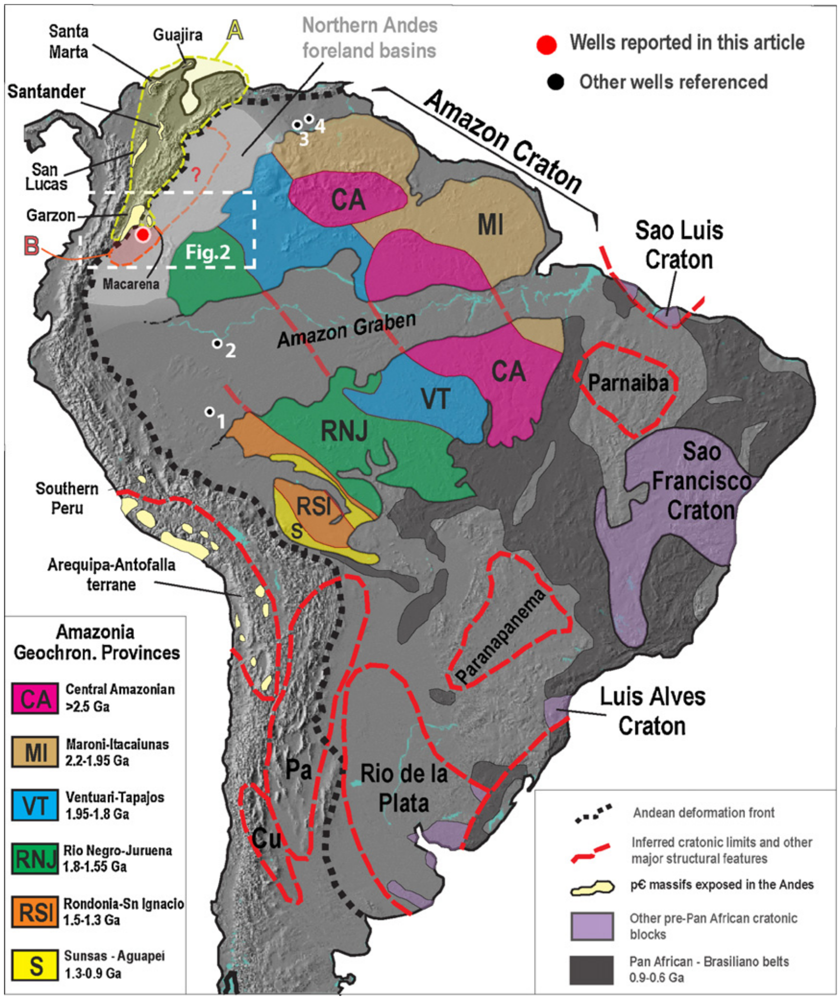


**Fig. 1.** Tectonic map of South America illustrating its major Precambrian constituent elements with emphasis on the provinces of the Amazon Carton. Modified from Cordani et al. (2000) and Fuck et al. (2008). The location of the north Andean foreland basins is highlighted along with the location of drilling-wells from which core samples and geochronological data have been obtained. (A) Area enclosing the known extent of late Meso- to early Neoproterozoic basement in the Northern Andes (fringing terranes). (B) Autochthonous Putumayo Orogen underlying the Andean foreland. A possible northward extension into the Llanos basin remains hypothetical. Red dot: location of the core samples presented in this study. Black dots: core samples presented by other authors; 1, Kovach et al. (1976); 2, de Souza Gorayeb et al. (2005); 3 and 4, Feo-Codecido et al. (1984). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

consists of gneissic–migmatitic terranes of granitic composition that yield Rb–Sr reference isochron ages of ca. 1.55 Ga (Priem et al., 1982), and are intruded by undeformed granitoids with zircon U–Pb crystallization ages between ∼1.55 and 1.48 Ga (multigrain TIMS by Priem et al., 1982). Some of these intrusives, like the Parguaza batholith of western Venezuela, display rapakivi textures and have commonly been interpreted as anorogenic in nature (Gaudette et al., 1978).

Despite the lack of direct geochronological evidence, it has been assumed that the Paleo- to early Mesoproterozoic provinces of the Amazon Craton extend beneath the north Andean foreland basins until they meet the Andes (Figs. 1 and 2), where they are thought to be truncated by "suspect terranes of Grenvillean-affinity" accreted to the continental margin during proposed collisional interactions with Laurentia (Forero-Suarez, 1990; Gómez et al., 2007; Kroonenberg, 1982, Restrepo-Pace et al., 1997). Rocks of apparent Paleoproterozoic age underlying these basins have only been traced west as far as the location of the BT-1 well of PETROBRAS reported by de Souza Gorayeb et al. (2005); these authors obtained $^{206}Pb/^{207}Pb$ zircon-evaporation apparent ages around 1720 Ma for a basement dacite in proximity to the Colombia–Peru–Brazil triple border (approximate location shown in Fig. 1).

### 3.2. North Andean inliers

Along the Andean orogen, isolated inliers of Proterozoic gneisses and granulites are known to be present in Colombia and have been the focus of intensive research (MacDonald and Hurley, 1969; Tschanz et al., 1974; Kroonenberg, 1982; Priem et al., 1989; Ramos, 2010; Restrepo-Pace et al., 1997; Ruiz et al., 1999; Ordonez-Carmona et al., 1999, 2002; Cordani et al., 2005; Cardona-Molina et al., 2006; Cardona et al., 2010). However, as is evident in a recent compilation of the available isotopic studies by Ordonez-Carmona et al. (2006), precise geochronological data is still lacking for many of the exposed units.

Recent paleomagnetic data acquired in the Colombian and Venezuelan Andes have shown the strong fragmentary character of the pre-Mesozoic basement that underlies the Eastern and Central Cordilleras of Colombia, the Santa Marta massif, and the Merida Andes and Perija Range of Venezuela (Bayona et al., 2006, 2010). It was shown by these authors that different fault-bounded blocks in the Cordillera, some of them associated with Proterozoic basement inliers, have experienced significant trench-parallel latitudinal transport of different magnitudes at least since Jurassic times. These data most likely preclude the idea of the "Garzón-Santa Marta granulite belt" as a coherent Precambrian terrane constituting the

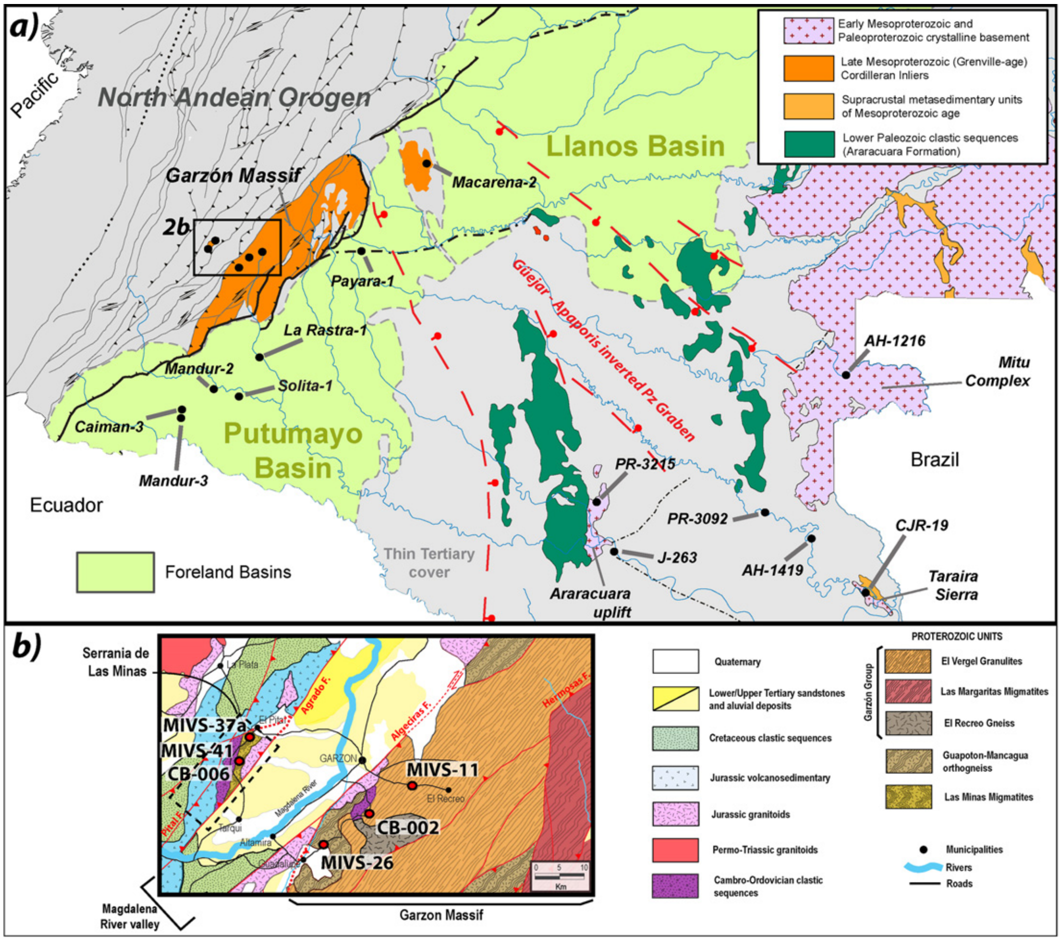


**Fig. 2.** Simplified geological map of our study area in south-central Colombia, showing the location of samples described in this study. (a) Major pre-Mesozoic features of Colombian geology and location of the Putumayo and Llanos north Andean foreland basins. Modified after Gómez et al. (2007), (b) detailed map of the west Garzón and Serrania de las Minas area in the Upper Magdalena Valley.
Modified from Gómez et al. (2007) and Jimenez Mejia et al. (2006).

basement of the Eastern Andes of Colombia (Kroonenberg, 1982; Restrepo-Pace et al., 1997). Some of these blocks, as is the case of the Santa Marta Massif, show displacements in excess of 1000 km in magnitude with respect to a dynamic South America reference framework (see Fig. 7 in Bayona et al., 2010) while others, like the Garzón massif, are considered to be relatively stable with respect to non-remobilized South America since at least the Paleozoic (Cardona et al., 2010; Toussaint, 1993). The cordilleran inliers sampled during the present study, the Garzón, La Macarena and Las Minas massifs, represent the southernmost inliers found in the Colombian Andes, located at approximately the same latitude as the wells we sampled from the Putumayo basin.

### 3.2.1. *Garzón Massif*

This basement inlier located in the southern portion of the Eastern Cordillera of Colombia (Figs. 1 and 2) constitutes the largest exposure of Precambrian crust in the northern Andes. Based on regional mapping and mesoscopic characteristics of the different metamorphic rocks, it has been informally subdivided in four lithostratigraphic units shown in Fig. 2b and summarized by Jimenez Mejia et al. (2006): (1) Las Margaritas migmatites, located along the eastern side of the massif dominated by metasedimentary gneisses and migmatites with mineral assemblages indicative of amphibolite-grade metamorphic conditions; (2) El Vergel granulites, a unit dominantly composed by felsic granulites and garnetiferous paragneisses with subordinate mafic granulites. This unit covers most of the massif's western flank and is in contact with the Las Margaritas migmatites along the east-verging Las Hermosas reverse fault (Fig. 2b); (3) El Recreo gneiss, an orthogneissic unit of interpreted anatectic origin, and (4) the Guapotón-Mancagua orthogneiss, a biotite-amphibole gneiss of granitic composition that is exposed along the western margin of the massif and displays a foliation that is concordant with that of the El Vergel granulites. The first three units are also known as the "Garzón Group" (Kroonenberg, 1982; Restrepo-Pace et al., 1997). Geochronological data for this massif comes from the works of Alvarez and Cordani (1980) and Priem et al. (1989), followed by Restrepo-Pace et al. (1997) and Cordani et al. (2005).

### 3.2.2. *Serrania de la Macarena uplift*

The geology of the Macarena range (Fig. 2) was originally studied by Augusto Gansser (in Trumpy, 1943), who described its basement as an association of mica-schists and alkali-feldspar gneisses, hornblende gneisses, amphibolites and deformed syenogranitic gneisses (Trumpy, 1943, p. 1282). Their Precambrian age was established based on stratigraphic relations with the Güejar group, a clastic sedimentary unit composed of micaceous and quartz-rich sandstones that rests unconformably on metamorphic basement and contains trilobites determined as Cambro-Ordovician in age (Harrington and Kay, 1951) but no radiometric dates were available for the crystalline rocks. Toussaint (1993) suggested that the basement of this sierra could potentially be correlated with the Garzón massif as part of a larger crustal block accreted to Amazonia during Precambrian times.

