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Chapter 6

The Putumayo Orogen of Amazonia: A Synthesis

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Abstract Meso– and Neoproterozoic paleogeographic reconstructions indicate that Amazonia played an important role in the assembly of Rodinia, and that its incorporation into this supercontinent led to continent–continent collision(s) with the Grenville Orogen of Laurentia and the Sveconorwegian Orogen of Baltica. The Sunsás–Aguapeí belt of SW Amazonia has traditionally been regarded as the geological evidence of such interactions, although it is becoming increasing clear that the metamorphic and tectonic history of this margin does not match the grade and timing that would be expected from interactions with the (near)–Adirondian margin of the Grenville, or with the Sveconorwegian margin of Fennoscandia. Massifs of amphibolite– to granulite–facies basement of late Proterozoic age have been known to exist in the northern Andes for many decades, but an autochthonous late Meso– to early Neoproterozoic orogenic belt in the western Guiana Shield that is un–remobilized by Andean tectonics, remained unknown. The recent discovery of such a belt, hidden under the Putumayo Foreland Basin, allowed, for the first time, to directly link the basement inliers of the Colombian Andes with the western Guiana Shield. Furthermore, the improved geochronologic database of some cordilleran inliers and Putumayo Basin basement, using high–spatial–resolution U–Pb methods, has permitted a more complete reconstruction of their evolution. This orogenic belt, which owing to its geographical location obtained the name 'Putumayo Orogen', holds key information about Amazonia's Meso– to early Neoproterozoic tectonics and is of great geodynamic significance in understanding the role played by this craton during amalgamation of the Rodinia supercontinent. This chapter provides a brief overview of the currently available geochronologic data and hypothesized tectonic evolution of the Putumayo Orogenic Cycle, with particular emphasis on its reconstruction within a dynamic framework of Laurentia–Amazonia–Baltica interactions in the second half of the Proterozoic Eon and during Rodinia supercontinent accretion.

Keywords: *Amazonia, Putumayo Orogen, Rodinia, Proterozoic tectonics, collisional orogenesis.*

Resumen Reconstrucciones paleogeográficas de los periodos Meso– y Neoproterozoico indican que Amazonia jugó un papel importante durante la amalgamación de Rodinia, y que su incorporación al núcleo de este supercontinente involucró colisiones continente–continente con el Orógeno Grenville de Laurentia y el Orógeno Sueco–Noruego de Báltica. El cinturón orogénico Sunsás–Aguapeí en la margen SW de Amazonia ha sido tradicionalmente considerado como la principal evidencia geológica de dichas interacciones; sin embargo, cada vez es más claro que la historia metamórfica y tectónica de este orógeno no coincide ni en grado metamórfico ni en edad con lo que se esperaría si este hubiese colisionado con la margen adiron-

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diana del Orógeno Grenville o la margen sueco–noruega de Fenoscandia. Aunque la ocurrencia de bloques de basamento con asociaciones metamórficas en facies anfibolita a granulita y edad proterozoica tardía en los Andes del norte es bien conocida desde hace varias décadas, la existencia de un cinturón orogénico autóctono mesoproterozoico tardío a neoproterozoico temprano en la margen occidental del Escudo de Guayana, el cual no haya sido retrabajado durante la Orogenia Andina, fue por mucho tiempo desconocida. El reciente descubrimiento de dicho cinturón orogénico bajo la cuña sedimentaria de la cuenca de antepaís del Putumayo ha permitido, por primera vez, una correlación directa entre los bloques de basamento expuestos en los Andes colombianos y la margen occidental del Escudo de Guayana. En adición a esto, los esfuerzos recientes realizados para expandir la base de datos geocronológica de los bloques de basamento cordilleranos y el basamento de la Cuenca del Putumayo, particularmente utilizando métodos de datación U–Pb de alta resolución espacial, han permitido realizar una reconstrucción más completa de su evolución tectónica. Este cinturón orogénico, que debido a su localización geográfica ha recibido el nombre de 'Orógeno Putumayo', contiene información crucial sobre la evolución tectónica meso– neoproterozoica temprana de Amazonia y es de gran importancia geodinámica para entender el rol de este gran bloque continental en la amalgamación del supercontinente Rodinia. El objetivo de este capítulo es proporcionar una breve síntesis de la información geocronológica existente y la evolución tectónica propuesta del Ciclo Orogénico Putumayo, haciendo énfasis particular en su reconstrucción dentro de un marco dinámico global de interacciones entre Laurentia, Amazonia y Báltica en la segunda mitad del Proterozoico y durante la acreción del supercontinente Rodinia.

Palabras clave: *Amazonia, Orógeno Putumayo, Rodinia, tectónica proterozoica, orogenia colisional.*

1. Introduction

The supercontinent cycle is thought to have exerted a major control on the development and preservation of Earth's crust through geologic time (e.g., Cawood et al., 2013; Hawkesworth et al., 2013), and is a first–order feature –and inevitable consequence– of terrestrial plate tectonics. In this cycle, continental land–masses break apart along continental rift zones, thereby opening ocean basins that separate previously adjoining continental fragments, and continental land–masses collide, thereby consuming ocean basins by subduction and resulting in pervasive deformation and high–temperature (± pressure) metamorphism of cratonic margins. Therefore, unraveling the timing, tempo, and physical conditions of these processes in ancient orogenic belts is the best–suited approach to quantitatively reconstruct the tectonic history of our planet, and to understand the chemical/structural development of Earth's lithosphere.

The Amazonian Craton is one of the largest Precambrian continental nuclei on Earth and a key piece of the supercontinent puzzle (Cordani et al., 2009). This cratonic block is thought to encompass two exposed shield areas (Figure 1), namely the Guiana Shield to the north of the Amazon Basin and the Central Brazil (or Guaporé) Shield south of the Amazon Basin. Besides preserving an extensive geological record of Proterozoic magmatism, arc development, and potentially also crustal growth (Cordani & Teixeira, 2007; Tassinari & Macambira, 1999), the craton known as Amazonia is thought to be one of the principal building blocks during the assembly of the Nuna/Columbia (e.g., Bispo–Santos et al., 2014) and Rodinia (e.g., Li et al., 2008) Proterozoic supercontinents. Although geological evicendes of Amazonia's incorporation in Rodinia are widely exposed in the eastern plains of Bolivia and in northwestern Brazil, within an orogenic belt in the Central Brazilian Shield known as the Sunsás–Aguapeí Orogen (Boger et al., 2005; Litherland & Bloomfield, 1981; Litherland et al., 1989; Sadowski & Bettencourt, 1996; Teixeira et al., 2010; among others), geological records of this period in the Guiana Shield have proven more elusive to detect. For many decades, the occurrence of Proterozoic basement inliers with upper amphibolite– to granulite–facies metamorphic assemblages has been known in the Andes of Colombia (Kroonenberg, 1982, and references therein), but their relationship with respect to the Guiana Shield remained enigmatic for a long time. Such cordilleran blocks, often grouped within the so–called Garzón–Santa Marta granulite belt (after Kroonenberg, 1982), include the Garzón and Santander Massifs in the Colombian Eastern Cordillera, Las Minas and San Lucas

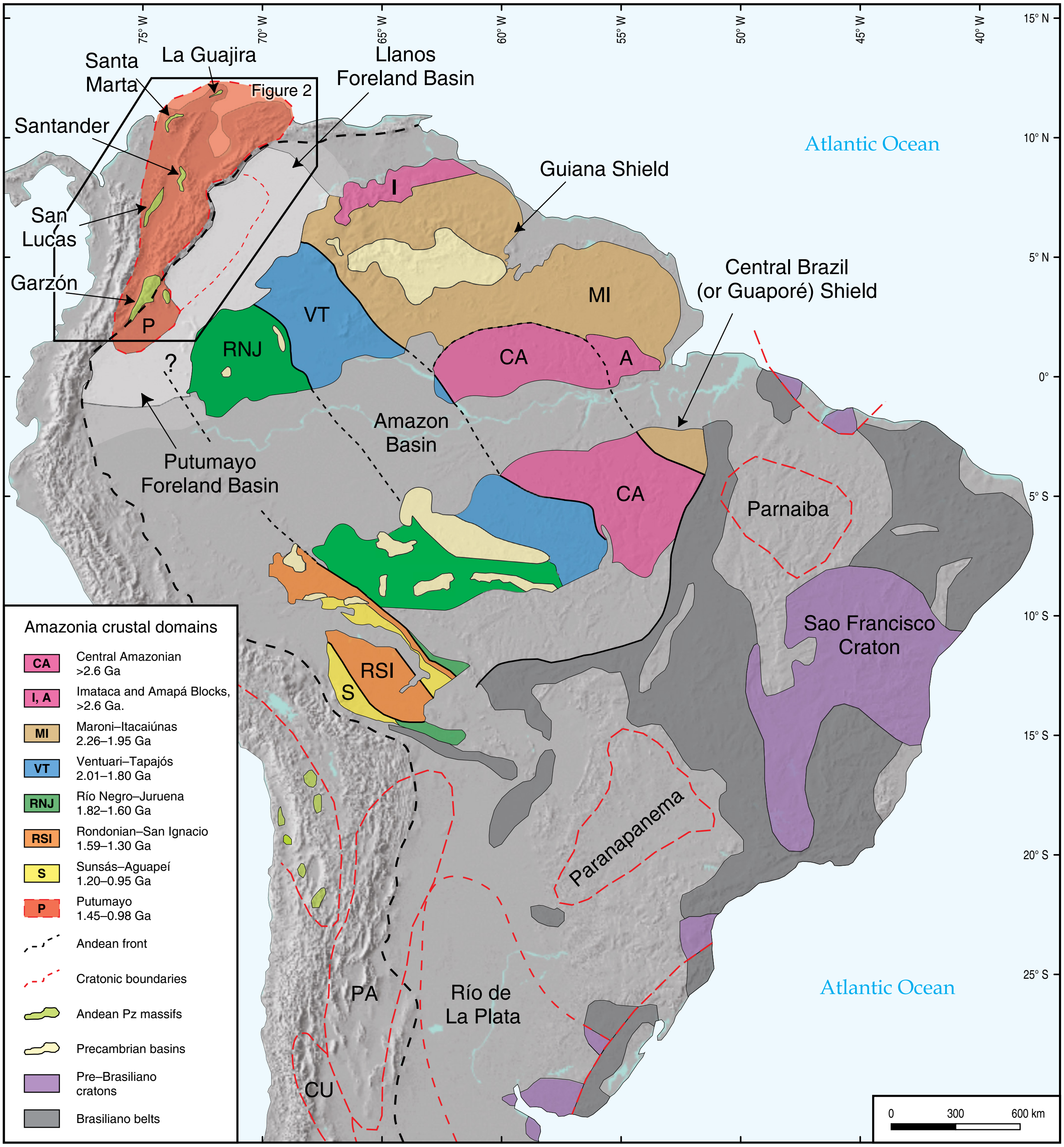


Figure 1. Simplified geo–tectonic map of South America, highlighting the approximate outline and terrane boundaries of the Amazonian Craton and the Guiana Shield. Adapted from Tassinari & Macambira (1999), Cordani & Teixeira (2007), Fuck et al. (2008), Ibañez–Mejia et al. (2015), and Teixeira et al. (2019). (CU) Cuyania Terrane, (PA) Pampia Terrane.

Massifs in the Central Cordillera, and the Sierra Nevada de Santa Marta and La Guajira Peninsula along the northernmost Colombia–Venezuela border (Figure 2).

It has also been recognized for several years that the geochronologic and geochemical record of units within the Garzón–Santa Marta granulite belt bear many similarities with the Proterozoic basement of south central Mexico, known as 'Oaxaquia' (Ortega–Gutiérrez et al., 1995). Mostly hidden underneath younger cover, Oaxaquia is exposed in various localities throughout Mexico including units known as the Novillo

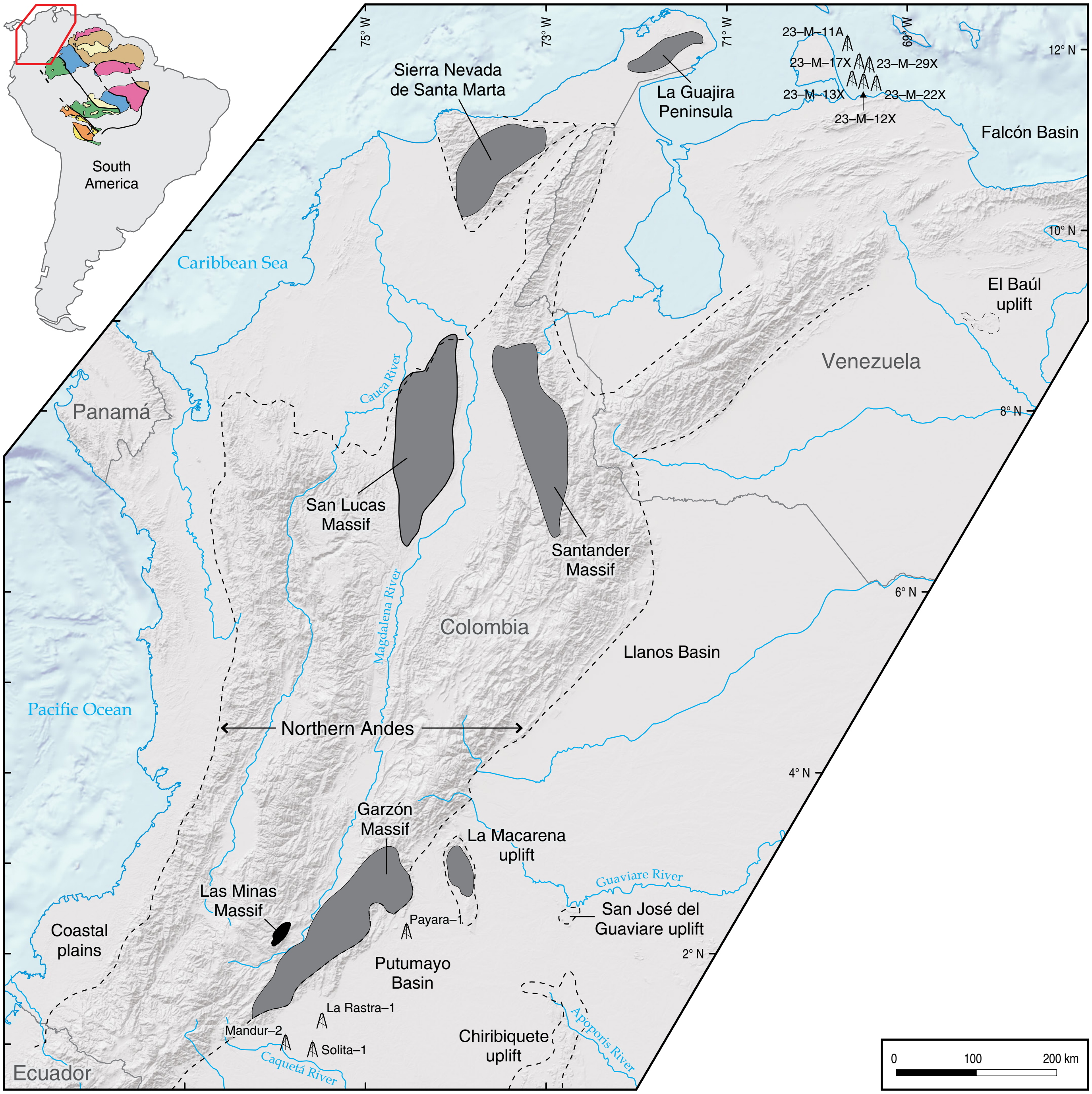


Figure 2. Simplified shaded relief image of NW South America showing the location of cordilleran basement inliers that form part of the Putumayo Orogen, and basement drilling cores in the Putumayo and Falcón Basins where late Meso– to early Neoproterozoic units have been dated using modern geochronologic methods. See Table 1 for references.

Gneiss, the Huiznopala Gneiss, the Guichicovi Complex, and the Oaxacan Complex (Ortega–Gutiérrez et al., 2018, and references therein). Based on Sm–Nd (Restrepo–Pace et al., 1997), Pb (Ruiz et al., 1999), and Lu–Hf (Weber et al., 2010) isotopic compositions, the strong geochemical resemblance between Oaxaquia and the Colombian cordilleran inliers has been well established over a decade. Nevertheless, a key part of the puzzle that was missing was a direct link to tie this now strongly dismembered 'Colombia/Oaxaquia' tectonic block back to its purported Amazonian ancestry. In 2011, dating of exploratory–borehole cores from the basement of the Putumayo Foreland Basin yielded ages similar to those found in the Garzón–Santa Marta granulite belt and Oaxaquia (Ibañez–Mejia et al., 2011), thus allowing linking these dismembered blocks (i.e., Colombia/Oaxaquia terrane) to the westernmost Guiana Shield and incorporating all these pieces into the definition of the 'Putumayo Orogen'. Since 2011, additional U–Pb, Sm–Nd, Lu–Hf, and O isotopic data from zircon and whole–rock samples have further strengthened the consanguinity of all blocks considered to form an integral part of, or be related to, the Putumayo Orogen (e.g., Baquero et al., 2015; Ibañez–Mejia et al., 2015, 2018; Solari et al., 2013; Weber & Schulze, 2014).

Although both the paleomagnetic and geochronologic datasets for Meso– and Neoproterozoic units in Oaxaquia and NW South America remain arguably very limited, the available geochronology/isotope geochemistry of the Putumayo Orogen, in concert with the existing Mesoproterozoic paleomagnetic poles available for Amazonia, are converging into a coherent tectonic picture for this time period (Cawood & Pisarevsky, 2017). This chapter presents a synthesis of the available geochronologic information for the Putumayo Orogen obtained using modern analytical methods, and their interpreted geologic significance within tectonic reconstructions at an orogen to cratonic scale. This reconstruction places particular emphasis on understanding this orogen within a continuously refining picture of Amazonia's role in Proterozoic paleogeography and the assembly of Rodinia, to elucidate possible tectonic correlations with the Grenville margin of Laurentia and/or the Sveconorwegian margin of Baltica. Nevertheless, successfully unraveling the geological history of continental collisions associated with Rodinia assembly, which are crucial for continuing to test and further enlighten plausible paleo–geographic and paleo–tectonic scenarios, will require continuous improvement of the geologic, geochronologic, petrologic, and paleomagnetic databases.

2. Summary of Available Geochronologic Data

The first geochronologic evidence for the occurrence of late Meso– to early Neoproterozoic orogenic events in NW South America date back to the seminal works of Pinson et al. (1962), MacDonald & Hurley (1969), Goldsmith et al. (1971), Tschanz et al. (1974), Alvarez & Cordani (1980), Alvarez (1981), and Priem et al. (1982, 1989). All these results, however, were obtained by means of K–Ar and Rb–Sr methods, which can be easily reset (totally or partially) by thermally–activated diffusion and/or fluid alteration even at moderate temperatures (Reiners et al., 2017). Therefore, although these results are important from an historical standpoint, they will not be considered further for the purposes of this chapter. The first zircon U–Pb results from the cordilleran basement inliers in Colombia were obtained by Restrepo–Pace et al. (1997), using the isotope dilution–thermal ionization mass spectrometry (ID–TIMS) method. Nevertheless, because of the complex growth history of zircon from the Garzón Massif, these bulk–crystal analyses yielded complex (i.e., mixed) results that prevent determining igneous protolith and/or metamorphic ages with accuracy.

Due to the textural complexity of zircon crystals in collisional orogens such as the Putumayo, where metamorphic overgrowths and/or sub–solidus recrystallization of inherited nuclei are commonplace (see Ibañez–Mejia et al., 2015 and references therein), this chapter only considers U–Pb dates obtained using spatially–resolved analytical techniques, such as secondary ion mass spectrometry (SIMS) or laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS). The zircon U–Pb geochronologic database for portions of the Putumayo Orogen identified to date in NW South America is summarized in Table 1. Note that, for the sake of brevity, Table 1 does not include the available geochronology from Oaxaquia; for this, the interested reader is pointed to the recent review of Ortega–Gutiérrez et al. (2018) and references therein. In chronologic order, the dataset presented here was compiled from the works of Cardona (2003), Cordani et al. (2005), Cardona et al. (2010), Ibañez–Mejia et al. (2011), Leal–Mejía (2011), Cuadros et al. (2014), Baquero et al. (2015), Ibañez–Mejia et al. (2015), Urbani et al. (2015), and van der Lelij et al. (2016). Only a handful of isochron dates obtained by the Sm–Nd and Lu–Hf methods are available for samples of the Putumayo Orogen, from the works of Cordani et al. (2005), Ordóñez–Carmona et al. (2006), and Ibañez–Mejia et al. (2018); these dates are also included in Table 1.

3. Mesoproterozoic Paleogeography and Amazonia in Rodinia

Paleogeographic reconstructions of the Proterozoic Earth commonly rely on one or several of three key sources of information: (1) robust paleomagnetic data (e.g., Evans, 2013; Pisarevsky et al., 2014), which can be used to infer the paleo–latitude of sample–sets/terranes at the time of magnetic–remanence blocking; (2) geological matching of orogenic belts, magmatic arcs, and/or basins across once adjoining cratons or crustal blocks (e.g., Dalziel, 1991; Hoffman, 1991); and/or (3) matching of mafic dike swarms or other large igneous province (LIP) features (e.g., Bleeker & Ernst, 2006; Ernst et al., 2013). Paleogeographic solutions drawn from applying each of these lines of evidence by itself can be non–unique, but solutions that take into consideration the broadest spectrum of information are more likely to approach an accurate picture (Li et al., 2008).

Laurentia (North American Craton), Baltica (East European Craton), and Amazonia (northern South American Craton) are three key Precambrian crustal nuclei thought to form the core of Rodinia (Figure 3), and their most accepted positions within the fully assembled supercontinent at ca. 1.00–0.95 Ga are shown in Figure 3a. This configuration, which remains similar to the earliest reconstructions of the late Proterozoic supercontinent now known as Rodinia (e.g., Bond et al., 1984; Hoffman,

Table 1. Compilation of published geochronologic data from the Putumayo Orogen using modern U–Pb, Sm–Nd, and Lu–Hf methods.