*3.2.3. Las Minas Massif*

The Serrania de Las Minas is a NE-trending elongated range of about 17 km in length and 6 km in width, located west of the Garzón Massif (Fig. 2b). Structurally, this range sits along the axis of a pop-up structure bounded on both sides by reverse faults that thrust the Las Minas migmatites and gneisses onto Tertiary alluvial deposits to the east, and Jurassic volcanosedimentary sequences the west (Fig. 2b). The stratigraphic succession in this range comprises a high-grade metamorphic basement overlain by a clastic sedimentary sequence of graptolite-bearing Ordovician shales and sandstones of the El Higado Formation (Mojica et al., 1987). The only geochronological result available for the metamorphic rocks is an hornblende Ar–Ar age obtained from an amphibolite (Restrepo-Pace et al., 1997, sample HP-3) which defines a plateau cooling age of 911 ± 2 Ma, similar to other K–Ar and Ar–Ar cooling ages reported for the Garzón massif (Priem et al., 1989; Restrepo-Pace et al., 1997; Cordani et al., 2005).

During this study we identified the metamorphic sequence as a series of stromatic metasedimentary migmatites overlying an orthogneissic unit consisting of porphyroclastic augen-gneisses of granitic composition. Most of the observed migmatites are stromatic metatexites with apparent low degrees of partial melting, and the sedimentary origin of their protolith is evidenced by relict sedimentary structures such as cross-bedding observed in psammitic layers that did not undergo anatexis. The foliated texture and disposition of the granitic leucosomes, parallel to subparallel with respect to the dominant metamorphic foliation in the host gneisses suggests that shearing and deformation were simultaneous with the melting event (e.g. Kemp and Gray, 1999).

## 4. Analytical methods: U/Pb zircon geochronology by LA-MC-ICP-MS

Zircon separates were obtained by standard methods combining jaw crushing, roller-mill pulverizing, water-table concentration, magnetic separation using a Frantz® LB-1 barrier separator, and final heavy-liquid separation using 3.32 g/cm$^3$ methylene iodide. Approximately 100–150 individual grains were handpicked, mounted in epoxy, polished and imaged by SEM cathodoluminescence (CL) both prior and after the analysis. Zircon textures description follow the nomenclatures presented by Corfu et al. (2003) and Hoskin and Black (2000). Interested readers are encouraged to download the high-resolution, color-cathodoluminescence images that are included in the supplementary material, where the different recrystallization textures and ablation-pit mixing complexities discussed throughout the text are exemplified.

All U–Th/Pb isotopic measurements were performed by LA-MC-ICP-MS at the Laserchron center facilities in the University of Arizona following the procedure outlined by Gehrels et al. (2008) using a GV-Instruments Isoprobe MC-ICP-MS, or a slightly modified procedure adopted for a Nu-instruments HR-MC-ICP-MS. Both spectrometers are coupled to Excimer laser systems operating at a wavelength of 193 nm, and both have multicollector blocks capable of simultaneously measuring $^{238}$U, $^{232}$Th, $^{208}$Pb, $^{207}$Pb, and $^{206}$Pb isotopes in faraday cups while $^{204}$Pb is always measured in a channeltron® detector or an ion-multiplier. This configuration was applied for analyses performed using ablation spot-sizes between 40 μm and 22 μm in diameter whereas, in very small and complexly zoned zircons, we utilized 10 μm or 18 μm laser spot-sizes. For the small spot-size analyses masses 208, 207, 206 and 204 were all measured on ion-multipliers in order to allow reliable measurement of the Pb isotopes with low ablation volumes, following procedures similar to those presented by Johnston et al. (2009). Uranium and thorium concentrations are estimated using an empirical intensity/concentration factor derived from the average $^{238}$U and $^{232}$Th intensities measured on our Sri Lanka zircon standard (average U of 518 ppm and Th of 68 ppm); the accuracy of our concentration determinations and derived U/Th ratios is better than 20% (Gehrels et al., 2008). Common lead corrections were performed using measured $^{204}$Pb assuming a Stacey and Kramers (1975) model. The 202 mass was monitored in order to subtract Hg isobaric interferences in the $^{204}$Pb peak using the natural ratio of $^{202}$Hg/$^{204}$Hg = 4.34.

Final ages reported in the concordia plots, discussed throughout this paper, and summarized in Table 1, are concordia ages calculated using the Isoplot Excel® macro of Ludwig (2003) unless otherwise noted. Detailed concordia plots of the ca. 1.0 Ga metamorphic overgrowths are made available in supplementary material. Whenever a coherent cluster of concordant analyses is available for a group of zircons (or overgrowths) in a sample, the concordia age arguably represents the best age estimate (Ludwig, 1998); ages given in the text and figures are quoted at a 2$\sigma$ confidence level, and MSWD values reported represent those of combined equivalence + concordance (Ludwig, 1998). All analytical results are included in supplementary material and errors are reported at ±1$\sigma$.

For metasedimentary samples, analyses of inherited cores were carefully performed using the CL images in order to avoid areas of obvious metamorphic recrystallization. However, as will be evident from the concordia plots below, some of the core analyses show departures from concordia either along a chord that goes towards the age of the metamorphic overprint, affected by normal (young) Pb-loss, or a mixture of both. Therefore, caution must be taken when interpreting one-dimensional probability density plots that consider only one isotopic ratio for the calculation of the "preferred age", as Pb-loss events at non-zero ages can generate artificial distribution peaks and lead to misinterpreting detrital zircon signatures (as illustrated by Nemchin and Cawood, 2005). For the probability density plot of each sample presented here (see Fig. 7), we took an approach similar to Collins et al. (2007) and plotted both the entire dataset of each sample (shaded in red), and the data filtered at <5% discordance (black solid line). Although some of the smaller young peaks that are present in the plots of the entire dataset disappear when the data is filtered (possibly generated by mixing, recrystallization or Pb-loss), the position of the dominant peaks and their age maxima do not show any significant variation, which gives us further confidence in the robustness of the obtained detrital zircon data.

## 5. Samples description and geochronological results

For the present study we analyzed samples of (a) gneisses, granulites and migmatites collected from three cordilleran inliers of the Northern Andes (the Garzón, Las Minas and Macarena massifs); (b) drilling-core samples of deep exploratory wells that pierced the crystalline basement of the Putumayo foreland basin of Colombia, east of the frontal thrust systems of the northern Andes, and (c) undeformed or slightly deformed intrusive rocks from the northwesternmost cratonic exposures in the Amazonas region of Colombia. Sample locations and other geographic names referenced in the text are shown in Figs. 1 and 2. Mineral abbreviations are after Whitney and Evans (2010).

*5.1. Cordilleran inliers*

Seven samples collected in three of the basement inliers were analyzed (Fig. 2), three of them from the Garzón massif (MIVS-11,

**Table 1**
Summary of the new U–Pb geochronological data presented in this article.

| Sample | Unit/location | Coordinates | Rock type | Event | Age[a] ± 2σ (Ma) |
|---|---|---|---|---|---|
| Cordilleran Inliers – Northern Andes | | | | | |
| *MIVS-11* | Garzón group | N2°09′33.4″ W75°35′37.0″ | Felsic granulite | met | 992 ± 05 |
| | | | | maxdep | 1115 ± 04 |
| *MIVS-26* | Guapotón gneiss (Garzón massif) | N2°03′19.2″ W75°42′47.6″ | Augen-gneiss | met | 990 ± 08 |
| | | | | ign | 1135 ± 06 |
| *CB-002* | Garzón group | N2°07′37.7″ W75°37′41.9″ | Metased gneiss | met | 992 ± 08 |
| | | | | max dep | 1016 ± 05 |
| *MACARENA-2* | Macarena gneisses | N3°01′45.0″ W73°52′13.5″ | Felsic mylonite | ign | 1461 ± 10 |
| *MIVS-41* | Minas augen-gneiss | N2°13′34.0″ W75°50′30.3″ | Augen-gneiss | met | 990 ± 07 |
| | | | | ign | 1325 ± 05 |
| *CB-006* | Zancudo migmatites (Las Minas massif) | N2°13′26.5″ W75°50′22.0″ | Mafic gneiss | met | 972 ± 12 |
| | | | | max dep | 1088 ± 24 |
| *MIVS-37A* | Pital migmatites (Las Minas massif) | N2°15′37.3″ W75°49′49.9″ | Felsic gneiss | max dep | 1005 ± 23 |
| Exploratory wells – Putumayo Basin | | | | | |
| *PAYARA-1* | Putumayo | N2°07′31.3″ W74°33′35.9″ | Migmatite | met | 986 ± 17 |
| | Putumayo | | | ign | 1606 ± 06 |
| *SOLITA-1* | Putumayo | N0°52′28.6″ W75°37′21.3″ | Metased migmatite | met | 1046 ± 23 |
| *MANDUR-2* | Putumayo | N0°55′24.5″ W75°52′34.1″ | Amphibolite | met | 1019 ± 08 |
| | Putumayo | | | ign | 1592 ± 08 |
| | Putumayo | | Syenogranite | ign | 1017 ± 04 |
| *CAIMAN-3* | Putumayo | N0°45′13.6″ W76°09′45.4″ | Metased diatexite | met | 989 ± 11 |
| | Putumayo | | | maxdep | 1444 ± 15 |
| | Putumayo | | Leucogranite | ign | 952 ± 19 |
| Cratonic exposures – Caqueta and Vaupes regions | | | | | |
| *PR-3215* | Araracuara | S0°10′23.8″ W72°17′24.2″ | Syenogranite | ign | 1756 ± 08 |
| *J-263* | Araracuara | S0°40′20.7″ W72°05′13.7″ | Syenogranite | ign | 1732 ± 17 |
| *AH-1216* | Vaupes | N0°59′31.9″ W69°54′24.6″ | Monzogranite | ign | 1574 ± 10 |
| *PR-3092* | Apaporis | S0°19′08.1″ W70°39′02.6″ | Syenogranite | ign | 1578 ± 27 |
| *AH-1419* | Apaporis | S0°34′45.5″ W70°15′26.1″ | Monzogranite | ign | 1530 ± 21 |
| *CJR-19* | Apaporis | S1°01′10.3″ W69°45′11.6″ | Syenogranite | ign | 1593 ± 06 |

[a] *Note*: ages reported in this table are concordia ages unless otherwise noted (except DZ maxdep, see text for details). For every sample/population, 206Pb/207Pb weighted mean ages are always in agreement with the concordia ages, but uncertainties are increased by about a 0.5–1% factor.

MIVS-26 and CB-002), three from Las Minas massif (MIVS-37a and MIVS-41 and CB-006), and one from the Serrania de la Macarena range (Macarena-2).

#### 5.1.1. *Garzón Massif*

Three samples were analyzed from the western flank of the Garzón massif (Fig. 2b): MIVS-11 and CB-002 were collected from the El Vergel granulites unit and they correspond to a melanocratic granulite and a banded leucocratic gneiss, respectively; MIVS-26 is a coarse-grained granitic augen-gneiss collected from the Guapoton orthogneiss unit.

*Sample MIVS-11 (N2°09′33.4″ W75°35′37.0″)* is a Hyp-Kfs-Pl-Qz felsic granulite with Hbl reaction rims around Opx as a result of amphibolite-grade retrograde overprint. Zircons recovered from this sample were mostly rounded to subrounded in shape, colorless to light pink, with 1:1 to 1:3 width:length ratios and generally smaller than 200 μm in size. CL imaging shows that most of them exhibit textures indicative of growth and/or recrystallization under metamorphic conditions (Fig. 3a, supplementary CL files) evidenced by relatively homogeneous grains displaying only weak sector-zonation or rims with no internal structure that appear as overgrowths around more complexly zoned cores. U–Pb isotopic analyses of the metamorphic overgrowths are all concordant (Fig. 3a), and yield an age of 992 ± 5 Ma (MSWD = 0.32, $n$ = 27) interpreted as the timing of peak granulite-grade metamorphism for this unit. Many of the grains contain xenocrystic cores, some of which are characterized by oscillatory zoning typical of magmatic zircons while others exhibit complex chaotic zoning patterns. The wide range of ages obtained for these xenocrysts, ranging from ca. 1011 to 1490 Ma, reflects the detrital nature of these grains inherited from a possible volcanosedimentary protolith. A total of 89 detrital core analyses were performed, 62 of which are <5% discordant. The pattern is characterized by a multi-modal age peak distribution dominated exclusively by Mesoproterozoic grains, with the most prominent maxima at ca. 1120, 1300, 1370 and 1450 Ma. A maximum age of deposition for the protolith can be estimated by the two youngest, >95% concordant grains of the detrital population. Two concordant to nearly concordant grains, with ages of 1115 ± 4 and 1118 ± 20 Ma and whose error ellipses do not overlap with the age of metamorphism (supplementary data), place a limit for the age of sedimentation that is constrained between the age of the youngest detrital grain (1115 ± 4 Ma), and the age of metamorphism (992 ± 5 Ma).

*Sample CB-002 (N2°07′37.7″ W75°37′41.9″)* is a sillimanite-bearing Qz-Fsp gneiss with biotite as the only ferromagnesian phase, also interpreted to be of metasedimentary origin. Zircons from this sample are mostly uncolored, but relatively more prismatic than those of sample MIVS-11 displaying width:length ratios from 1:3 to 1:5. CL imaging shows a wide variety of internal grain morphologies similar to sample MIVS-11, although elongated zircons with igneous zoning are more abundant. This sample shows evidence of extensive solid-state recrystallization of inherited zircon cores by the granulite-grade metamorphic overprint, observed as widespread "ghost" oscillatory zoning patches in recrystallized portions of zircon grains and the presence of recrystallization fronts (e.g. Hoskin and Black, 2000, supplementary CL file). This feature is also evident in the U–Pb systematics, where many analyses obtained from these recrystallized areas are discordant and older than the age of metamorphism (Fig. 3b). The analysis of nine metamorphic overgrowths and individual crystals that display homogenous, bright and unzoned textures under CL, are all concordant and consistent with an age of 992 ± 8 Ma (MSWD = 0.3, $n$ = 9) for the metamorphism, indistinguishable from the metamorphic age obtained for sample MIVS-11 described above. A more cautious approach was taken for the analysis of the detrital component of this sample given the strong metamorphic

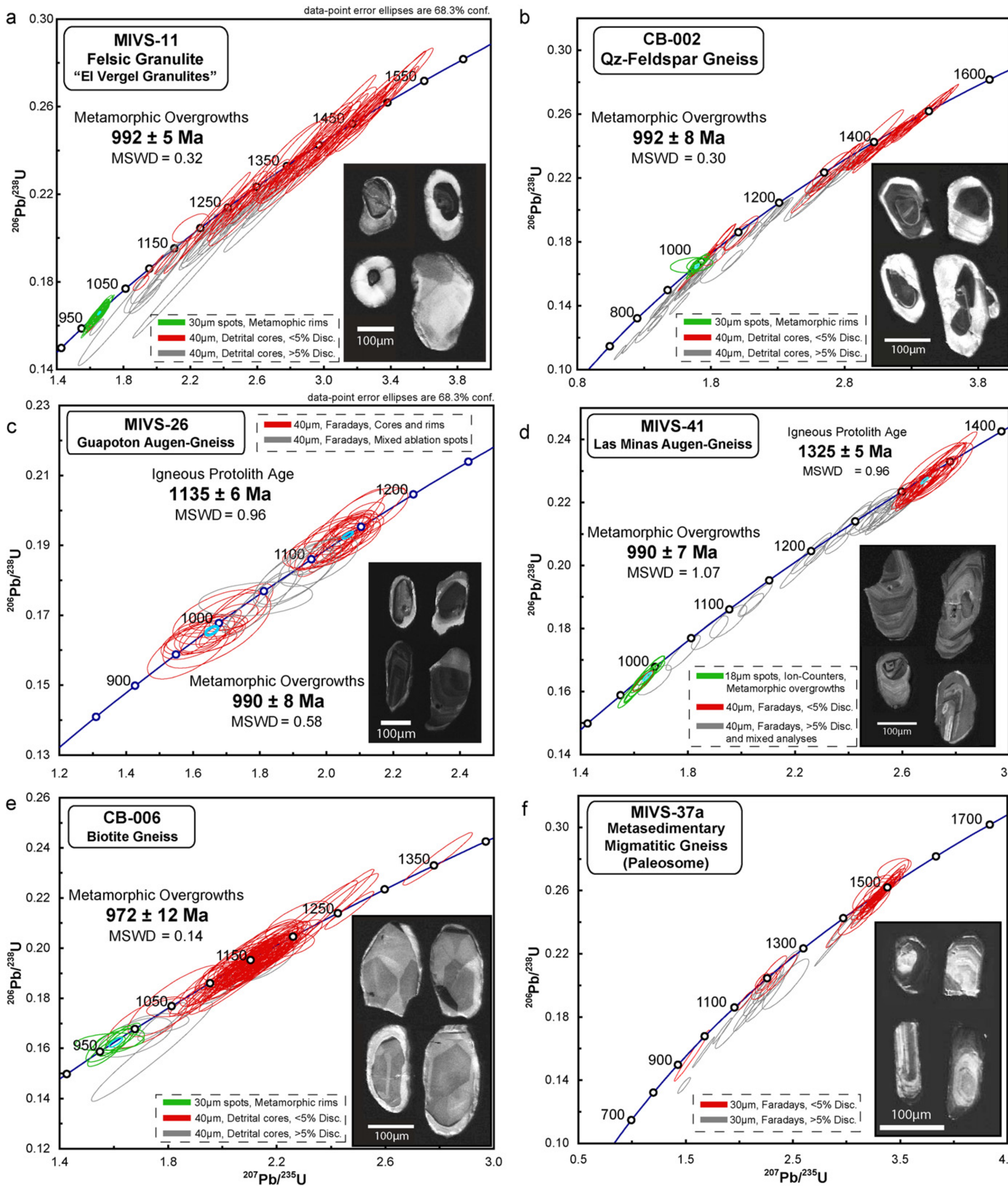


**Fig. 3.** U–Pb concordia diagrams for samples analyzed from the Garzón and Las Minas cordilleran inliers.

overprint observed in the zircon xenocrysts; analytical spots where carefully selected away from areas where recrystallization is evident and placed in cores where original zoning is better preserved. Additionally, results plotted in the probability plot shown in Fig. 8 were filtered to discard xenocryst grains whose calculated $^{206}Pb/^{207}Pb$ age overlap within analytical error with the age of metamorphism in an attempt to reduce some of the "noise" introduced by recrystallization. All analytical data, including those excluded from plotting, are reported in the repository data. The detrital age spectrum for this sample shows a multi-modal age peak distribution of early Mesoproterozoic components similar to sample MIVS-11, with peak modes at ca. 1340, 1420, 1450 and 1480 Ma (Fig. 7). Even after filtering the data as described above, there is a group of 11 inherited crystals whose ages cluster around 1016 ± 5 Ma (weighted mean age). This gives us confidence to constrain the age of deposition for the sedimentary protolith between 1016 ± 5 Ma and the age of metamorphism at 992 ± 8 Ma.

*Sample MIVS-26 (N2°03′19.2″ W75°42′47.6″)* was collected in a small quarry close to the Guapotón municipality (Fig. 2b). It corresponds to an augen orthogneiss with centimetric Kfs porphyroclasts in a matrix of finer-grained and oriented Hbl-Bt-Pl-Qz that define the metamorphic foliation. Zircons from this sample are mostly uncolored, ranging in size from ~150 to 300 μm, with width:length ratios of 1:2 to 1:3. CL imaging showed that they consist of oscillatory-zoned igneous cores rimmed by more homogeneous, unzoned, metamorphic overgrowths (Fig. 3c, supplementary CL file). Concordant U–Pb analyses from the igneous cores yield an age of 1135 ± 6 Ma (Fig. 3c) that is interpreted as representing the time of crystallization for the igneous protolith. This age is within error of the SHRIMP age of 1158 ± 22 Ma reported by Cordani et al. (2005) for this same unit. Analyses performed on the rims result in an age of 990 ± 8 Ma (MSWD = 1.15, $n$ = 15) that we interpret as reflecting the timing of peak metamorphism of this metagranite, synchronous with granulitization of the El Vergel unit (obtained from samples MIVS-11 and CB-002) and slightly younger but more precise (although within error) with respect to the 1000 ± 25 Ma SHRIMP age reported by Cordani et al. (2005).

### 5.1.2. Las Minas Massif

Three samples were analyzed from the Minas massif: MIVS-41, collected from the granitic augen-gneiss that forms the core of the range and the exposed metamorphic rocks; CB-006, a Bt-rich melanosome from a metasedimentary migmatite in proximity to the orthogneissic unit; and MIVS-37a collected from an outcrop of metasedimentary Qz-Fsp migmatitic gneisses on the northern termination of the range (Fig. 2b).

*Sample MIVS-41 (N2°13′34.0″ W75°50′30.3″)* is a Hbl-Bt-Mc-Pl-Qz augen-gneiss that forms the core of the massif and is well exposed along the Zancudo creek that drains the eastern portion of the range. Along this creek, outcrops of granitic gneiss are apparently overlain by metasedimentary migmatites but the contact between the two units was not observed. Zircons from this sample are light pink in color, have width:length ratios between 1:3 and 1:4, and reach up to 400 μm in length. Internal grain structures are characterized by igneous oscillatory-zoning, which in some grains is affected by partial recrystallization interpreted as a result of amphibolite-grade metamorphism (Fig. 3d, supplementary CL file). U–Pb analyses performed on the igneous cores reveal a mid-Mesoproterozoic age for the magmatic precursor of the gneiss, calculated at 1325 ± 5 Ma (MSWD = 0.96, $n$ = 23). There is a subset of analyses that, although <5% discordant, clearly define a discordia mixing chord between the age of the igneous precursor and a younger age component. Using the small-spot ion-counter configuration (12 μm) we were able to obtain a group of concordant analyses from thin, unzoned, brighter metamorphic overgrowths, which yield a value of 990 ± 7 Ma (MSWD = 1.07, $n$ = 8) for the age of the metamorphic event. This age is undistinguishable within error with respect to the ages of metamorphism discussed above for samples from the Garzón massif.

*Sample CB-006 (N2°13′26.5″ W75°50′22.0″)* was also taken along the Zancudo creek a few tens of meters downstream (east) from the location where sample MIVS-41 was collected. In this location, metatexic migmatites of metasedimentary origin display well developed stromatic structures, characterized by an interleaving of 5–10 cm thick granitic leucosomes with laterally persistent bands of Bt-Hbl gneisses. The analyzed sample is a sillimanite-bearing Bt-rich gneiss with amphibole and clinopyroxene interpreted as a melanosome from these metatexites. Zircons recovered are mostly rounded to subrounded in shape, displaying width:length ratios of 1:2 to 1:3 and average sizes between 50 and 250 μm; CL imaging shows that most of the grains have xenocrystic cores surrounded by bright, unzoned overgrowths presumably developed during metamorphism. Analyses performed on the metamorphic overgrowths yield an age of 972 ± 12 Ma (MSWD = 0.14, $n$ = 7) for the high-grade event (Fig. 3e). Interestingly in this sample, most of the xenocrysts are characterized by sector-zoning textures that are suggestive of growth under metamorphic conditions (inset Fig. 3e), and have low-U concentrations typically between 70 and 250 ppm (see supplementary data). This observation contrasts with all the other metasedimentary samples presented in this study, where most of the xenocrystic cores display textures indicative of igneous crystallization. The probability function age plot for the detrital component is dominated by a restricted population within the range from 1100 to 1200 Ma (Fig. 8), with a few restricted grains falling outside this range. These outlier grains all show igneous zoning textures and are also low in uranium. The 10 youngest grains of the detrital component cluster around an age of 1088 ± 24 Ma ($^{206}Pb/^{207}Pb$ weighted mean; MSWD = 0.21), and constrain the maximum timing of deposition for the sedimentary protolith between this age and metamorphism at 972 ± 12 Ma.

*Sample MIVS-37a (N2°15′37.3″ W75°49′49.9″)* was collected from the northwestern termination of the Las Minas massif metamorphic core. It consists of a leucocratic, Qz-Fsp migmatitic gneiss with biotite (extensively retrograded to chlorite) as the only ferromagnesian metamorphic phase. The outcrop is crosscut by a series of slightly folded mafic dikes of unknown age. The analyzed sample is interpreted to be a paleosome of these migmatites with some thin crosscutting leucocratic veins. CL imaging showed that most of the grains have igneous growth-zoning patterns and resorption textures, but lack evident metamorphic overgrowths or extensive recrystallization. U–Pb analyses confirm that the analyzed grains are detrital in character and that zircon did not grow or recrystallize during the metamorphic event but, instead, was probably resorbed during anatexis. The entire age spectra obtained ranges from 1005 ± 23 Ma to 1516 ± 21 Ma, and the dominant peak of the distribution has a maximum at ca. 1490 Ma. Grains that fall out of this range constitute small subsidiary peaks at ~1160 and ~1210 Ma. The youngest grain found in this sample is 2.3% discordant and, overlapping concordia within analytical error, has a $^{206}Pb/^{207}Pb$ calculated age of 1005 ± 23 Ma. Although inferring maximum depositional ages from the youngest single-crystal analysis of a DZ distribution is a meaningful approach in most cases (Dickinson and Gehrels, 2009), the possible complexities in the U–Pb systematics introduced by metamorphism could also imply that this young age might well be an artifact of partial age resetting of an older core during the ca. 990 Ma metamorphic event. We adopt a maximum depositional age of ca. 1005 Ma for the protolith of these gneisses because (1) it could be a geologically reasonable scenario and (2) is in agreement with results obtained for other metasedimentary samples presented in this study, but emphasize that additional work needs to be done on this unit in order to obtain a more robust estimate.