Sample name	Latitude N	Longitude W	Unit	Rock type	Mean	±2σ	Event	Method	Reference
				Putumayo Basin basement					
Caimán–3 (Leuco)	0° 45' 13.6"	76° 9' 45.4"	Putumayo Basin well	Leucogranite	952	± 19	Ign.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011)
Caimán–3 (Metased)	0° 45' 13.6"	76° 9' 45.4"	Putumayo Basin well	Metased. migmatite	989	± 11	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011)
Payara–1	2° 7' 31.3"	74° 33' 35.9"	Putumayo Basin well	Metaign. migmatite	987	± 17	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
					1606	± 6	Ign.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
Mandur–2 (Leuco)	0° 55' 24.5"	75° 52' 34.1"	Putumayo Basin well	Syenogranite	1017	± 4	Ign.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
Mandur–2 (Melano)	0° 55' 24.5"	75° 52' 34.1"	Putumayo Basin well	Migmat. amphibolite	1019	± 8	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
					1592	± 8	Ign.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
Solita–1	0° 52' 28.6"	75° 37' 21.3"	Putumayo Basin well	Metased. migmatite	1046	± 23	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011)
La Rastra–1	1° 9' 58"	75° 30' 13"	Putumayo Basin well	Metased. migmatite	1007.0	± 2.9	Cool	Sm–Nd isochron	Ibañez–Mejia et al. (2018)
					1070.8	± 5.6		Lu–Hf isochron*	Ibañez–Mejia et al. (2018)
				Falcón Basin basement in La Vela Bay					
23–M–22X–1	11° 34' 30"	69° 31' 26.4"	Falcón Basin well	Metawacke	984.8	± 6.7	Met.	U–Pb, SHRIMP	Baquero et al. (2015)
					DZ	≥1029	Sed.	U–Pb, SHRIMP	Baquero et al. (2015)
23–M–22X–3	11° 34' 30"	69° 31' 26.4"	Falcón Basin well	Metapelite	981	± 10	Met.	U–Pb, SHRIMP	Baquero et al. (2015)
					DZ	≥1044	Sed.	U–Pb, SHRIMP	Baquero et al. (2015)
23–M–22X–4	11° 34' 30"	69° 31' 26.4"	Falcón Basin well	Mafic granulite	967	± 8	Met.	U–Pb, SHRIMP	Baquero et al. (2015)
					1034	± 12	Ign.	U–Pb, SHRIMP	Baquero et al. (2015)
				Cordilleran inliers–Colombian Central and Eastern Cordilleras					
PCM–1105	7° 17' 57.8"	72° 53' 17.87"	Bucaramanga Gneiss	Biotite gneiss	DZ	≥864	Sed.	U–Pb, SHRIMP	Cordani et al. (2005)
CC–1	6° 29' 38"	74° 46' 8.71"	Nus Gneiss	Bt–Sill gneiss	DZ	≥969	Sed.	U–Pb, SHRIMP	Cardona (2003)
CB–006	2° 13' 26.5"	75° 50' 22"	Zancudo Migmatites	Metased. migmatite	972	± 12	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
MIVS–26	2° 3' 19.2"	75° 42' 47.6"	Guapotón Gneiss	Augen–gneiss	990	± 8	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
					1135	± 6	Ign.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
MIVS–41	2° 13' 34"	75° 50' 30.3"	Las Minas Gneiss	Augen–gneiss	990	± 7	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
					1325	± 5	Ign.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
MIVS–11	2° 9' 33.4"	75° 35' 37"	El Vergel Granulites	Felsic granulite	992	± 5	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011)
CB–002	2° 7' 37.7"	75° 37' 41.9"	El Vergel Granulites	Felsic paragneiss	992	± 8	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011)
MIVS–12	2° 9' 20.7"	75° 35' 27.4"	El Vergel Granulites	Felsic granulite	997	± 17	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2015)
V–198	1° 49' 14.6"	75° 47' 12.6"	Guapotón Gneiss	Augen–gneiss	1000	± 25	Met.	U–Pb, SHRIMP	Cordani et al. (2005)
					1158	± 22	Ign.	U–Pb, SHRIMP	Cordani et al. (2005)
MIVS–16A	2° 8' 11.7"	75° 36' 55.7"	El Vergel Granulites	Grt–bearing leucosome	1001	± 12	Met.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2015)
MIVS–15A	2° 8' 28.2"	75° 36' 44.7"	El Vergel Granulites	Granitic pegmatite	1022.3	± 8.8	Ign.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2015)
MIVS–13	2° 8' 9"	75° 35' 22.7"	El Vergel Granulites	Felsic paragneiss	DZ	≥1000	Sed.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2015)
MIVS–37A	2° 15' 37.3"	75° 49' 49.9"	Pital Migmatites	Metased. migmatite	DZ	≥1005	Sed.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011)
Gr–29	1° 45' 50.6"	75° 44' 8.68"	El Vergel Granulites	Enderbite	DZ	≥1005	Sed.	U–Pb, SHRIMP	Cordani et al. (2005)
Gr–15	1° 32' 31"	75° 26' 18.43"	Florencia Migmatites	Leucosome	1015	± 8	Met.	U–Pb, SHRIMP	Cordani et al. (2005)
10VDL61	7° 9' 59"	73° 5' 17"	Río Suratá granodiorite	Enclaves	1018	± 9	Ign.?	U–Pb, LA–ICP–MS	van der Lelij et al. (2016)
WR–219	7° 44' 25"	74° 29' 2"	Guamoco orthogneiss	Qz–Fsp–Bt gneiss	1048	± 24	Met.	U–Pb, LA–ICP–MS	Leal–Mejía (2011)
					1280	± 36	Ign.	U–Pb, LA–ICP–MS	Leal–Mejía (2011)
Macarena–2	3° 1' 45"	73° 52' 13.5"	La Macarena Gneiss	Felsic mylonitic gneiss	1461	± 10	Ign.	U–Pb, LA–ICP–MS	Ibañez–Mejia et al. (2011, 2015)
017–05	8° 34' 6.3"	74° 5' 44.98"	San Lucas Gneiss	Granitic gneiss	1502	± 18	Ign.	U–Pb, LA–ICP–MS	Cuadros et al. (2014)
020–03	8° 40' 25.2"	74° 5' 48.85"	San Lucas Gneiss	Metamonzogabbro	1507	± 6	Ign.	U–Pb, LA–ICP–MS	Cuadros et al. (2014)
PGG–18	8° 40' 45.6"	74° 5' 20.92"	San Lucas Gneiss	Granitic gneiss	1508	± 15	Ign.	U–Pb, LA–ICP–MS	Cuadros et al. (2014)
					1527	± 10	Ign.	U–Pb, LA–ICP–MS	Cuadros et al. (2014)

Table 1. Compilation of published geochronologic data from the Putumayo Orogen using modern U–Pb, Sm–Nd, and Lu–Hf methods (*continued*).

Sample name	Latitude N	Longitude W	Unit	Rock type	Mean	±2σ	Event	Method	Reference
Cordilleran inliers–Colombian Central and Eastern Cordilleras									
022–01	8° 39’ 5”	74° 5’ 39.4”	San Lucas Gneiss	Granitic gneiss	1527	± 14	Ign.	U–Pb, LA–ICP–MS	Cuadros et al. (2014)
020–02	8° 40’ 25.2”	74° 5’ 48.85”	San Lucas Gneiss	Metamonzogabbro	1530	± 11	Ign.	U–Pb, LA–ICP–MS	Cuadros et al. (2014)
D–982	2° 9’ 35.7”	75° 29’ 47”	El Vergel Granulites	Garnet gneiss	925	± 7	Cool	Sm–Nd isochron**	Cordani et al. (2005)
V–332	1° 46’ 56.9”	75° 46’ 2.34”	El Vergel Granulites	Charnockite	935	± 5	Cool	Sm–Nd isochron**	Cordani et al. (2005)
C–32	1° 42’ 49.8”	75° 18’ 30.94”	Florencia Migmatites	Paragneiss	990	± 8	Cool	Sm–Nd isochron**	Cordani et al. (2005)
Gr–15p	1° 32’ 31.7”	75° 26’ 18.43”	Florencia Migmatites	Paragneiss	1034	± 6	Cool	Sm–Nd isochron**	Cordani et al. (2005)
Cordilleran inliers–Sierra Nevada de Santa Marta									
A–49	11° 12’ 24.3”	73° 12’ 37.16”	Dibulla Gneiss	Biotite gneiss	991	± 12	Met.	U–Pb, SHRIMP	Cordani et al. (2005)
					1374	± 13	Ign.	U–Pb, SHRIMP	Cordani et al. (2005)
JRG–20–96	N.R.	N.R.	Los Mangos Granulites	Paragneiss	991	± 12	Met.	U–Pb, LA–ICP–MS	Cardona et al. (2010)
GRM–10	N.R.	N.R.	Los Mangos Granulites	Garnet gneiss	971	± 8	Cool	Sm–Nd isochron**	Ordóñez–Carmona et al. (2006)
Cordilleran inliers–La Guajira Peninsula and Venezuelan Cordillera de La Costa									
Jojon–1	11° 52’ 13.92”	72° 1’ 26.58”	Jojoncito Gneiss	Qz–Fsp gneiss	916	± 19	Met.?	U–Pb, SHRIMP	Cordani et al. (2005)
Ya–235B	N.R.	N.R.	El Guayabo Complex	Charnockite	986	± 5	Met.	U–Pb, SHRIMP	Urbani et al. (2015)
					1167	± 7	Ign.	U–Pb, SHRIMP	Urbani et al. (2015)
08VDL11	8° 41’ 41”	70° 53’ 31”	Micarache orthogneiss	Sillimanite gneiss	1009	± 7	Ign.?	U–Pb, LA–ICP–MS	van der Lelij et al. (2016)
Zu–6	11° 40’ 60”	71° 46’ 60”	Atuschon Gneiss	Qz–Fsp gneiss	1028.7	± 4.4	Met.	U–Pb, SHRIMP	Baquero et al. (2015)

*Isochron affected by Lu–Hf diffusive decoupling–see reference for details.

**2–point isochrons. Rarely reliable.

N.R.: Sampling coordinates not reported.

Cool: Cooling age; DZ: Detrital zircon; Ign: Age of igneous crystallization; Met: Age of metamorphism; Sed: Maximum age of sedimentation from DZ U–Pb results.

1991), has stood the test of time and to date remains the most plausible and widely–accepted reconstruction (Cawood & Pisarevski, 2017; D’Agrella–Filho et al., 2016a; Li et al., 2008; Weil et al., 1998). Some key aspects of this reconstruction, and the relative role of these three major cratons just prior to and during the assembly of Rodinia, are summarized below.

D’Agrella–Filho et al. (2016a) presented a recent up–to–date discussion of the paleomagnetic poles available for Amazonia, and interested readers are referred to their work for an in–depth discussion. In brief, robust paleo–magnetic constraints for the position of Amazonia within Rodinia come from two key poles in NW Brazil: (1) The Nova Floresta pole (Tohver et al., 2002), dated at ca. 1.2 Ga; and (2) the Fortuna pole of the Aguapeí Group (D’Agrella–Filho et al., 2008), dated at 1149 ± 7 Ma. Both of these poles are consistent with SW Amazonia as being positioned near the Grenville margin of North America during the Stenian, therefore confirming previous reconstructions (e.g., Hoffman, 1991; Weil et al., 1998) in which Amazonia’s position was inferred from other lines of geological evidence since no paleomagnetic information was then available. The relative positions of the Nova Floresta and Fortuna poles indicate that an oblique collision between Amazonia and Laurentia took place in the Mesoproterozoic (Cordani et al., 2009; D’Agrella–Filho et al., 2016a; Tohver et al., 2002, 2004), and these results have been used to infer that collision first took place between the Llano and Sunsás–Aguapei margins of Laurentia and Amazonia, respectively (Figure 3b), followed by sinistral strike–slip displacement between the two cratons (Figure 3c) until these attained their final Rodinia configuration (Figure 3a).