### 5.1.3. Serrania de la Macarena uplift

One sample was analyzed from the metamorphic basement of this sierra (*Macarena-2, N3°01′45.0″ W73°52′13.5″*). It consists of a melanocratic Bt-Ep-Mc-Pl-Qz mylonitic gneiss with abundant sphene, suggestive of dynamic metamorphism under at least upper-greenschist-grade conditions. Sub-grain rotation deformation mechanisms observed in Qz and Fsp crystals suggest intermediate temperatures for the mylonitization event of at least 400 °C (Passchier and Trouw, 2005), that did not generate a strong metamorphic imprint on U–Pb systematics of the analyzed zircon crystals (Fig. 4). CL images from handpicked zircons show that all the grains have oscillatory-zoned textures indicative of igneous crystallization (Fig. 4, supplementary CL file), and most of the point

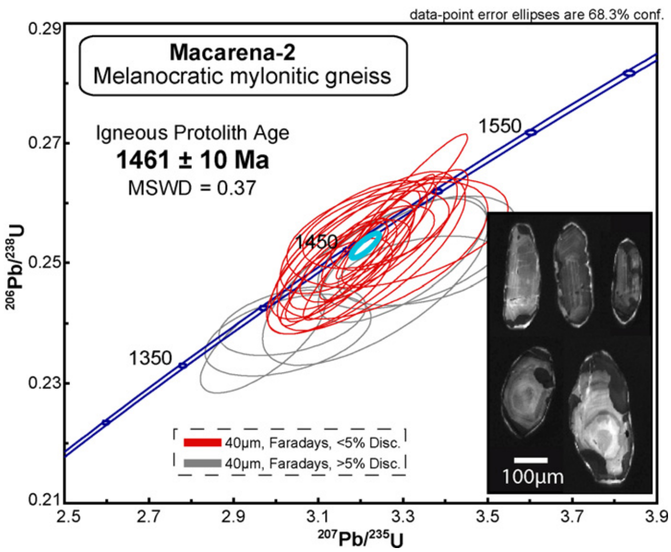


**Fig. 4.** U–Pb concordia diagram for the sample analyzed from the basement of the Serrania de la Macarena.

analyses performed were >95% concordant. A concordia age calculated with 19 individual analyses yields a value of 1461 ± 10 Ma (MSWD = 0.37, $n$ = 19) for the igneous precursor of these mylonites. In some grains, the normal igneous textures appear to be partially obliterated by incipient recrystallization of the zircons probably due to the mylonitization event, but spot analyses performed in these areas resulted in only slightly discordant ages that are very close to those obtained from the unaffected portions of the grains, thus not allowing to place any constraints on the age of the Pb-loss event. Some of the imaged grains also display bright-CL rims that appear to be mantling the igneous crystals, which could very likely be low-U overgrowths of metamorphic origin. However, due to its small size of <10 μm in width, they were not possible to date with our analytical approach.

### 5.2. The basement underlying the foreland basins

The North Andean foreland basins of Colombia can broadly be divided in two sub-basin, the Putumayo to the south which represents the northern extension of the Marañon-Oriente basins of Peru and Ecuador, and the Llanos to the north that continues northeastward into Venezuela (Figs. 1 and 2). These two basins are separated by a series of NW trending basement structures, namely the Macarena-Chiribiquete structural high and the Vaupes arch, which extend from the borders with Peru and Brazil in southeastern Colombia to the Serrania de la Macarena next to the Andean chain (Fig. 2).

Many exploratory wells in the foreland basins of Colombia have drilled below the unconformity between the crystalline basement and the overlying Phanerozoic sedimentary cover, but not many of them have retrieved core samples. The depth to the crystalline basement is highly variable and depends on the relative position of each well with respect to the foredeep and the horst/graben basement structures, but in general the basement is shallower in the Putumayo basin than in the Llanos. In the Putumayo basin, on those wells where basement cores have been recovered, Cretaceous rocks directly overlie the Precambrian units whereas a section of Paleozoic sediments in excess of 1000 m in thickness has been drilled in several locations around the Llanos basin.

For the purposes of this study, we sampled six different exploratory wells that recovered core samples from the crystalline basement of the Putumayo Basin. From north to south they are the Payara-1, La Rastra-1, Solita-1, Mandur-2, Caiman-3, and Mandur-3 wells (Fig. 2), which drilled through basement rocks at depths below 1064 m, 940 m, 1120 m, 1710 m, 2350 m and 2290 m, respectively. These are not the only wells that reached the crystalline basement in the region but, to our knowledge, are most – if not all – of the few that recovered cores accessible for sampling. These cores represent the only available means to study the petrology and geochronology of the basement of the proximal Andean foreland in Colombia. Samples processed from the Mandur-3 and La Rastra-1 wells did not yield zircon concentrates so they will not be discussed further. They are an epidote-amphibolite-facies metabasite, and a kyanite-bearing Grt-Cpx-Hbl-Bt-Pl-Qz melanocratic schist, respectively.

#### 5.2.1. Putumayo basin basement cores

*The Payara-1 well (N2°07′31.3″ W74°33′35.9″)* was drilled in the northern part of the basin and is the northernmost of the basement wells presented in this study piercing the crystalline basement along the western flank of the Macarena arch (Fig. 2a). The core sample consists of an Opx-Sil-Grt-Hbl-Bt-Pl-Qz migmatitic gneiss interpreted to have been metamorphosed under granulite-grade conditions. CL images of zircons recovered from this sample have oscillatory-zoned cores that indicate an igneous origin, and appear mantled by thin rims of unzoned bright metamorphic zircon (inset, Fig. 6a). Small zircons grains tend to show a subtle fading of the original igneous growth zoning, a feature which can be due to the effect of partial solid-state metamorphic recrystallization under granulite-grade conditions (e.g. Connelly, 2001). This observation is also supported by the U–Pb isotopic data, where it is evident that spot analyses performed in smaller grains are slightly discordant and lie along a chord that trends towards the age of metamorphism as the lower intercept (Fig. 6a). Calculation of a concordia age using 16 core analyses that are <3% discordant yields an age of 1606 ± 6 Ma (MSWD = 0.97, $n$ = 16) for the crystallization of the igneous protolith. Given the thin width of the metamorphic overgrowths (<30 μm), analyses were performed using an 18 μm diameter spot size with the ion-counter configuration. Seven analyses were acquired from these overgrowths, four of them being <4% discordant. Of these four, one is 10% normal discordant, another one is 8% reverse discordant, and the last one is 5% discordant but is significantly older than the others and lying along a chord that goes towards the age of the igneous cores. This last analysis is an example of a mixed ablation spot, and incorporation of core material can be clearly seen in the detailed CL (Plate 4, supplementary CL file). The four <4% discordant analyses yield a concordia age of 986 ± 17 Ma (MSWD = 0.49) for the granulite-grade event, considered to be the best estimate for the age of metamorphism of this gneiss. A $^{206}$Pb/$^{207}$Pb weighted mean age of the six non-mixed analyses defines an equivalent but less-precise age of 985 ± 23 Ma (MSWD = 0.70), but as in previous samples the concordia age is preferred. Note the very low U concentrations measured on the overgrowths, estimated between 15 and 20 ppm (supplementary data).

*The Solita-1 well (N0°52′28.6″ W75°37′21.3″)* was drilled in the central part of the basin, coring basement rocks of the Florencia arch. The analyzed sample consists of strongly deformed Amp-Bt-Ep-Pl-Qz migmatitic gneisses, whose textures suggest syn-deformational metamorphism and melting under amphibolite-grade conditions. Recovered zircons are small in size, generally <150 μm in length, displaying 1:2 to 1:4 width:length ratios. Most of the crystals are cloudy with reddish and brownish tones and show strong suppression of their CL emission, observations that suggest a considerable degree of metamictization (inset, Fig. 6b). Xenocrystic cores are common in most of the imaged crystals and U–Pb analyses performed produce a complex concordia plot (Fig. 6b). Most of the spots placed on the dark overgrowths

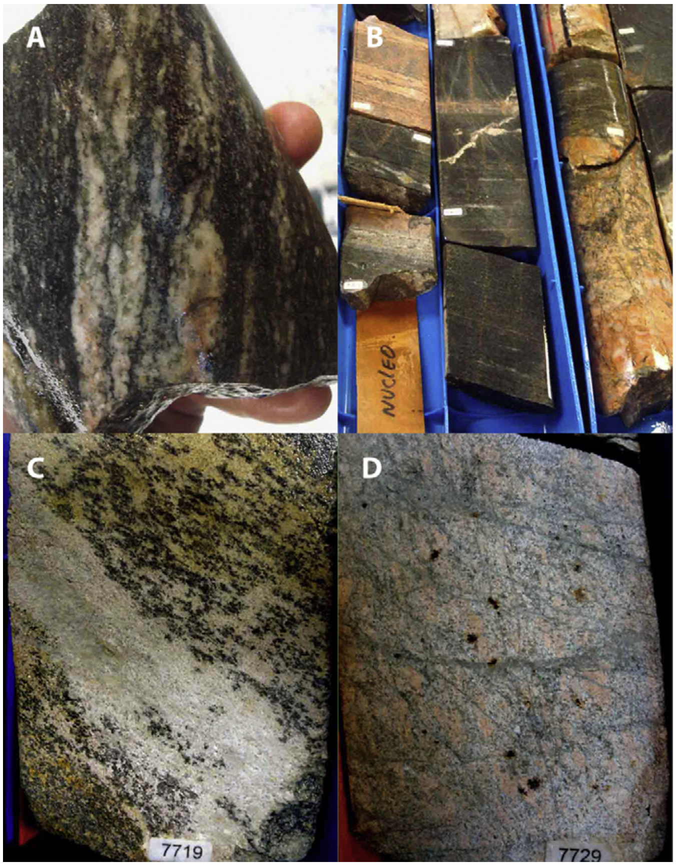


**Fig. 5.** Photographs from some of the drilling-core samples analyzed during the present study. (a) Migmatitic gneisses from the Payara-1 well, (b) Stromatic migmatites injected by granitic sills from the Mandur-2 well, (c) Metasedimentary Qz-Fsp migmatites from the Caiman-3 well, and (d) Leucogranites that crosscut the metamorphic foliation of the migmatites in the Caiman-3 well.

appear to be aligned defining a recent Pb-loss event and a weighted mean $^{206}Pb/^{207}Pb$ age of 1046 ± 23 Ma (Fig. 6b) considered to represent the age of metamorphism and melting, calculated using 12 analyses that are less than 30% discordant. Ellipses shown in blue in Fig. 6b represent analyses that are either xenocrystic cores or ablation spots that represent mixtures between the inherited component and the ca. 1.05 Ga overgrowths. Older analyses, with ages of 1.73 and 1.85 Ga, are interpreted as detrital grains from a sedimentary protolith, and some of the discordant analyses appear to be aligned along a mixing chord between the metamorphic age and an inferred ca. 2.0 Ga component. Two important geological events that affected the western Putumayo basin could be responsible for the observed recent Pb loss: (1) hydrothermal water circulation from the Cordillera towards the foreland during Oligo-Miocene Andean uplift pulses and orogenic development (Parra et al., 2009), and (2) thermal effects and hydrothermal water circulation during nearby late Miocene mafic magmatism (Vasquez et al., 2009).

*The Mandur-2 well (N0°55′24.5″ W75°52′34.1″)* cored basement rocks beneath the west-central part of the basin, and consists of an intercalation of melanocratic migmatitic gneisses and centimetric to decimetric coarse-grained leucocratic veins and sills of muscovite-bearing syenogranites (Fig. 5b). Given the size of the granitic layers and the lack of evident melanosomes and/or reaction margins (selvedges) along the contact with the surrounding gneiss, we interpret these dikes as granitic melts injected into the melanocratic migmatitic gneisses, but bearing no genetic relation (as derivation through partial melting) with its more mafic host rock. The granitoid intrusions display clear textures of crystallization from a silicate melt but also display flow and shearing structures indicative of injection and crystallization under differential stress conditions. The melanocratic host rocks for the dikes are Amp-Bt-Pl-Qz gneisses deformed under at least under amphibolite-grade conditions, in which thin leucocratic stromata of tonalitic composition were developed parallel to the foliation of the gneisses suggesting an incipient degree of partial melting. We thus interpret the overall stromatic morphology as the result of layer-parallel injection of the syenogranitic melt, although the presence of thin trondhjemitic neosomes in the gneisses also indicates some degree of partial melting of the host rocks.

We analyzed two separate samples from this core; one zircon concentrate was obtained from a sample of an approximately 70 cm thick coarse-grained leucocratic dike, and the other from the host melanocratic amphibole-gneisses. Zircons from the gneiss display complex internal morphologies under CL (Fig. 6c, supplementary CL file), characterized by cores with oscillatory zoning patterns that are enclosed by low-luminescent, high-U rims inferred to have crystallized under metamorphic conditions. Textures indicative of solid-state recrystallization were also observed, evidenced as bright margins with lobate terminations inboard of the metamorphic overgrowths that clearly crosscut the primary igneous zonation of the cores (e.g. Hoskin and Black, 2000). Isotopic analyses performed on the low-luminescent metamorphic overgrowths are concordant to moderately discordant (Fig. 6c). From a cluster of four concordant analyses we obtained an age of 1019 ± 8 Ma (MSWD = 0.56, $n$ = 4) for the amphibolite-facies event, similar to that found in the Solita-1 well but older than the granulite-facies imprint dated from the Payara-1 well. Most of the cores with oscillatory-zoned textures appear to pertain to a single population variably affected by Pb-loss effects, and a cluster of concordant grains from this group displays an earliest Mesoproterozoic age of 1592 ± 8 Ma (MSWD = 1.06) for the protolith. Many core analyses are strongly discordant and define a mixing chord between the two previously discussed populations with variable superposed Pb-loss (gray ellipses in Fig. 6c), while a few cores with non-oscillatory zoned textures yield older concordant ages up to 1713 Ma inherited from a possible volcanosedimentary protolith.

Zircons from the leucocratic sills are mostly elongated and prismatic, displaying width:length ratios between 1:3 and 1:5 and sometimes up to 500 μm in length. Internal CL images showed that the grains have oscillatory-zoned textures indicative of crystallization from a melt, but some internal complexities are apparent from the presence of bright rims surrounding darker cores which sometimes appear to truncate previous zoning patterns (Fig. 6d, supplementary CL file). Around 60 U–Pb spots were performed over the different textural areas and complexities of the grains but they produced a fairly simple age pattern (Fig. 6d), with all the analyses overlapping concordia and defining a rather homogeneous population with an age of 1017 ± 4 Ma (MSWD = 0.66). This age, interpreted as reflecting the timing of crystallization of the granitic melt, is more precise but still within error with respect to the age of metamorphism measured from the zircons overgrowths of the host gneisses described above. We thus consider that peak regional metamorphism and injection of granitic melt were relatively synchronous in this area of the basin as suggested by textural observations and supported by the geochronological results.

*The Caiman-3 well (N0°45′13.6″ W76°09′45.4″)* cored approximately 10 m of basement in the southwestern part of the basin, sampling a depth interval between 2350 and 2360 m just below the unconformity with the overlying Cretaceous strata. This core broadly consists of two different rock types: an upper part of felsic migmatites (Fig. 5c), and a lower part of undeformed leucogranites that crosscut the foliation of the metamorphic rocks (Fig. 5d). The migmatites display leucosomes that are sub-parallel with respect to a subtle foliation defined by the orientation of biotites, quartz and

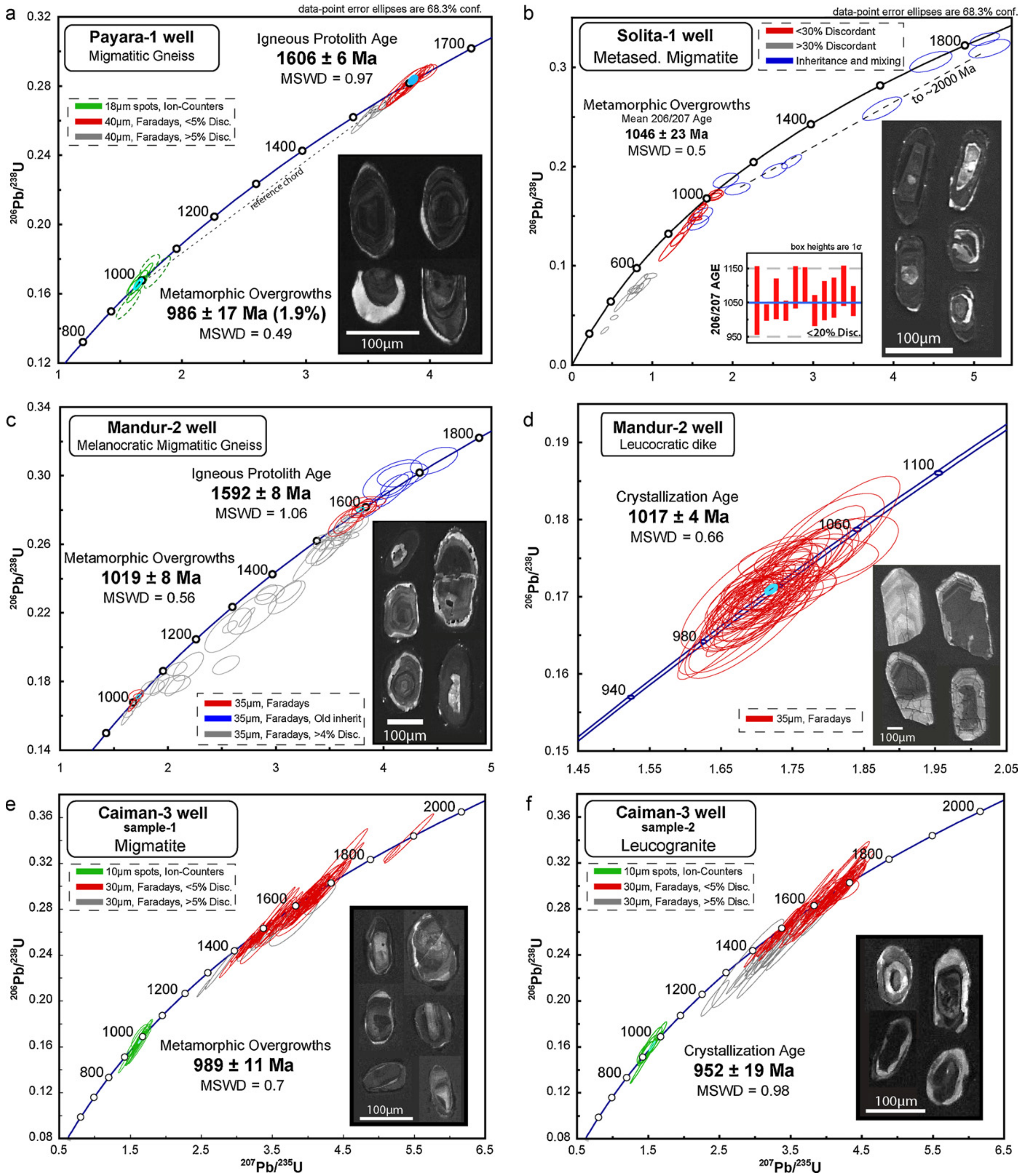


**Fig. 6.** U–Pb concordia diagrams for samples analyzed from drill-core samples of the Putumayo basin basement.

plagioclase, and is classified as a leucocratic diatexite. We analyzed different zircon fractions for each rock type.

Zircons extracted from the migmatites from a segment of the core between 2352.6 and 2353.75 m (corresponding to Fig. 5c) have rounded to sub-rounded external shapes and length:width ratios from 1:1 to 2:1. CL images revealed a complex internal morphology in these grains, characterized by cores with mostly oscillatory-zoning that are mantled by low luminescent thin metamorphic rims (Fig. 6e, supplementary CL file). Individual grains are generally not larger than 110 μm, and metamorphic rims do not exceed 20 μm in thickness. We performed 85 spot analyses on the xenocrysts utilizing a 30 μm laser diameter, and 20 analyses on the overgrowths using a 10 μm laser-beam diameter on ion-counter configuration. From the rim analyses, only 12 clustered around an age of ~990 Ma (Fig. 6e) while the remaining gave ages that were much older, reflecting partial zircon recrystallization with Pb inheritance

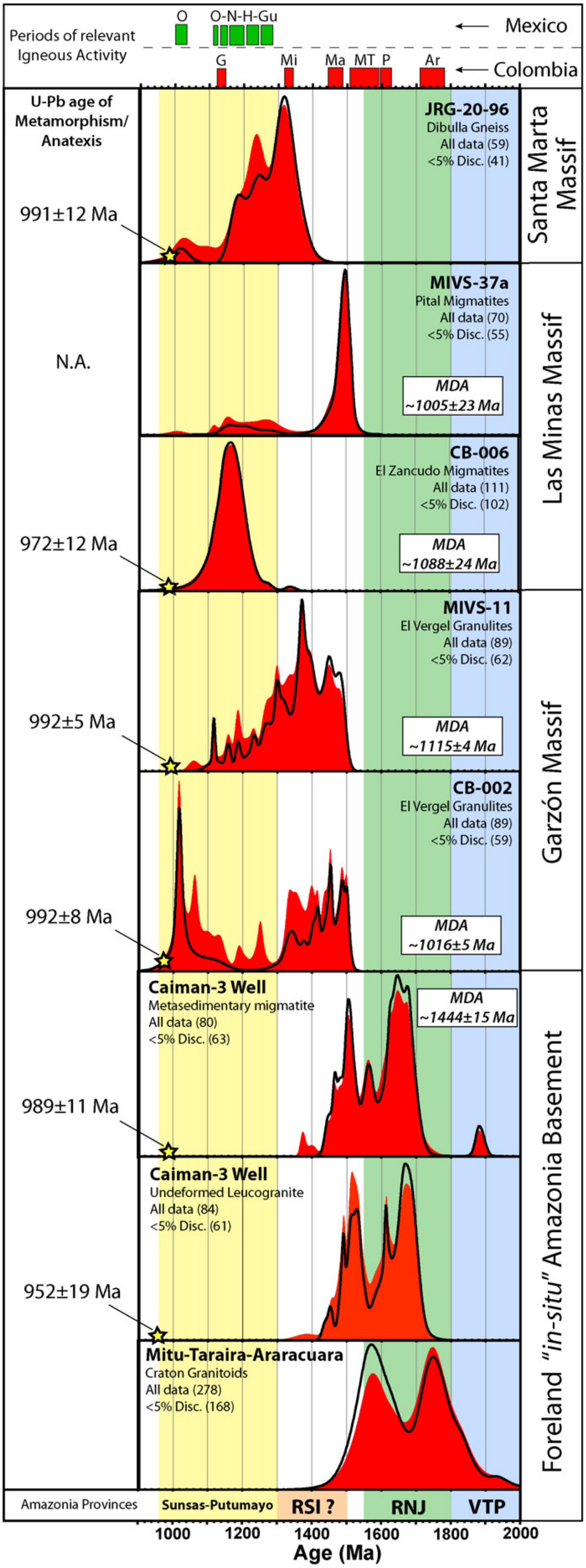


**Fig. 7.**

or mixing of old core material in the ablation sites. A concordia age calculated from the rims data yields a value of 989 ± 14 Ma (MSWD = 0.7, $n$ = 12), interpreted as the age of the metamorphic event. From the xenocryst core results, 11 of them resulted in >30% discordant ages and were discarded, while the remaining 74 revealed to be derived from late Paleoproterozoic to early Mesoproterozoic source areas. From the concordia plot of Fig. 6e it can readily be observed that many of the analyzed xenocrysts have been affected by varying degrees of Pb-loss, possibly by partial recrystallization during the metamorphic event. If this is the case, and the observed discordance is effectively related to metamorphism, then individual ellipses would be slightly displaced from their "true" age towards apparent younger $^{206}Pb/^{207}Pb$ ages, lying along a discordia chord that is subparalel to concordia. This effect, however, although difficult to quantify, would only reinforce the observation that all of the detrital grains analyzed have crystallization ages older than about 1.45 Ga. The diverse range of ages obtained for the xenocrystic cores reflects the detrital nature for the protolith of this rock and provides valuable information about the provenance of this unit. The age spectrum, which is shown in Fig. 7, is dominated by peak modes at ca. 1470, 1500, 1570, and in the range from 1650 to 1680 Ma.

The second sample analyzed from the Caiman-3 well, corresponding to the lower segment of leucogranites, is a muscovite-bearing monzogranite taken from the depth interval between 2355.60 and 2355.80 m. Zircons recovered from this sample have more elongated and prismatic shapes in comparison to the rounded edges of the zircons recovered from the host migmatites, and display width:length rations between 1:2 and 1:4 (Fig. 6f, supplementary CL file). Most of them are characterized by bright overgrowths enclosing darker xenocryst cores, and some of these overgrowths have oscillatory-zoning patterns indicating crystallization from a silicate melt. Analyses from this sample were carried out the same way as in zircons from the migmatites, using 10 μm ion-counter configuration for the rims and 30 μm faraday configuration for the cores. Twenty-three spots were analyzed from the overgrowths but only seven of them were younger than ~1 Ga, reflecting significant mixing of older material in most of the ablation pits. A concordia age calculated from these young analyses yields a value of 952 ± 21 Ma (MSWD = 0.98, $n$ = 7) for the igneous crystallization event, confirming the cross-cutting relationships observed from the drill-core. From the xenocrysts, 61 out of the 84 analyses performed are <5% discordant and they yield ages ranging from ca. 1440 to 1700 Ma with distribution peak maxima at ~1460, ~1490, ~1530, ~1615 and ~1677 Ma. This age distribution closely resembles that of the migmatites from this same well (Fig. 7), suggesting that these leucogranites may represent anatectic melts derived from metasediments similar to those in which they are hosted.