The relative position of Baltica within Rodinia and with respect to Laurentia during the second half of the Mesoproterozoic, as inferred from paleomagnetic data, is well established (Li

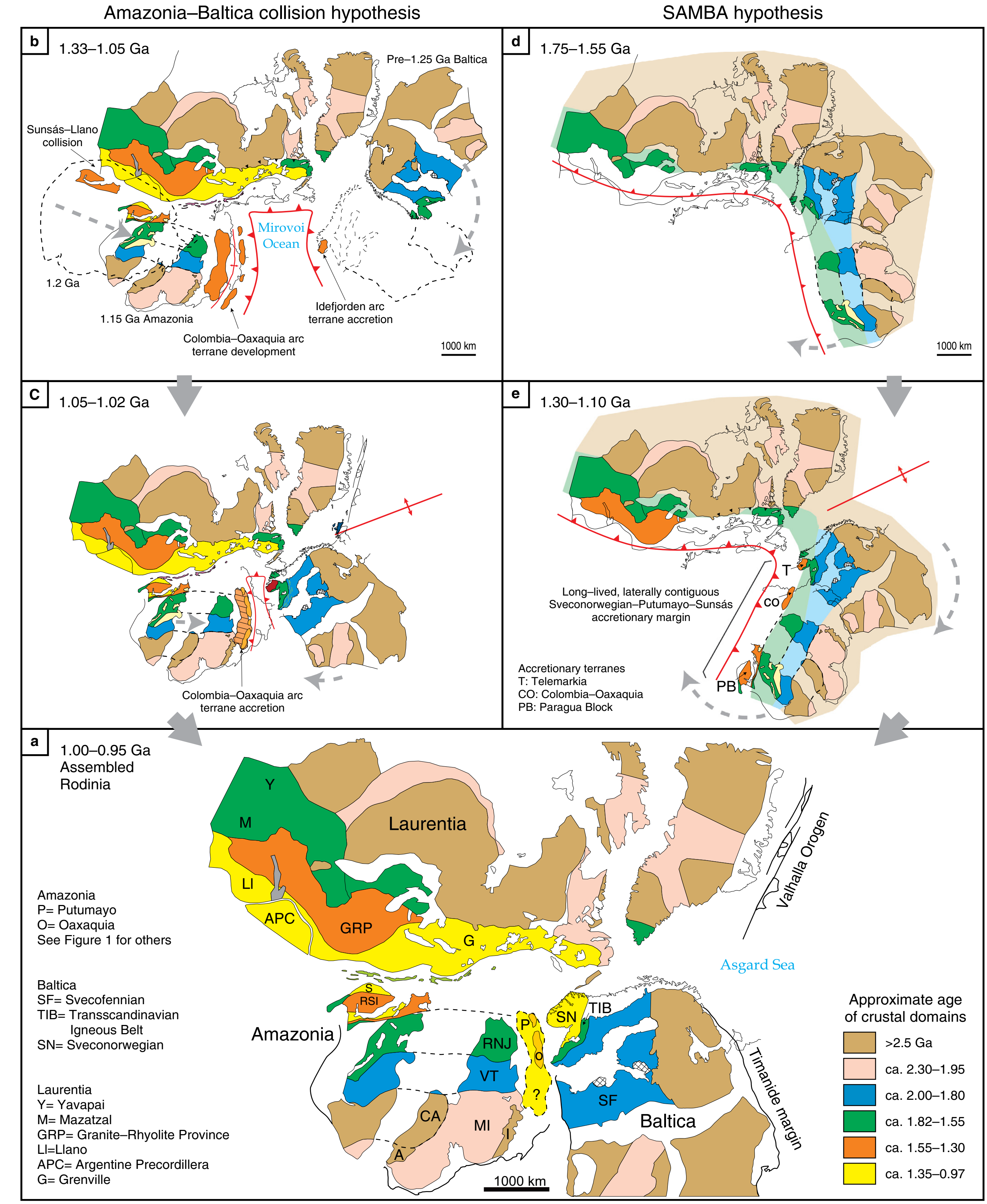


Figure 3. Two possible tectonic reconstructions for Laurentia–Amazonia–Baltica interactions in the Mesoproterozoic leading to the assembly of Rodinia. Panel **(a)** show the most widely accepted configuration of these three cratons within Rodinia. Panels **(b)** and **(c)** illustrate the Amazonia–Baltica collision reconstruction (preferred model discussed in this chapter), while panels **(d)** and **(e)** illustrate two snapshots of the SAMBA reconstruction (no Amazonia–Baltica collision). See text for details and references.

et al., 2008; Pisarevsky et al., 2014). Paleomagnetic and geologic data indicate that, prior to ca. 1265 Ma, the northern margin of Baltica lay adjacent to modern Eastern Greenland (Figure 3b; Cawood and Pisarevsky, 2006; Cawood et al., 2010), and the available poles between ca. 1265 and 1000 Ma indicate that northern Baltica rifted away from Laurentia during the Mesoproterozoic, causing a clockwise oroclinal rotation with NW Fennoscandia as the approximate fulcrum (Figure 3c). The geological expression of this rotation is recorded in the opening of the Asgard Sea and initiation of the Valhalla Orogen in NE Laurentia (Cawood et al., 2010). At approximately 1 Ga, Baltica reached its final position within Rodinia (Figure 3a), with the Sveconorwegian margin laterally adjacent to the Grenville Province and directly facing Amazonia.

These paleomagnetic reconstructions for the incorporation of Amazonia and Baltica within Rodinia were used by Bogdanova et al. (2008) to suggest that the Stenian – Tonian contractional deformation of the Sveconorwegian margin was a result of collisional interactions with Amazonia. This 'oblique collision' model, suggested by the limited paleomagnetic database from Amazonia, results in several other important (and testable) geological predictions such as: (1) An early collision between Laurentia and Amazonia should have occurred prior to final Rodinia assembly (e.g., Tohver et al., 2002); (2) an ocean basin would have been closed between Amazonia and Baltica as they approached their final positions within Rodinia, implying that both (or at least one) of their leading margins experienced a long history of subduction–driven accretionary tectonics; (3) closure of an ocean basin would culminate with continental collision between Amazonia and Baltica, so their margins would exhibit a congruent collisional tectono–metamorphic history; and (4) if correct, this scenario would lead to the development of two separate orogenic belts in Amazonia, reflecting its two–stage collisional incorporation into Rodinia by early interactions with Laurentia (Sunsás–Aguapeí) and later by collision with Baltica (Putumayo–Oaxaquia).

An alternative model for Laurentia, Baltica, and Amazonia interactions leading to Rodinia assembly postulates that Amazonia and Baltica never collided during the Meso– Neoproterozoic, but instead that they behaved coherently as a single tectonic plate (along with West Africa) since at least the Paleoproterozoic and throughout Meso– Neoproterozoic supercontinent assembly; this idea is known as the SAMBA (South America Baltica) connection (Johansson, 2009). In this model, the (modern) northern margin of Amazonia and southern margin of Baltica were purportedly connected from at least 2 Ga onwards (Johansson, 2009), and evolution of the joint Ventuari–Tapajós (Am) – Svecoffenian (Ba) and Río Negro–Juruena (Am) – Gothian/Transscandinavian Igneous Belt (Ba) provinces would have taken place along a common, long–lived accretionary margin (Figure 3d). At approximately 1.3 Ga, rifting would have initiated along the Laurentia–Baltica margin, opening the Asgard Sea –thus satisfying the clockwise rotation of Baltica constrained from robust paleomagnetic data (Cawood et al., 2010)– while keeping Baltica–Amazonia as a coherent plate (Figure 3e). This rotation would have driven compressional accretionary tectonics along the western Amazonian margin, driving the docking of para–autochthonous Amazonian crust such as the Paragua Block (Figure 3e; Johansson, 2009) and culminating with continental collision along the Sunsás–Grenville margin. Although appealing for its simplicity, the SAMBA model has multiple issues, namely: (1) It does not explain the disparate tectonometamorphic history of the Sunsás and Putumayo Orogens of Amazonia (Ibañez–Mejia et al., 2011); (2) it violates paleomagnetic constraints on the location of Amazonia during the Stenian placed by the Nova Floresta and Fortuna Formation poles (D'Agrella–Filho et al., 2016a); and (3) it also violates early Mesoproterozoic poles for Baltica and Amazonia at ca. 1.42 Ga (i.e., Indiavaí; D'Agrella–Filho et al., 2012 and Nova Guarita; Bispo–Santos et al., 2012), which indicate significant distance between Amazonia and Baltica during the Calymmian following the break–up of Nuna/Columbia.

Considering the current paleomagnetic and geochronologic databases, the only scenario under which both the SAMBA and the Amazonia–Baltica collision hypotheses could be simultaneously satisfied is if the northern portion of the Amazonian Craton (i.e., Guiana Shield) and the southern portion (i.e., Central Brazil Shield) did not behave as a single tectonic block through most of the Mesoproterozoic. Because both the Nova Floresta and Fortuna Formation poles were obtained from localities in NW Brazil, strictly speaking these results only constrain the Stenian paleolatitude of the Central Brazil Shield. Therefore, one could argue that no paleomagnetic data yet exist for determining the Stenian paleolatitude of the Guiana Shield. Under this scenario, it is at least permissible to consider that the two shields could have had different paleogeographic histories prior to the assembly of Rodinia, with the Guiana Shield attached to Baltica and co–evolving with it in a SAMBA–like configuration, while the Central Brazilian Shield was colliding obliquely with Laurentia along the Sunsás–Aguapeí and Llano margins. This scenario has some partial support from the dissimilar paleolatitudes of the coeval 1.79 Ga Colider (Central Brazilian shield; Bispo–Santos et al., 2008) and Avanavero (Guiana; Bispo–Santos et al., 2014; Reis et al., 2013) poles, and the seemingly contrasting geologic histories of the Guiana and Central Brazilian Shields in the early– to mid–Mesoproterozoic (e.g., lack of a clear Rondonia–San Ignacio–like province in the Guiana Shield; Ibañez–Mejia et al., 2011, 2015; see also chapter 4 in this volume by Ibañez–Mejia & Cordani, 2020). This alternative, however, would make the Proterozoic tectonic evolution of 'Amazonia' far more complex than currently accepted, e.g., by requiring a hitherto unknown Mesoproterozoic collisional belt between the Guiana and Central Brazil Shields to be present, and is thus beyond the scope of this chapter. Nevertheless, future studies should be aimed at obtaining robust Mesoproterozoic paleomagnetic records for the Guiana Shield to independently constrain its paleolatitude and compare them with the record from the Central Brazil Shield.

Following the discussion above, the SAMBA model as proposed by Johansson (2009) is considered here to be unsupported, and instead it is argued that the Amazonia–Baltica collision (Figure 3b, 3c) remains a more feasible dynamic model to explain the evolution of the Putumayo Orogen (see discussion below) as well as all the existing paleomagnetic data (Cawood & Pisarevsky, 2017; D'Agrella–Filho et al., 2016a). Consequently, the rest of this chapter will be developed using the Amazonia–Baltica collision model (Figure 3a–c) as the global dynamic framework leading to Rodinia assembly.