**Fig. 7.** Probability plots for the detrital age components of Mesoproterozoic metasedimentary units included within the Putumayo Orogen, indicating their respective ages of metamorphism measured by zircon U–Pb and calculated protolith maximum depositional ages. Shaded red areas represent the spectra plotted from the entire dataset of each sample while black solid lines show data filtered to <5% discordance. In addition to the metasedimentary samples, the inherited component of anatectic leucogranites found in the Caiman-3 is plotted, as well as a synthetic diagram combining all the individual spot ages analyzed from granitoids of the Mitu–Tararira–Araracuara areas. In the upper portion of the plot, ranges of relevant magmatic activity from the Proterozoic of Mexico and Colombia are shown for reference (data from Mexico: Cameron et al., 2004; Weber et al., 2010). Colored columns have the same coding as Fig. 1 and represent the age ranges for the different provinces of the Amazon Craton (Tassinari and Macambira, 1999). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### *5.3. Cratonic exposures*

As part of this study, we also analyzed six samples of granitoid rocks from the neighboring shield outcropping east of the Putumayo basin in order to: (a) test for the occurrence of late Meso- to early Neoproterozoic rocks exposed within this largely unknown portion of the shield, and (b) to use these as a cratonic reference for evaluating the detrital zircon populations and protolith ages obtained from drill-core samples analyzed from the Putumayo basin basement (Fig. 7). Although relevant as a reference for the final discussion, the obtained ages are not strictly crucial for the development of the Putumayo Orogen so the results will only be briefly mentioned and included in Table 1, while the concordia plots and analytical data are included in supplementary material.

In summary, samples PR-3215 and J-263 from the Araracuara basement high (Fig. 2) are both epidote-bearing syenogranitic gneisses that yield late Paleoproterozoic ages of 1756 ± 18 Ma and 1732 ± 24 Ma, respectively. Granitoids from the Apaporis and Vaupes rivers further east (samples PR-3092, AH-1419, CJR-19 and AH-1216) are all coarse-grained monzo- and syenogranites with biotite and amphibole, and yield ages that cluster between 1530 and 1588 Ma. Whereas no inheritance was observed in the Araracuara samples, this is a very common feature in the Mesoproterozoic granites where xenocryst ages generally range from ca. 1600 to 2000 Ma, with few restricted grains as old as ∼2.5 Ga. No evidences for magmatic or high-grade metamorphic events younger-than ∼1.5 Ga were found in the exposed shield.

## 6. Discussion. Proposed evolution of the Putumayo orogen within a Rodinian context

The participation of the Amazon Craton in the assembly of the Rodinia supercontinent has for long been inferred, using the Bolivian-Brazilian Sunsás-Aguapei orogenic belt as a tie to other Stenian–Tonian orogenic segments worldwide (Cordani et al., 2009; Hoffman, 1991; Li et al., 2008). Continuation of this Meso-Neoproterozoic belt towards the northwest, extending beneath the Amazon River graben and the north Andean foreland basins is commonly inferred by some authors, but this assumption has so far only been based on indirect evidence such as: (1) the widespread occurrence of ∼1 Ga zircon populations in parautochthonous lower Paleozoic sequences of the Peruvian Andes (Cardona et al., 2009; Chew et al., 2007, 2008; Cordani et al., 2010), and (2) the occurrence of Grenville-age inliers in the Andes of Colombia (Fuck et al., 2008; Li et al., 2008; Restrepo-Pace et al., 1997). The geochronological results presented in this paper provide the first direct evidence that shows the existence of an autochthonous Ectasian-Tonian orogenic belt along the northwestern margin of Amazonia, which serves both as a basis for global intercratonic correlations and as a reference against which Cordilleran inliers and peri-Amazonian crustal blocks can be compared or correlated. As will be further expanded below, the new geological and geochronological data presented here suggest that the Meso-Neoproterozoic evolution of NW Amazonia's margin is very different from that of the Sunsás-Aguapei orogen; consequently, we propose the name Putumayo Orogen for a distinct segment of a Ectasian-Tonian mobile belt in northern South America, whose paleogeographic significance and global tectonic implications should also be distinct from those of the Sunsás belt according to the nature and timing of the major geologic events that locally characterized its evolution (Fig. 8). Given the new timing constraints, we propose a three-stage magmatic/metamorphic history for the Putumayo Orogen, characterized by the development of a fringing-arc complex followed by terrane accretion and final ocean closure during continent–continent collision. The following discussion will be subdivided into three temporal intervals, following the schematic paleogeographic model presented in Fig. 9 and the correlation of geological events that took place in the different provinces as summarized in Fig. 8.

### *6.1. Pre-Rodinian framework (∼1.3 to 1.1 Ga):*

The position of Amazonia during this time period, constrained by a few paleomagnetic poles obtained from the SW portion of the Amazon Craton, suggest initial oblique collision and continued strike-slip displacement between Laurentia and Amazonia along the Llano-Sunsás segments between ca. 1.2 and 1.15 Ga (Tohver et al., 2002; D'Agrella-Filho et al., 2008). Additional evidence supporting this model include the presence of exotic, Amazonian-affine crust in the Blue Ridge/Mars hill inlier of the southern Appalachians (Loewy et al., 2003; Tohver et al., 2004a), as well as the timing of final inversion and high-grade metamorphism along the Nova Brasilandia intracontinental rift of central-western Brazil (Tohver et al., 2004b). Significant deformation in both provinces culminated in the occurrence of undeformed intrusions, represented by the Sunsás granite suite dated at 1076 ± 18 Ma in the Sunsás-Aguapei belt (Boger et al., 2005) and undeformed rhyolitic dikes dated at 1098 ± 10 Ma from the eastern Llano uplift (Mosher, 1998; Walker, 1992).

The relative position of Baltica with respect to Laurentia during this time period is also shown in Fig. 9, constrained by both paleomagnetic and geologic data (Cawood and Pisarevsky, 2006; Cawood et al., 2010; Pisarevsky et al., 2003 and references therein). Prior to ∼1.25 Ga, Baltica is though to have been attached to the modern eastern coast of Greenland (Fig. 9a) before it started a late Mesoproterozoic clockwise rotation on its way to its final position within Rodinia (Cawood and Pisarevsky, 2006; Cawood et al., 2010). During this rotation, accretionary tectonics were triggered along Baltica's leading edge during the early stages of the Sveconorwegian orogeny (Bingen et al., 2008b; Bogdanova et al., 2008).

#### *6.1.1. Geochronological structure of Amazonia's continental leading margin*

U–Pb zircon geochronological results presented in this study confirm the late Paleo- to early Mesoproterozoic character of the crystalline basement rocks exposed in the eastern Colombian lowlands. In this area of the craton, undeformed alkaline granitoids with crystallization ages between 1.53 and 1.58 Ga intrude a basement that is predominantly older than ca. 1.70 Ga, as suggested by the ages of inherited zircon xenocrysts found in the Mesoproterozoic intrusives (see supplementary material) and granitic gneisses sampled from the Araracuara basement window (samples J-263 and PR-3215). These results seem to be broadly in agreement with a northwestward extension of the RNJ province from Brazil towards Colombia (Tassinari et al., 1996; Tassinari and Macambira, 1999; Cordani and Teixeira, 2007). Additionally, late Paleo- to earliest Mesoproterozoic protolith ages obtained from drilling cores of migmatitic gneisses underlying the Putumayo foreland (wells Mandur-2 and Payara-1, Fig. 2) suggest that, previous to the inception of the Putumayo orogen, the late Paleo- to early Mesoproterozoic basement of NW Amazonia extended all the way towards the cratonic margin (modern proximal foreland basement). In this area, the new information obtained from drill-core samples also shows that sedimentary basins with cratonic provenance were developed during mid Mesoproterozoic times, possibly covering the late Paleoproterozoic marginal basement, as evidenced by metasedimentary migmatites from the Caiman-3 well that yield a maximum depositional age estimated to 1444 ± 15 Ma and clearly show detrital zircon age spectra dominated by cratonic, mostly RNJP-like ages (Fig. 7). These observations contrast with the regional structure of the craton in SW Amazonia, where the regionally extensive Rondonia-San Ignacio Mesoproterozoic

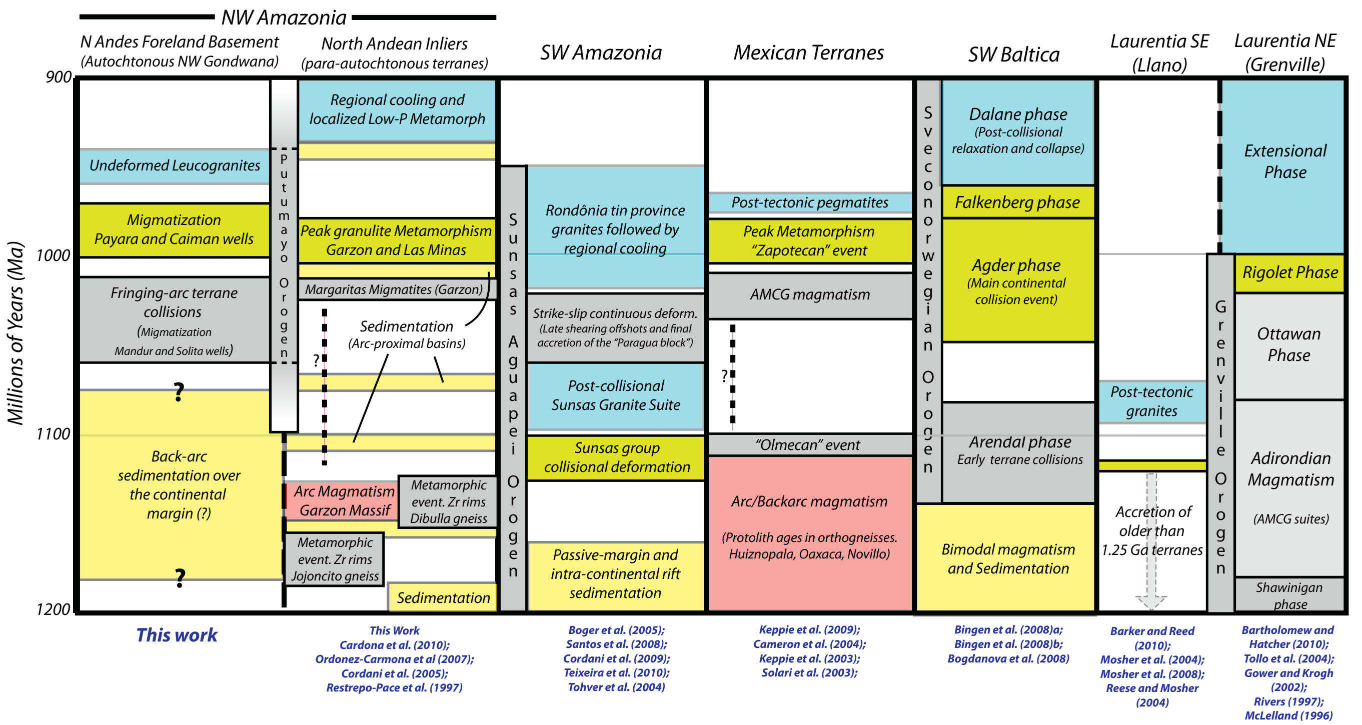


**Fig. 8.** Events correlation chart for different provinces of Amazonia, Baltica and Laurentia during the time interval from 1200 to 900 Ma, relevant for paleogeographic correlations discussed throughout the paper. References used for each region are listed in the figure.

orogen lies outboard of the RNJ and separates the later from the Sunsás-Aguapei orogen (Fig. 1; Bettencourt et al., 2010; Cordani and Teixeira, 2007). Following from the presently available geochronologic data, we can conclude that a correlative Mesoproterozoic orogenic belt that is equivalent in magnitude to the Rondonia-San Ignacio province of Brazil seems to be missing in northwestern South America.