4. The Putumayo Orogenic Cycle and its Geologic Components

Orogenic belts are comprised by several recognizable tectonic–stratigraphic elements, each one of key importance to decipher the history of mountain building and, in collisional settings, their pre–collisional architecture. The existing geochronologic data from different units of the Putumayo Orogen can be used for reconstructing portions of its Mesoproterozoic tectonic history and place this margin of Amazonia within a global tectonic framework prior to, and during, its collisional incorporation into Rodinia. In the sections below, a reconstruction of the Putumayo Orogen is presented, based on interpretations of the available isotopic and geochronologic data. As will be shown below, given the similar geologic histories of Oaxaquia and fragments of the Putumayo Orogen preserved in NW South America, Oaxaquia will be treated as an integral part of the Putumayo Orogen throughout this chapter. Figure 4 shows a series of schematic cross–sections summarizing the tectonic history of the Putumayo Orogen as currently understood and its interactions with the Sveconorwegian margin of Baltica. The time snapshots in these cross sections will be used as a guide for the discussion below. For more details about different aspects of the interpretations below, the interested reader is referred to the original works of Cardona et al. (2010), Weber et al. (2010), Ibañez–Mejia et al. (2011, 2015, 2018), Solari et al. (2013), Weber & Schultze (2014), and references therein. The tectonic evolution of Baltica in Figure 4 is based on data and reconstructions by Bogdanova et al. (2008), Bingen et al. (2008a), Cawood & Pisarevsky (2017), and Bingen & Viola (2018).

4.1. Pre–Putumayo Architecture (>1.46 Ga)

The westernmost exposed extension of the Guiana Shield in South America is comprised of late Paleo– and early Mesoproterozoic basement, presumably belonging to the Río Negro–Juruena (RNJ) Province of the Amazonian Craton (see Chapter 4 in this volume by Ibañez–Mejia & Cordani, 2020). Mesoproterozoic units dated in the exposed portions of the Guiana Shield in eastern Colombia consist of ca. 1.60 to 1.50 Ga deformed biotite granites, and ca. 1.4 Ga anorogenic granites associated with the Parguaza Intrusive Complex (Ibañez–Mejia & Cordani, 2020). Due to the still limited basement–core repository from the north Andean foreland basins, it remains uncertain whether basement of this age continues all the way to the Andean deformation front underneath the Llanos Basin. Nevertheless, two basement cores from the Putumayo Foreland Basin, namely the Payara–1 and Mandur–2 (Figure 2), have retrieved orthogneisses with protolith ages of 1606 ± 6 Ma and 1592 ± 8 Ma, respectively (Table 1; Ibañez–Mejia et al., 2011, 2015). Consequently, the current geochronologic dataset allows inferring that RNJ–type basement extends under the Putumayo Foreland Basin, implying that: (1) the Putumayo Orogen was initially developed in juxtaposition to, and thus likely reworked, Mesoproterozoic basement of the RNJ (Figure 4a), and (2) a Rondonian–San Ignacio (RSI)–type province, as exposed along the western Central Brazilian Shield (Bettencourt et al., 2010) appears to be absent in the Guiana Shield (see Ibañez–Mejia & Cordani, 2020 for additional discussion). Further evidence for the reworking of Mesoproterozoic basement of possible RNJ affinity within the Putumayo Orogen is provided by orthogneisses exposed in the San Lucas Massif (Figure 2), which yield protolith crystallization ages between 1.53 and 1.50 Ga and metamorphic overgrowths at ca. 1.01–0.99 Ga (Cuadros et al. 2014).

4.2. Proto–Putumayo and Proto–Oaxaquia Phase (ca. 1.46 to 1.33 Ga)

The precise timing of initiation of the Putumayo Orogenic Cycle, which began as an accretionary orogen along a convergent plate margin, remains uncertain. This is due to the limited exposures along the westernmost Guiana Shield (i.e., basement remains buried underneath the thick Putumayo and Llanos Foreland Basins; see Figure 1 and Ibañez–Mejia & Cordani, 2020) and the still limited geochronologic/geochemical database. Within the cordilleran inliers of the northern Andes, at least within those that contain an extensive record of Ectasian to Stenian arc building, the oldest igneous protoliths dated thus far yielded an age of 1461 ± 10 Ma and correspond to mylonitic orthogneisses of the serranía de La Macarena (Ibañez–Mejia et al., 2011). Based on zircon $^{176}Hf/^{177}Hf$ and $\delta^{18}O$ data, Ibañez–Mejia et al. (2015) suggested that the igneous protolith of La Macarena gneisses may correspond to an early pulse of magmatism associated with the nascent arc of the Putumayo Orogen. The relatively low initial $^{176}Hf/^{177}Hf$ composition of La Macarena gneiss protolith, which yields an $\varepsilon Hf_{(t)} = +0.6 \pm 2.2$, indicates significant reworking of crustal components (Figure 5a; Table 2; Ibañez–Mejia et al., 2015). Furthermore, the 'heavy' oxygen isotopic composition of these zircons, with

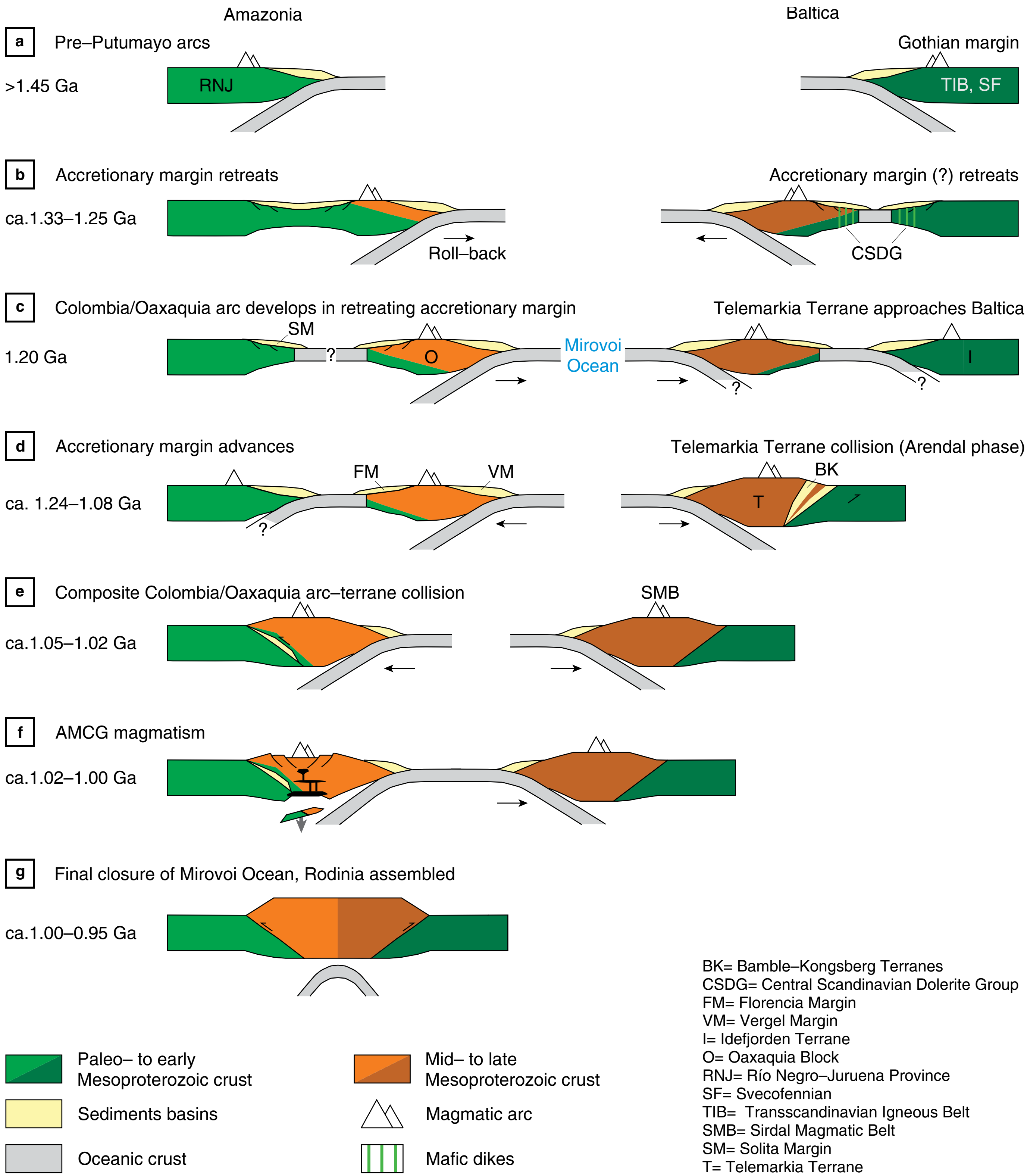
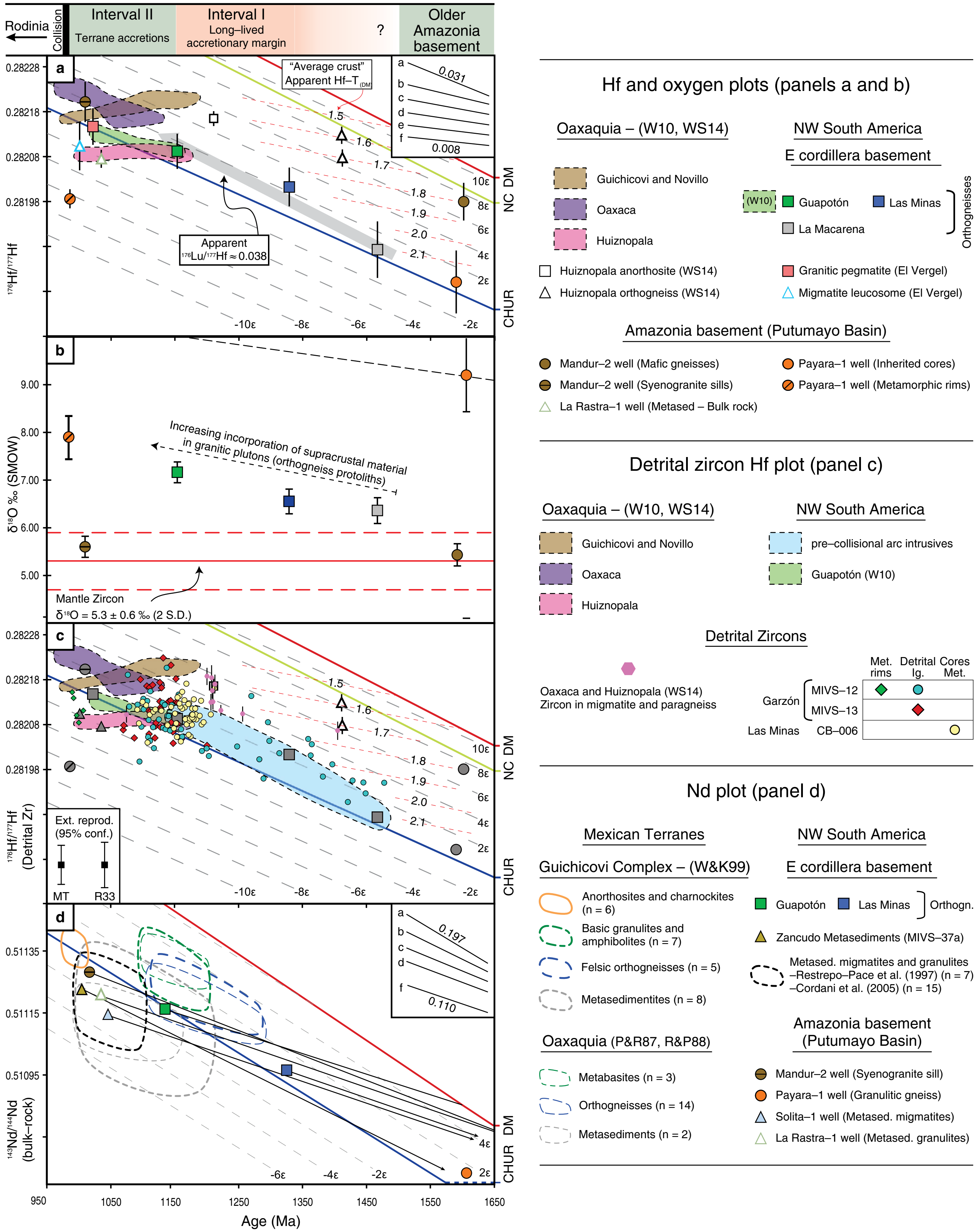


Figure 4. Schematic orogen–scale cross–sections illustrating the tectonic history of the Putumayo Orogen of Amazonia as discussed throughout the text. The tectonic evolution of Baltica is based on Bogdanova et al. (2008), Bingen et al. (2008a), Cawood & Pisarevsky (2017), and Bingen & Viola (2018).