### *6.2. The Colombian–Oaxaquian fringing-arc system (ca. 1.30–1.10 Ga)*

High-grade metasedimentary units dated from the Las Minas and Garzón cordilleran inliers display characteristics that suggest their protoliths formed in proximity to an active-arc system, such as: (1) the short time gap that exists between estimated maximum depositional ages and those of metamorphism, indicating that young DZ populations must approximate the true depositional age of the sedimentary protoliths (Fig. 7); this observation indicates the occurrence of nearby contemporaneous igneous activity (e.g. Cawood et al., 1999; Dickinson and Gehrels, 2009), and (2) the ubiquitous presence of feldspar in all the analyzed samples implies that their protoliths were probably arkosic sands, with variable proportions of ferromagnesian material needed in order to form the observed metamorphic mafic-mineral-bearing assemblages. These observations support previous interpretations that suggest volcanosedimentary sequences to be the protoliths for the metasedimentary gneisses and felsic granulites of the Garzón massif (Kroonenberg, 1982).

Although the stratigraphic relation between the Guapoton orthogneiss and the Vergel metasediments was not observed, it is clear that protolith sedimentation of the later unit postdates the granitic-protolith crystallization of the orthogneiss (Fig. 7). It is possible that the ca. 1.14 Ga granites correspond to the local basement of the area over which the sedimentary sequences now represented by the Vergel metasediments were originally deposited, and such a stratigraphic relationship could also be the case for the Las Minas massif with the Zancudo creek metasedimentary migmatites (CB-006) overlying an orthogneissic unit (MIVS-41). In the case of the Zancudo creek metatexites, the large proportion of inherited zircon cores with textures suggesting a metamorphic origin (Supplementary CL file, Plate 2) is still puzzling, and the dominantly unimodal age distribution obtained from these cores implies either (1) sedimentary sourcing from a very restricted basin that drained metamorphic rocks with an age ca. 1.15 Ga, or (2) that these grains were formed in situ by a previous metamorphic event affecting this sedimentary sequence. Although the presently available data is not sufficient to conclusively rule out any of these two hypotheses above, it provides strong evidence to infer that metamorphism was locally occurring ca. 1.15 Ga and was coeval with granitic magmatism (e.g. Guapoton gneiss protolith, Fig. 8). Zircon rims of similar age have also been reported from detrital grains found in the Jojoncito and Dibulla paragneisses from the Guajira and Santa Marta massifs, respectively (Cordani et al., 2005), thus suggesting that a metamorphic event of this age may have been a more widespread feature within the arc. We conclude that the (metamorphosed) sedimentary basins and associated underlying granites now represented by sequences of the Garzón and Las Minas massif developed in an active-margin setting (similar to active-margin assemblage 1 of Cawood et al., 2007) where magmatism and metamorphism intermittently took place during the age range from 1.32 to 1.1 Ga and, as it is discussed below, they may have evolved as parautochthonous arc terranes outboard of Amazonia.

In many Mesoproterozoic paleogeographic reconstructions, Oaxaquia is commonly positioned along the northwestern margin of Amazonia in close association with the Colombian Andean inliers, where they have also been interpreted as parautochthonous arcs latter to be trapped between colliding continental blocks during the assembly of Rodinia (Bogdanova et al., 2008; Cardona et al., 2010; Keppie et al., 2001; Keppie and Dostal, 2007; Keppie and Ortega-Gutierrez, 2010; Keppie and Ramos, 1999; Li et al., 2008). The Proterozoic basement blocks of Mexico, known as the Novillo gneiss, Huiznopala gneiss, the Oaxacan complex, and the Guichicovi complex (Fig. 1 in Keppie and Ortega-Gutierrez, 2010), are characterized by a similar Proterozoic history consisting of

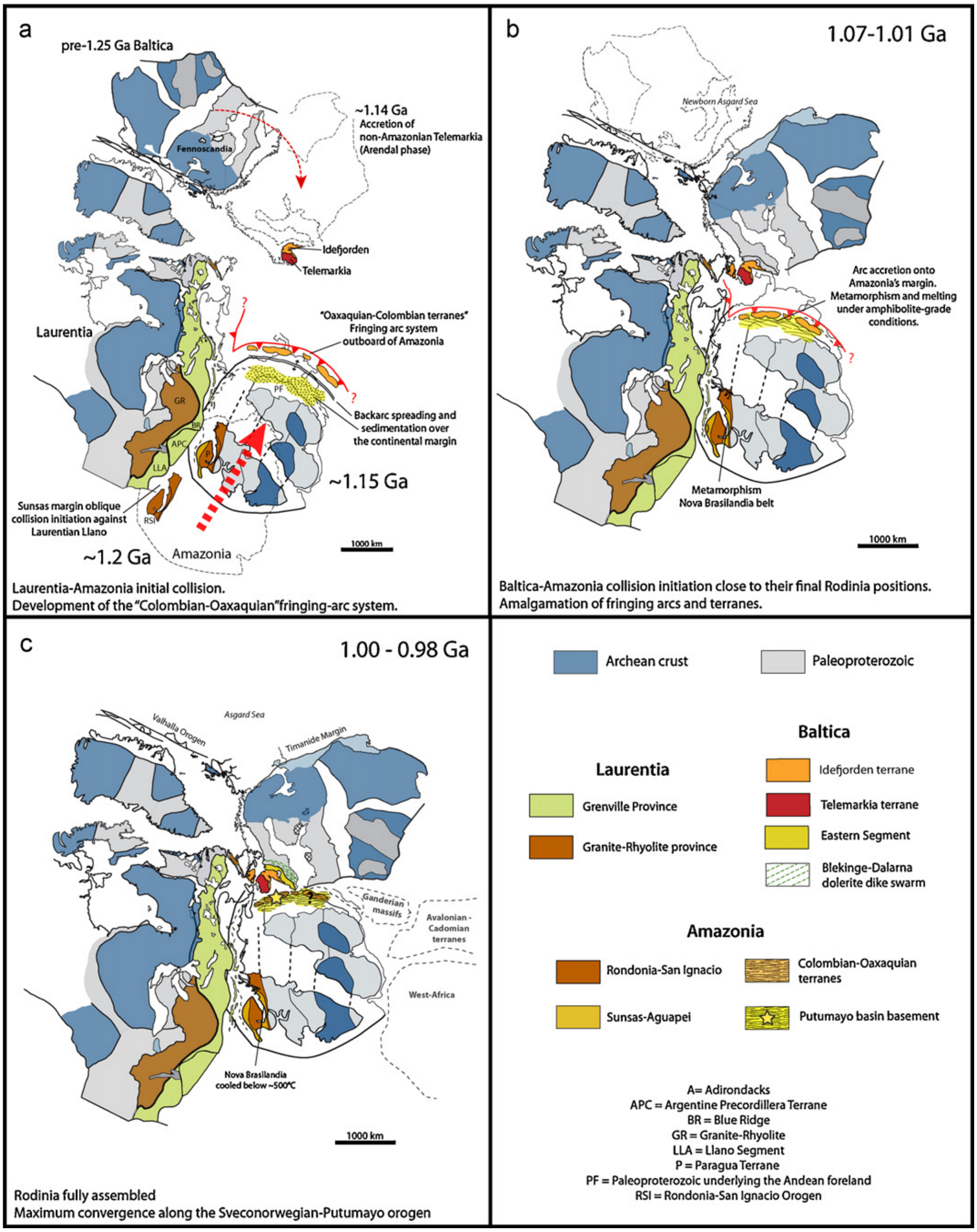


**Fig. 9.** Proposed tectonic evolution of the Putumayo orogen from the late Mesoproterozoic to early Neoproterozoic and proposed paleogeographic correlations between Amazonia, Baltica and Laurentia. Other blocks and cratons were omitted for simplicity. Outline and provinces of Laurentia modified from Cawood et al. (2007); Baltica from Bingen et al. (2008b) and Bogdanova et al. (2008); Amazonia from Cordani et al. (2000). See text for discussion and other references used.

granitic intrusives with arc and backarc chemical affinities during the interval ~1.3 to 1.15 Ga, intrusion of AMC complexes around 1.01 Ga, and high-grade granulite-facies metamorphism at around 0.99 Ga (Cameron et al., 2004; Keppie and Ortega-Gutierrez, 2010; Solari et al., 2003; Weber and Hecht, 2003; Weber and Kohler, 1999). Similarities in Pb isotopic compositions, U–Pb ages of granulite-grade rocks, and Paleozoic fossil faunas from Colombia and Mexico led Ruiz et al. (1999) to suggests a correlation between the Proterozoic inliers of these two regions, specially between the Garzón, Santa Marta and Guichicovi inliers, correlation that has found further support with recent zircon Hf isotopic data (Weber et al., 2010). Following the various lines of evidence that tie the Proterozoic evolution of the Colombian and the Mexican inliers, we include the Colombian cordilleran inliers and the Mexican terranes in our reconstruction as part of a commonly evolving "Colombian–Oaxaquian" peri-Amazonian fringing arc system located outboard of Amazonia's leading edge during late Mesoproterozoic times (Figs. 9a and 10).

According to Busby et al. (1998), long-lived convergent margins facing a large ocean basin may evolve through three distinct phases: (1) a strongly extensional intraoceanic-arc phase, (2) a mildly extensional arc system, and (3) a compressional continental-arc phase following accretion of the fringing-arc terranes. We propose that our hypothesized Colombian–Oaxaquian fringing arc may have evolved in a similar fashion, as many of these stages can potentially be identified from its Mesoproterozoic geological record: initiation of the strongly extensional arc phase would be represented by the occurrence of 1.3 Ga rift related basalts (now transformed into mafic granulites) of the north Oaxaca complex (Keppie and Dostal, 2007) and bimodal igneous suites with backarc

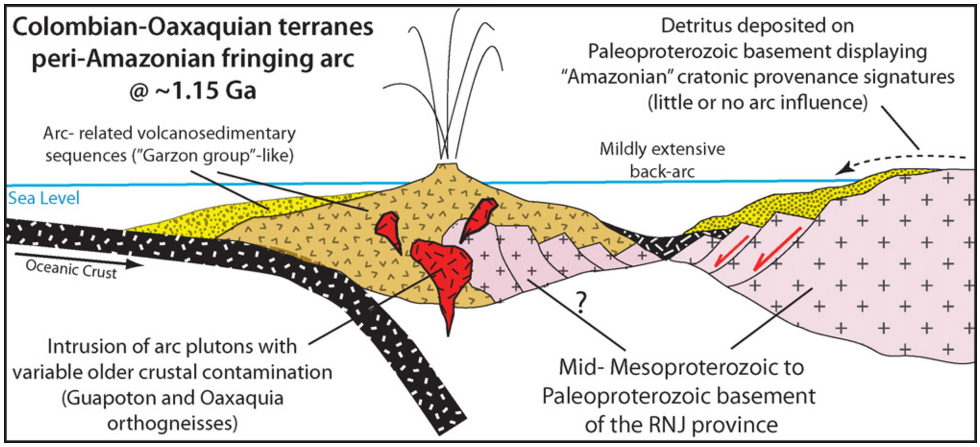


**Fig. 10.** Schematic section for the proposed configuration of the Colombian–Oaxaquian fringing-arc system at ca. 1.15 Ga. Modified from Busby (2004).

geochemical signatures of the Novillo gneiss (Keppie and Ortega-Gutierrez, 2010). Rifting from Amazonia would have been followed by the development of an intraoceanic arc (phase 2) characterized by widespread arc-related juvenile magmatism between 1.3 and 1.2 Ga such as that found in Oaxaquia (Keppie et al., 2001; Keppie and Ortega-Gutierrez, 2010; Weber and Hecht, 2003; Weber and Kohler, 1999; Weber et al., 2010), later evolving towards more mature isotopic compositions like those exemplified by the Guapotón orthogneiss in the Garzón massif (Restrepo-Pace et al., 1997). Coeval accumulation of thick volcanosedimentary sequences may have taken place during this phase, resulting in units that are now represented by thrust slices of the El Vergel migmatites included within the Garzón group; in this unit, metasedimentary felsic granulites and gneisses metamorphosed at ca. 0.99 Ga yield estimated maximum depositional ages that are generally younger than 1.15 Ga as evidenced by their inherited DZ component. The detrital zircon signatures from these units can be explained in terms of derivation from granitic sources included within the same Colombian–Oaxaquian arc terrane (Fig. 7), while the lack of detritus sourced from continental Amazonia is evident by the paucity of ages older than 1.5 Ga (Rio Negro-Juruena) in the spectrum.

Conversely, geochronological results from core samples recovered in the Putumayo basin basement do not support the existence of a late Mesoproterozoic active margin developed on autochthonous Amazonia crust. Instead, our data show that the cratonic margin of northwestern South America is characterized by Stenian–Tonian metamorphic reworking of late Paleoproterozoic basement and associated mid-Mesoproterozoic cover sequences, but was otherwise relatively stable with only sedimentation occurring (i.e. Caiman-3 cores sedimentary protoliths) and no magmatic events were identified in the interval from ca. 1.59 to 1.01 Ga. Consequently, in our schematic reconstruction of Fig. 10, we include all the late Mesoproterozoic Colombian and Mexican inliers in a common fringing arc system outboard of Amazonia instead of separated in two sub-parallel arcs as proposed by Weber et al. (2010).

Following this period of intensive arc plutonism in the Colombian and Mexican inliers there was an interval of magmatic quiescence that spanned the age range between 1100 and 1050 (Fig. 9). A possible reason for the sudden shutting down of magmatism could be a drastic change in the overall stress conditions along the arc, such as those that could derive from transitioning between a mildly extensive regime to compressive one (similar to the transition from phase 2 to phase 3 in Busby et al., 1998). A switch of this type could have been responsible for increased plate coupling along the margin, resulting in continent-directed trench migration and final collapse of the arc against the continental margin at the same time as decreased absolute rates of subduction generate the magmatic lull (e.g. Busby, 2004). The termination of magmatic activity along the peri-cratonic arc marks the initiation of collisional events recorded in the Putumayo orogen.

### *6.3. Rodinia assembly initiation: terrane and arc accretion onto Amazonia's cratonic margin (1.1–1.01 Ga)*

Although largely obliterated by the later granulite-grade metamorphic overprint, there are geological and geochronological evidences supporting the existence of an early metamorphic event between 1.05 and 1.01 Ga, both in the Andean cordilleran inliers and in the basement of the Putumayo basin. Metamorphism of the Las Margaritas unit in the eastern flank of the Garzón massif is constrained to 1015 ± 7.8 Ma by U–Pb SHRIMP dating of a leucosome from a migmatitic paragneiss, as well as by a Sm–Nd garnet-whole rock isochron age of 1034 ± 16 Ma (Cordani et al., 2005). Similar ages are also reported in this article for the basement of the Putumayo basin, where amphibolite-grade migmatites identified in the Mandur-2 and Solita-1 wells yield ages of 1019 ± 8 Ma and 1046 ± 23 Ma, respectively (Fig. 9), supporting an early metamorphic event that we hypothesise could be the result of accretionary events against this segment of the continental margin. This event, an age-equivalent for the Laurentian Ottawan orogeny (McLelland et al., 1996), has been noted by Santos et al. (2008) to be absent from the geological record in the Sunsás orogen of southwestern Amazonia.

In Oaxaquia, late Mesoproterozoic tectonothermal events have also been identified in the age range between 1.1 and 1.07 Ga (Solari et al., 2003; Weber et al., 2010), where they have been grouped within the Olmecan orogeny (Fig. 8). Following the connections previously drawn between Oaxaquia and the Colombian inliers, we interpret these metamorphic ages as constraining the timing of accretion of the Colombian–Oaxaquian parauthochtonous arc onto Amazonia's continental margin. This event was probably shortly followed by slab-break off and melting of the lower crust, leading to the generation of the AMC intrusive complexes that are widespread among the Oaxaquian terranes (Weber et al., 2010) and possibly also present in the Sierra Nevada de Santa Marta massif in the northernmost Colombian Andes (Tschanz et al., 1974).

It is worth noting that, in Baltica, metamorphism of the Bamble and Kongsberg tectonic wedges marks the timing of early terrane accretions onto Fennoscandian crust and the collision of Telemarkia against the Idefjorden terrane (the Arendal phase, Bingen et al., 2008b). The Bamble and the Kongsberg terranes comprise variably metamorphosed supra-subduction complexes whose metamorphic ages constrain these collisions to have occurred between ∼1140 and 1090 Ma, clearly earlier that the timing of initial accretion along Amazonia's margin as recorded in the Putumayo Orogen and Oaxaquia. Additionally, marked differences between the detrital zircon age spectra of Telemarkia's metasedimentary units (Bingen et al., 2001, 2003), and those from NW autochtonous/parautochtonous Amazonia (this study) lead us to conclude that, regardless of the exotic or indigenous origin of Telemarkia with respect to Fennoscandia, an Amazonian ancestry for this terrane and/or its accretion to Baltica at ca. 1.1 Ga by early collisional interactions with Amazonia are both very unlikely.

### 6.4. Final Rodinia assembly: collision along the Putumayo-Sveconorwegian orogen (1.00–0.98 Ga)

New zircon U–Pb data presented in this paper demonstrate the existence of a Tonian orogenic belt in NW South America that is buried under the Andean foreland basin sequences, providing a direct link to correlate granulite-facies tectonothermal events occurring in NW cratonic Amazonia, the Colombian Cordilleran inliers, Oaxaquia, and arguably also the Sveconorwegian orogen (Fig. 9).

As noted by Bogdanova et al. (2008), paleogeographic reconstructions between Laurentia and Baltica imply the necessity of a "third continent" in order to explain the timing and geometry of the Sveconorwegian province, and they suggest collision with Amazonia as a feasible tectonic scenario. Available geochronological data from granulite-facies rocks in the Sveconorwegian indicate that crustal shortening was still underway along this orogen while extensional regimes were already dominating the Laurentian Grenville margin (Bingen et al., 2008b; Bogdanova et al., 2008; Gower and Krogh, 2002; Gower et al., 2008), but as was noted by Bogdanova et al. (2008) they coincide with the Zapotecan event in Oaxaquia at ca. 990 Ma (Cameron et al., 2004; Keppie and Ortega-Gutierrez, 2010; Lawlor et al., 1999; Ruiz et al., 1999; Solari et al., 2003; Weber and Kohler, 1999). The new geochronological data presented by us demonstrates that this granulite-grade metamorphic event at 0.99 Ga is also widespread in the Colombian inliers and, most importantly, the basement of the Putumayo Andean foreland basin; this evidence allows us to extend the correlation previously drawn between Baltica and Oaxaquia to a larger scale, now to include the north Andean Colombian Cordilleran inliers, the Putumayo basin basement and thus, cratonic Amazonia.

In line with this chronological evidence, our reconstruction displays final collision occurring between Baltica and Amazonia along a juxtaposed Putumayo-Sveconorwegian internal orogen at ca. 990 Ma, defining a separate belt with a structural trend that lies almost orthogonal with respect to the Sunsás-Grenville orogenic tract (Fig. 9). Continuation of the Putumayo Orogen in Amazonia towards the northeast underlying the foreland Llanos basins of northern Colombia and Venezuela still awaits for conclusive evidence, although there are observations that may suggest this could be the case; occurrences of Meso- to early Neoproterozoic tectonothermal events in Venezuela are known from: (1) K–Ar cooling ages in the range from 1.36 to 0.86 Ga from various basement drilling-cores in the Llanos basin presented by Feo-Codecido et al. (1984), (2) U–Pb LA-ICP-MS ages from basement drilling cores in the La Vela gulf dated between ca. 1.1 and 1.3 Ga (Baquero et al., 2011; Marvin Baquero, personal communication), and (3) the wide variety of high-grade metamorphic rocks closely resembling the granulites of the Colombian Andes such as those found in the Nirgua inlier of the northern Merida Andes and other locations discussed by Grande and Urbani (2009) (and references therein).

Following collision, shortening and crustal thickening may have continued along the Putumayo-Sveconorwegian orogen, identified in southern Scandinavia as continued deformation along the mylonite zone between 980 and 970 Ma, foreland basin propagation, and eclogite-facies metamorphism on the eastern segment at 970 Ma (Bingen et al., 2008b; Johansson et al., 2001). These late tectonothermal events are also recorded in the Colombian inliers where metatexic migmatites of the Las Minas massif yield ages of 972 ± 12 Ma for the anatectic event (sample CB-006), similar to other ages of ca. 0.97 Ga found elsewhere in Oaxaquia (Cameron et al., 2004; Weber et al., 2010). In the Putumayo basin, the undeformed leucogranite that intrudes the migmatites cored in the Caiman-3 well provides a minimum age of 952 ± 19 Ma for pervasive deformation occurring in this sector of the Putumayo orogen. This age is similar to that obtained for undeformed granitic pegmatites in Oaxaquia, constrained to ca. 0.97 Ga as discussed by Solari et al. (2003).

In different parts of the Colombian Andes, medium- to low-temperature cooling of the high-grade basement of the cordilleran inliers is constrained by K–Ar and Ar–Ar ages that mostly cluster in a restricted range from 970 to 910 Ma (Cordani et al., 2005; Restrepo-Pace et al., 1997). These ages imply relatively fast rates of exhumation and cooling for the granulites of the Colombian cordilleran inliers following the 990 Ma metamorphic peak.

Finally, metamorphic rims in zircons from the Santander and Jojoncito paragneisses yield U–Pb ages of metamorphism at 864 ± 66 Ma and 916 ± 19 Ma, respectively (Cordani et al., 2005), distinctly younger than any of the other Proterozoic metamorphic events reported here. Although inherited zircon analyses from the detrital protolith of these gneisses resemble those from other metasedimentary units presented in this paper, the presence of ca. 990 Ma zircons in their detrital component indicate that sedimentation of the Bucaramanga and Jojoncito gneisses protoliths postdated the regional granulite-grade metamorphic event and were possibly influenced by reworking of older Putumayo metaigneous and metasedimentary units such as those presented here from the Garzón and Minas massifs. In that case, their deposition possibly took place in basins that were internal to the orogen, equivalent to assemblage 3 basins of Cawood et al. (2007).

## 7. Concluding remarks

(1) Zircon U–Pb geochronological data presented in this contribution comprise the first evidence for the existence of a Meso-Neoproterozoic orogenic belt in autochthonous NW Amazonia, buried underneath Meso-Cenozoic sedimentary sequences of the north Andean Putumayo foreland basin. Samples distributed among the Garzón and Minas massifs and the Putumayo foreland basin basement enclose an area of at least ∼50,000 km$^2$ that are underlain by crust reworked during Stenian–Tonian times, expanding the known extent of metamorphic events in northern South America caused by continental collisions during Rodinia assembly.

(2) Although many details about the geochemistry, petrology and medium- to low-temperature history of the proposed Putumayo Orogen are still to be discovered, the new geochronological data obtained allowed us to identify distinct phases of magmatism and metamorphism that comprise its evolution. We propose that igneous and sedimentary protoliths for the metamorphic units exposed in the cordilleran terranes formed during mid- to late Mesoproterozoic times in a parauthochtonous fringing-arc system to Amazonia, herein termed the Colombian–Oaxaquian arc, later to be accreted to the continental margin at ca. 1.02 Ga and trapped within Rodinian internal collisional orogens at 0.99 Ga.

(3) In addition to the differences in timing for the metamorphic events with respect to the Sunsás-Aguapei orogen, protolith ages for samples recovered from the basement of the Putumayo

basin suggest that there are marked differences with respect to the Mesoproterozoic evolution of the SW Amazonian margin, and we suggest that a orogenic belt correlative to the Rondonia – San Ignacio province may be lacking in northwestern South America.

(4) The consistency of the metamorphic ages obtained from the granulite-grade rocks in the cordilleran inliers and the foreland basement, all of them clustering around ca. 990 Ma, reinforce correlations between the Colombian and the Mexican inliers and add new links between these terranes and cratonic Amazonia. The metamorphic history proposed here for the Putumayo Orogen is more consistent with collisional interactions against the Sveconorwegian orogen of Baltica at the heart of Rodinia, as opposed to against the Laurentian Grenville province as has been commonly considered. It should be noted, however, that the new data presented in this study do not necessarily preclude correlations that suggest a long-lived connection between Amazonia and Baltica throughout the Mesoproterozoic and part of the Paleoproterozoic (the SAMBA connection, Johansson, 2009), but we chose a paleogeographic model which is in line with other paleomagnetic (D'Agrella-Filho et al., 2008; Tohver et al., 2002), thermochronologic (Tohver et al., 2006) and isotopic (Loewy et al., 2003; Tohver et al., 2004a) data that strongly support collisional interactions between Laurentia and Amazonia along the Sunsás margin during mid- to late Mesoproterozoic times.

(5) The existence of the Stenian–Tonian Putumayo Orogen in NW South America also has implications for peri-Gondwanan terrane tectonics after the breakup of Rodinia such as: (1) it provides a cratonic reference for evaluating the affinity of crustal blocks with inferred Amazonian ancestries. For example, it strengthens reconstructions that correlate the Proterozoic inliers of Mexico, Colombia and autochthonous Amazonia crust (discussed above), and (2) it provides a feasible source area for the origin of "Grenville-age" detritus found in terranes that may have interacted with northern Amazonia at some point in their history (e.g. Marañon complex, Cardona et al., 2009; Maya block, Weber et al., 2008; Avalonian terranes, Strachan et al., 2007; Ganderian-type massifs, Gutierrez-Alonso et al., 2005, Nance et al., 2007; Finnmarkian Nappes, Corfu et al., 2007, among others).

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2011.09.005.

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