Rodinia
Collision
Interval II
Terrane accretions
Interval I
Long–lived accretionary margin
?
Older Amazonia basement
a
"Average crust" Apparent Hf–T(DM)
Apparent 176Lu/177Hf ≈ 0.038
0.031
0.008
1.5
1.6
1.7
1.8
1.9
2.0
2.1
10ε
8ε
6ε
4ε
2ε
-10ε
-8ε
-6ε
-4ε
-2ε
NC DM
CHUR
176Hf/177Hf
0.28228
0.28218
0.28208
0.28198
b
Increasing incorporation of supracrustal material in granitic plutons (orthogneiss protoliths)
Mantle Zircon
δ18O = 5.3 ± 0.6 ‰ (2 S.D.)
δ18O ‰ (SMOW)
9.00
8.00
7.00
6.00
5.00
c
Ext. reprod. (95% conf.)
MT
R33
176Hf/177Hf (Detrital Zr)
d
0.197
0.110
-6ε
-4ε
-2ε
143Nd/144Nd (bulk–rock)
0.51135
0.51115
0.51095
950
1050
1150
1250
1350
1450
1550
1650
Age (Ma)
Hf and oxygen plots (panels a and b)
Oaxaquia – (W10, WS14)
Guichicovi and Novillo
Oaxaca
Huiznopala
NW South America
E cordillera basement
(W10)
Guapotón
Las Minas
La Macarena
Orthogneisses
Huiznopala anorthosite (WS14)
Huiznopala orthogneiss (WS14)
Granitic pegmatite (El Vergel)
Migmatite leucosome (El Vergel)
Amazonia basement (Putumayo Basin)
Mandur–2 well (Mafic gneisses)
Mandur–2 well (Syenogranite sills)
La Rastra–1 well (Metased – Bulk rock)
Payara–1 well (Inherited cores)
Payara–1 well (Metamorphic rims)
Detrital zircon Hf plot (panel c)
Oaxaquia – (W10, WS14)
Guichicovi and Novillo
Oaxaca
Huiznopala
NW South America
pre–collisional arc intrusives
Guapotón (W10)
Detrital Zircons
Oaxaca and Huiznopala (WS14) Zircon in migmatite and paragneiss
Met. rims
Detrital Cores Ig. Met.
Garzón
MIVS–12
MIVS–13
Las Minas
CB–006
Nd plot (panel d)
Mexican Terranes
Guichicovi Complex – (W&K99)
Anorthosites and charnockites (n = 6)
Basic granulites and amphibolites (n = 7)
Felsic orthogneisses (n = 5)
Metasedimentites (n = 8)
Oaxaquia (P&R87, R&P88)
Metabasites (n = 3)
Orthogneisses (n = 14)
Metasediments (n = 2)
NW South America
E cordillera basement
Guapotón
Las Minas
Orthogn.
Zancudo Metasediments (MIVS–37a)
Metased. migmatites and granulites –Restrepo–Pace et al. (1997) (n = 7) –Cordani et al. (2005) (n = 15)
Amazonia basement (Putumayo Basin)
Mandur–2 well (Syenogranite sill)
Payara–1 well (Granulitic gneiss)
Solita–1 well (Metased. migmatites)
La Rastra–1 well (Metased. granulites)

←

Figure 5. U–Pb age, Lu–Hf, Sm–Nd, and O isotopic data from basement igneous, metaigneous, and metasedimentary rocks of the Putumayo Orogen. **(a)** Age–corrected $^{176}Hf/^{177}Hf$ vs. U–Pb age for granitoids, orthogneisses, and migmatites. εHf values plotted with respect to CHUR (Bouvier et al., 2008). Red dotted lines are apparent iso–T_{DM} contours, showing values for the apparent model ages calculated by assuming a reservoir Lu/Hf composition of 'average crust' (i.e., $^{176}Lu/^{177}Hf$ = 0.015; Condie et al., 2005). Other reservoir slopes shown in inset are: (a) Island arc crust (Hawkesworth et al., 2010); (b) bulk lower–crust (Rudnick & Gao, 2014); (c) global subducting sediments (GLOOS; Plank & Langmuir, 1998); (d) bulk continental crust (Rudnick & Gao, 2014); (e) average Precambrian granites (Vervoort & Patchett, 1996); (f) bulk upper–crust (Rudnick & Gao, 2014). DM is the juvenile–crust depleted mantle model using the data of Vervoort & Blichert–Toft (1999); NC is the 'New Crust' model of Dhuime et al. (2011). Fields for different terranes within Oaxaquia are from Weber et al. (2010), and individual orthogneiss protoliths and anorthosite samples from the Huiznopala Complex are from Weber & Schulze (2014). **(b)** $\delta^{18}O$ zircon compositions vs. age for granitoids and orthogneisses. **(c)** $^{176}Hf/^{177}Hf$ vs. apparent $^{207}Pb/^{206}Pb$ date of detrital zircons from metasedimentary granulites and migmatites of the Garzón and Las Minas Massifs from the Colombian Andes, and from migmatites and metasedimentites of the Oaxaca and Huiznopala Complexes (Weber & Schulze, 2014). External reproducibility (at 95% confidence) of low Yb (Mud Tank) and high Yb (R33) values from zircon crystals are shown as reference for the typical uncertainty bars of individual analyses. **(d)** $^{143}Nd/^{144}Nd$ vs. age for metasedimentary (plotted at their age of metamorphism) and metaigneous units of the north Andean basement massifs and the basement of the Putumayo Basin. Analogous to the Hf plots, the y–axis of this plot is in $^{143}Nd/^{144}Nd$ values and εNd values are also shown as deviations in +2 and –2 increments around the CHUR composition. Slopes for the evolution of different reservoirs as a function of their Sm/Nd compositions (inset) follow the same nomenclature as panel (a). Fields for the different units and lithologies within Oaxaquia are recalculated from: P&R87 – Patchett & Ruiz (1987); R&P88 – Ruiz et al. (1988); W&K99 – Weber & Köhler (1999). The composition of metasedimentary migmatites and granulites of the north Andean Precambrian basement massifs are recalculated after Restrepo–Pace et al. (1997) and Cordani et al. (2005). Figure reproduced with modifications from Ibañez–Mejia et al. (2015), with permission of Elsevier.

Table 2. Compilation of published $^{176}Hf/^{177}Hf$, εHf, and O isotopic data from the Putumayo Orogen.

Sample name	$^{176}Hf/^{177}Hf_{(t)}$ ± 2SD	$\varepsilon Hf_{(t)}$ ± 2SD	U–Pb cryst. age	$\delta^{18}O$ ± 2SD (‰)	Reference
Putumayo Basin basement					
Mandur–2_Leuco	0.282197 ± 45 (n = 12)	+ 2.0 ± 1.6	1017 Ma	5.60 ± 0.22 (n = 11)	Ibañez–Mejia et al. (2015)
Mandur–2 Melano	0.281974 ± 42 (n = 18)	+ 7.6 ± 1.5	1602 Ma	5.43 ± 0.23 (n = 22)	Ibañez–Mejia et al. (2015)
Payara–1	0.281981 ± 21 (n = 4)	– 6.4 ± 0.8	986 Ma	– 6.4 ± 0.8 (n = 6)	Ibañez–Mejia et al. (2015)
Payara–1	0.281796 ± 70 (n = 11)	+ 0.8 ± 2.5	1606 Ma	ca. 9.0 to 9.4	Ibañez–Mejia et al. (2015)
La Macarena, Garzón, and Las Minas Massifs					
MIVS–26	0.282087 ± 39 (n = 10)	+ 1.2 ± 1.4	1135 Ma	7.16 ± 0.22 (n = 8)	Ibañez–Mejia et al. (2015)
MIVS–41	0.282007 ± 43 (n = 12)	+ 2.4 ± 1.5	1325 Ma	6.55 ± 0.26 (n = 8)	Ibañez–Mejia et al. (2015)
Macarena–2	0.281868 ± 63 (n = 13)	+ 0.6 ± 2.2	1461 Ma	6.36 ± 0.27 (n = 10)	Ibañez–Mejia et al. (2015)
MIVS–15A	0.282141 ± 40 (n = 23)	+ 0.1 ± 1.4	1022 Ma	–	Ibañez–Mejia et al. (2015)
MIVS–16A	0.282099 ± 54 (n = 10)	– 1.9 ± 1.9	1001 Ma	–	Ibañez–Mejia et al. (2015)

$\delta^{18}O$= +6.36 ± 0.27 ‰ (Figure 5b; Table 2), also reflects incorporation of supracrustally altered material (Valley et al., 2005), in agreement with the above interpretation.

Within Oaxaquia, orthogneisses with protolith crystallization ages between 1.44 and 1.39 Ga are known from the Huiznopala Gneiss, Guichicovi Complex, and Oaxaca Complex (Schulze, 2011; Solari et al. 2003; Weber & Schulze, 2014). Hafnium isotopic compositions of zircons from these orthogneisses reflect a combination of juvenile ($\varepsilon Hf_{(t)} \approx +8$) and more evolved ($\varepsilon Hf_{(t)} \approx +3$) sources (Figure 5a; Weber & Schulze, 2014), indicating that the early phases of the Oaxaquia arc involved both the generation of juvenile crust –presumably in an intra–oceanic and/or extensional arc setting– but also reworked older crustal material. Weber & Schulze (2014) interpreted this early phase of magmatism with juvenile components to represent an early phase of arc construction, which they termed proto–Oaxaquia. Similarly, it is possible that the ca. 1.46 Ga La Macarena orthogneiss protolith reflects the construction of a proto–Putumayo arc onto a continental margin (Ibañez–Mejia et al., 2015), but for which no juvenile components have yet been clearly identified.

4.3. Main Arc Development Phase (ca. 1.33 to 1.08 Ga)

For at least half of the Ectasian and most of the Stenian Periods, the Putumayo/Oaxaquia margin was characterized by subduction–driven magmatism and deformation, likely within a fringing arc–type accretionary margin (Figure 4b, 4c; Ibañez–Mejia et al., 2011). Several lines of geochemical and geochronologic evidence support this assertion: Within the Proterozoic basement inliers of the Eastern Cordillera of Colombia, orthogneisses with protolith crystallization ages between 1.33 and 1.15 Ga are present in Las Minas and Garzón Massifs (Ibañez–Mejia et al., 2011, 2015), the Colombian Central Cordillera (Leal–Mejía, 2011), the Yarucuy state in Venezuela (Urbani et al., 2015), and the basement of the Falcón Basin offshore northwestern Venezuela (Baquero et al., 2015). Orthogneisses from basement inliers comprising the Oaxaquia Terrane exhibit a similar range of igneous protolith crystallization ages (Cameron et al., 2004; Weber & Schulze, 2014; Weber et al., 2010). A progressive increase in initial $^{176}Hf/^{177}Hf$ compositions of inherited zircons from orthogneiss in the Colombian inliers as a function of younging age, along a trend with an apparent $^{176}Lu/^{177}Hf$ = 0.038 (Figure 5a), cannot be simply explained by radiogenic ingrowth and/or intra–crustal reworking (Ibañez–Mejia et al., 2015), but instead requires that this period was characterized by progressive rejuvenation of the arc–crust by addition of more radiogenic melts from the underlying mantle wedge. The concomitant increase in $^{176}Hf/^{177}Hf_{(t)}$ of orthogneiss protoliths of the Colombian inliers contrasts with their marked increase in (zircon) $\delta^{18}O$ compositions (Figure 5b), which implies that, in concert with the net new crustal additions needed to explain the $^{176}Hf/^{177}Hf$ data, this period also saw a progressive increase in the magnitude of supracrustally–altered material being reworked within the magmatic arc. This apparent dichotomy can result from increasing sediment underplating via subduction and/or enhanced tectonic erosion of a sediment–filled trench (and possibly also forearc crust), in a scenario akin to that of the modern Aleutian subduction zone (Scholl & von Huene, 2009) or the Paleozoic Tasmanide Orogen (Kemp et al., 2009). If the sediments comprising the prism are primarily derived from the arc itself instead of having a significant component of detritus sourced from an older cratonic interior (i.e., older Amazonia basement), then enhanced sedimentary reworking could lead to isotopically heavier $\delta^{18}O$ in magmas without driving the initial $^{176}Hf/^{177}Hf$ compositions towards less radiogenic values.

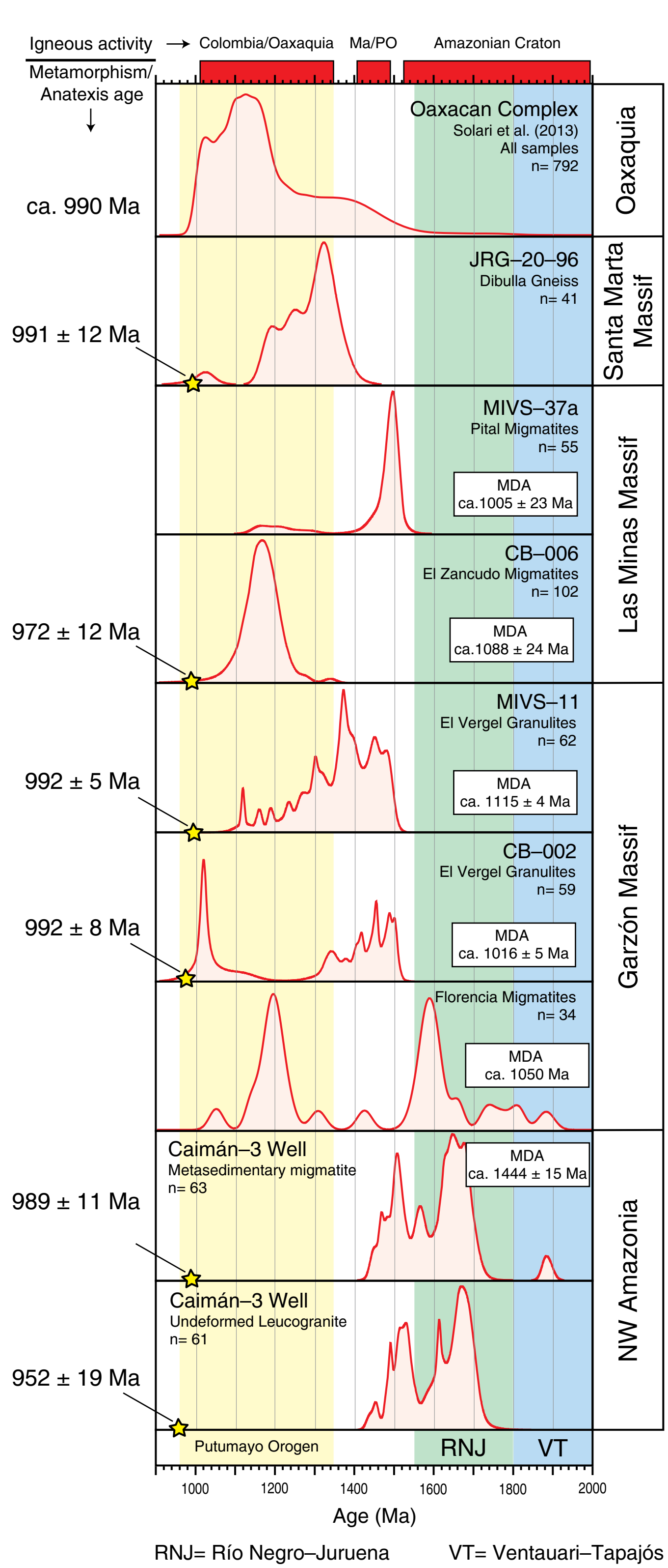
The sedimentary record and Nd isotopic compositions of units within the Putumayo/Oaxaquia composite arc are also in agreement with, and further support, paleogeographic connections between these now dispersed tectonic blocks as well as the inferences described above regarding the fringing arc nature of this composite margin (Figure 5c, 5d). High–grade metasedimentary units of the Santa Marta, Las Minas, and Garzón Massifs, as well as metasedimentary gneisses from Oaxaquia, contain a detrital zircon cargo with U–Pb ages dominantly in the range from 1.45 to 0.97 Ga (Ibañez–Mejia et al., 2011, 2015; Solari et al. 2013; Weber & Schulze, 2014) which excludes significant input of coarse–grained detritus from cratonic Amazonia (Figure 5c). Nevertheless, the presence of older continental material in Putumayo/Oaxaquia, possibly in the form of reworked crust within the arc, is evident from metaigneous and metasedimentary units with relatively unradiogenic $^{143}Nd/^{144}Nd$ initial compositions and crustal residence values generally greater than 1.45 Ga (Figure 5d).

Figure 6 summarizes the U–Pb detrital zircon age spectra (and metamorphic ages, if calculated by the authors) of Putumayo/Oaxaquia metasedimentary gneisses. In the case of Oaxaquia's detrital zircon U–Pb data of Solari et al. (2013), no cathodoluminescence images or spot–by–spot annotations were reported, so a distinction between inherited (detrital) xenocrysts, metamorphic rims, and/or mixed analyses cannot be made here. Thus, in an attempt to minimize the effects that the high–grade metamorphic overprint would have on the detrital–age probability density function, the Oaxaquia results shown in Figure 6 were filtered to exclude all spots which are younger than, or overlap within 2σ uncertainty, the metamorphic age of ca. 985 ± 10 Ma that is representative of Oaxaquian granulites (Ortega–Gutiérrez et al., 2018). Note, however, that this filtering is unlikely to remove all 'mixed' spot analyses, and that any inadvertent ablation mixtures would systematically bias the $^{207}Pb/^{206}Pb$ dates of individual spots/grains towards younger apparent dates.

Despite the limitations of the existing data, the detrital zircon spectra shown in Figure 6 clearly illustrate that ages older than ca. 1.45 Ga are virtually absent from Oaxaquia and the Colombian cordilleran inliers, thus indicating that cratonic Amazonia (or any other older continental nuclei, for that matter) was not a major source of coarse–grained detritus for the basins where the metasedimentary protoliths were deposited. The strongly quartzofeldspathic nature of the metasedimentary granulites and gneisses of El Vergel Unit in the Garzón Massif, along with the observation that most samples contain oscillatory–zoned xenocrystic zircon cores with dates that just precede the age of their metamorphic overgrowths outside of uncertainty (Figure 6), were used by Ibañez–Mejia et al. (2011) to infer that these units were deposited in close proximity to a volcanic arc, possibly in the forearc basin of a 'Colombia/Oaxaquia' fringing arc system. This interpretive forearc basin sequence is schematically depicted in Figure 4d and is termed the Vergel Margin (VM).

An exception to the above–mentioned provenance characteristics of metasedimentites from the Colombian inliers was recently discovered in the Florencia Migmatites of the eastern Garzón Massif by Restrepo & Giraldo (2018). A paleosome from a migmatitic paragneiss yielded a provenance spectrum characterized by two dominant modes, one at ca. 1.2 Ga and another one at ca. 1.6 Ga, with additional minor components ranging in age up to ca. 1.9 Ga (Figure 6). The younger zircon population was likely derived from the Colombia/Oaxaquia arc system, but the older group clearly denotes sourcing from Amazonia's cratonic interior. These older ages are similar to detrital zircon populations found in metasedimentites from the Putumayo Basin basement, thus indicating that coarse–grained

Figure 6. Probability density functions for U–Pb dates obtained from the detrital zircon 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. In addition to the metasedimentary samples, the inherited component of anatectic leucogranites found in the Caimán–3 basement well is also plotted. The upper portion of the plot shows the age ranges of relevant magmatic activity from the Proterozoic of Mexico and Colombia. Colored columns reflect the age ranges of crustal provinces of the Amazonian Craton found in the Guiana Shield (see Ibañez–Mejia & Cordani, 2020), and have the same color–coding as Figure 1. Figure reproduced with modifications from Ibañez–Mejia et al. (2011), with permission of Elsevier.



detritus with a cratonic–source component were deposited in the basin where the sedimentary protoliths of the Florencia Migmatites were formed. This suggests that, in contrast to the VM described above, the sedimentary protoliths of the Florencia Migmatites could represent the sedimentary infill of a back–arc basin to the Colombia/Oaxaquia fringing arc system (i.e., the 'Florencia Margin', FM in Figure 4d). The age of metamorphism of the Florencia Migmatites, as determined from U–Pb analyses of zircon overgrowths (sample Gr–15 of Cordani et al., 2005), is 1015 ± 8 Ma, which is distinctly older than the pervasive granulite–forming event around 990 Ma dated in the Vergel Granulites, as will be further discussed below (sections 4.4 and 4.5). There are, therefore, increasing observations suggesting that El Vergel Granulites and Florencia Migmatites might not only have different metamorphic histories, but may also preserve contrasting (and complementary) tectonic information for reconstructing the evolution of the Putumayo Orogen. If this were indeed the case, then the original definition of the Garzón Group, which includes metasedimentites of both El Vergel and Florencia Units (Jiménez–Mejia et al., 2006; Kroonenberg, 1982; Restrepo–Pace et al., 1997), is no longer adequate and needs to be re–visited. It is emphasized, however, that this interpretation currently relies on the results of only two samples from the Florencia Migmatites, dated by Cordani et al. (2005) and Restrepo & Giraldo (2018). Therefore, further geochronologic and isotopic studies will be necessary to confirm or negate the preliminary interpretations provided here.

Contrasting with the U–Pb age spectra of metasedimentites from the Andean inliers and Oaxaquia, detrital zircons from metasedimentites of the Putumayo Basin basement indicate an entirely different provenance. Metasedimentary migmatites and leucogranites recovered from the basement of the Solita–1, La Rastra–1, and Caimán–3 wells, have xenocrystic cores with ages exclusively older than 1.4 Ga and as old as ca. 2.0 Ga (Figure 6), which are unlike those that could be sourced from the Colombia/Oaxaquia arc terranes. Instead, these dates reflect sediment sources from the continental interior of Amazonia and are in good agreement with the age of Meso– and Paleoproterozoic basement domains of the westernmost Guiana Shield (Ibañez–Mejia & Cordani, 2020). Such provenance signatures indicate that the protoliths of these metasedimentites were deposited in a basin associated with cratonic Amazonia but disconnected from the arc system; such basins are schematically shown in Figure 4c as resting upon the rifted continental–margin of a wide back–arc basin, and are referred here as the 'Solita Margin' (SM in Figure 4). However, it should be noted that because these sediments were likely sourced from the cratonic interior and did not receive a significant proportion of detritus from active arc sources, xenocrystic zircon cores of detrital origin from these metasedimentites are unlikely to approach the age of sediment deposition (e.g., Cawood et al., 2012). As such, the youngest zircon populations in the detrital zircon U–Pb record of the Putumayo basement metasedimentites do not accurately constrain protolith deposition and thus the age of sediment accumulation in the SM is only a maximum estimate.

In summary, although the exact timing and magnitude of retreat of the Putumayo/Oaxaquia arc crust depicted in Figure 4b is not exactly known, it can be argued that extension was likely the driver of rapid crustal rejuvenation by mantle–derived magmatic fluxing (e.g., Kemp et al., 2009) and was responsible for maintaining the arc–proximal basins 'disconnected' from cratonic coarse–sediment sources. Two key pieces to this reconstruction that remain unknown are: (1) how wide was the back–arc basin between the Colombia/Oaxaquia arc and cratonic Amazonia? (Figure 4c); and (2) when the arc system was thrown back into compression, was the back–arc basin wide enough to initiate subduction of oceanic crust underneath Amazonia's cratonic margin as the arc system approached the continent prior to collision? (Figure 4d). Although no evidence currently exists to support the occurrence of a subduction margin along Amazonia's cratonic edge (i.e., in the modern Putumayo Basin basement) during the latest Mesoproterozoic (e.g., as depicted in Weber et al., 2010 and Cawood & Pisarevsky, 2017, and shown with a question mark in Figure 4d), this possibility certainly remains open but will necessitate further geochronologic research in the autochthonous Putumayo basement to be properly addressed.

4.4. Collision Initiation by Arc–Terrane Accretion (ca. 1.05 to 1.02 Ga)

Near the end of the Stenian Period, as Amazonia and Baltica approached their final positions within an assembled Rodinia configuration (Figure 3), the intervening ocean basin between these cratons, known as the Mirovoi Ocean (Cawood & Pisarevsky, 2017), was consumed, and the Colombia/Oaxaquia arc systems that had previously developed along Amazonia's leading edge switched from an extensional to a compressional regime. These arc terranes were ultimately docked against the continental margin prior to, or some fragments possibly during, final closure of the Mirovoi Ocean (Figure 4e). Accretion of arc terranes would have resulted in the closure of the back–arc basin(s) to the Colombia/Oaxaquia arc discussed in the previous section, thus resulting in tectonic burial and metamorphism of sedimentary sequences of the Solita, Florencia, and possibly also the Vergel Margins (Figure 4e). Indeed, Cordani et al. (2005) and Ibañez–Mejia et al. (2011, 2015) have identified an 'early' metamorphic event from zircon overgrowths found in amphibolite–facies metasedimentary units throughout the Putumayo Orogen, which Ibañez–Mejia et al. (2011, 2015) interpreted as reflecting a phase of basin closure and tectonic burial by arc–terrane accretion prior to final continent–continent collision. This event is constrained to have occurred in the time interval from ca. 1.05 to 1.02 Ga by: (i) U–Pb dating of zircon overgrowths in metasedimentary migmatites of the Solita–1 well (1046 ± 23 Ma; Ibañez–Mejia et al., 2011), (ii) a migmatitic ortho–amphibolite and associated syenogranitic injections in the Mandur–2 well (1019 ± 8 Ma and 1017 ± 4 Ma, respectively; Ibañez–Mejia et al., 2011), (iii) a metasedimentary migmatite of the Florencia Migmatites (1015 ± 8 Ma; Cordani et al., 2005), (iv) metasedimentary migmatites within El Vergel Granulites unit (1022 ± 9 Ma; Ibañez–Mejia et al., 2015), and (v) an orthogneiss from the Novillo Gneiss unit in Oaxaquia (1026 ± 9 Ma; Weber et al., 2010). Currently, little is known about the precise pressure–temperature conditions responsible for this metamorphic episode, so these remain a prime target for future research.

Metamorphic events associated with arc accretion episodes prior to continental collision are widespread in other collisional settings. For instance, in Laurentia, Mesoproterozoic arc terrane docking during the Grenville Orogenic Cycle in its (modern) northern segment has been well–documented and is responsible for what is locally known as the Shawinigan Orogeny (McLelland et al., 2010, and references therein; Rivers & Corrigan, 2000). This event is characterized by accretion of the Elzevirian arcs, Frontenac Terrane, and Adirondack highlands against the (proto–Grenville) Laurentian continental margin (Gower & Krogh, 2002; McLelland et al., 1996), resulting in widespread deformation and metamorphism of the central metasedimentary belt domain, a sedimentary sequence deposited in a back–arc basin behind the fringing arc terranes of the pre–collisional Grenville margin (McLelland et al., 2010). The reconstruction for the Putumayo Orogen shown in Figure 4 envisions a similar tectonic scenario and significance for the FM and SM (Figure 4c, 4d) as that of the Grenville Supergroup in the Adirondack Lowlands (e.g., Chiarenzelli et al., 2015) and other units included within the Central Metasedimentary Belt of Laurentia. Similarly, metasedimentary units were also metamorphosed along the Sveconorwegian margin of Baltica during the pre–collisional accretion of the Telemarkia Terrane at ca. 1.14–1.12 Ga (i.e., metasedimentites included within the Bamble and Kongsberg Terranes, metamorphosed during the Arendal phase; Figure

4d; Bingen et al., 2008a, 2018b), indicating this is a common phenomenon in collisional margins.

4.5. Anorthosite–Mangerite–Charnockite–Granite (AMCG) Magmatism (ca. 1.02 to 1.00 Ga)

Following arc–terrane accretion but prior to final continent–continent collision, widespread anorthosites and associated charnockitic magmas were emplaced throughout Oaxaquia between 1.02 and 1.00 Ga (Cameron et al., 2004; Cisneros de León et al., 2017; Keppie et al., 2003; Weber & Schulze, 2014; Weber et al., 2010). However, although a significant portion of the exposed Oaxaquian basement consists of these AMCG–type units, similar intrusives do not appear, at least to date, to be as abundant in the Colombian Proterozoic basement inliers. Although anorthosites are known to occur in association with Los Mangos Granulites in the Sierra Nevada de Santa Marta (Tschanz et al., 1969, 1974; Cardona et al., 2010), their age of igneous emplacement remains unconstrained, and no other AMCG–type bodies have yet been mapped in the Garzón, Santander, San Lucas, La Guajira, or Las Minas Massifs. There are two potential explanations for this apparent discrepancy: (1) detailed geologic mapping of most Colombian basement inliers remains arguably very limited, and thus these units may in fact be present but not yet clearly identified; or (2) following arc–terrane accretion, intrusions of AMCG–type magmas may have been focused on the portion of the Putumayo Orogen that is now represented by the Oaxaquia Terrane, and may mostly be absent –or present only in small volumes– in the limited basement exposures represented by the Colombian basement inliers. At any rate, future investigations of the Proterozoic basement of the Colombian Andes, including mapping and additional petrologic/geochronologic work, should place attention on documenting the occurrence (and field relations, if present) of AMCG–type intrusives.

Traditionally, massif–type anorthosites and AMCG complexes have been regarded as 'anorogenic' in nature (e.g., Anderson, 1983; Ashwal, 1993; Emslie, 1991; amongst many others), which has posed complexities for interpreting the AMCG magmatism within Oaxaquia (see discussion in Weber et al., 2010). Nevertheless, recent advances in our understanding of AMCG associations and their relationship with regional tectonic regimes using modern geochronologic methods, are shifting this long–standing view in favor a convergent (i.e., Andean–type) margin for their origin (e.g., Ashwal & Bybee, 2017; Bybee et al., 2019). Indeed, voluminous AMCG magmatism at 1.08–1.03 in the Grenville Orogen post–dates arc accretion (Shawinigan event) and predates collisional orogenesis (Ottawan event), and evidently took place within a convergent margin (e.g., Bickford et al., 2010; Hamilton et al., 2004; McLelland et al., 2004, 2010). Because it is widely agreed that AMCG magmatism requires some sort of extensional tectonic regime, particularly for allowing the ascent of plagioclase–rich (anorthositic) mushes from the lower crust to their final emplacement levels (see Ashwal & Bybee, 2017, and references therein), it has been suggested that the origin of the Grenville anorthosites is related to transient events of regional extension, driven by the convective removal of the lower lithosphere following compressional crustal thickening (e.g., Corrigan & Hanmer, 1997; McLelland et al., 2004). Thus, considering that, much as in the Grenville, AMCG magmatism in the Putumayo Orogen post–dates arc accretion (section 4.4) but pre–dates the main collisional event (section 4.6), the AMCG magmatism expressed in Oaxaquia also most likely took place in a convergent tectonic environment. It is suggested here that, following the orogenic event at ca. 1.05–1.02 Ga and associated crustal thickening due to arc accretion, gravitational, and/or convective removal of the lower lithosphere could have triggered regional extension within the Putumayo/Oaxaquia arc crust at ca. 1.02 to 1.00 Ga (Figure 4f), driving asthenospheric upwelling, regional basaltic underplating, and providing the necessary conditions for massif–type anorthosites and other charnockitic magmas to be developed and emplaced.

4.6. Main Collisional Event (ca. 1.00 to 0.95 Ga)

Final closure of the Mesoproterozoic ocean basins that once separated Laurentia, Baltica, and Amazonia (Li et al., 2008; Pisarevsky et al., 2014) brought about a series of continent–continent collisions at the heart of an assembling Rodinia (Figures 3, 4g). Collisions amongst the various segments of the 1000s–of–km–long margins comprising this Laurentia–Baltica–Amazonia orogenic 'triple–junction' were diachronous in nature, and the relative timing of metamorphic events amongst them is an important tectonic discriminator for establishing inter–cratonic correlations amongst the orogenic belts that developed.

On the Amazonian side of this collision, a widespread granulite–forming event at ca. 990–970 Ma has been dated by multiple groups in various units within Oaxaquia and northwestern South America. In Colombia and Venezuela, granulite–facies rocks around this age, dated by U–Pb methods, are known from the Garzón Massif (Cordani et al., 2005; Ibañez–Mejia et al., 2011, 2015; Weber et al., 2010), Las Minas Massif (Ibañez–Mejia et al., 2011, 2015), the Colombian Central Cordillera (Leal–Mejía, 2011), the Serranía de San Lucas Massif (Cuadros et al., 2014), the basement of the Putumayo Foreland Basin (Ibañez–Mejia et al., 2011, 2015), La Guajira Peninsula (Baquero et al., 2015), the Venezuelan Cordillera de la Costa (Urbani et al., 2015), and the offshore basement of the Falcón Basin (Baquero et al., 2015). In Mexico, this event is locally known as the Zapotecan Orogeny (Solari et al., 2003) and has been recognized in units from the Oaxacan Complex (Shchepetilnikova et al., 2015; Solari et al., 2003, 2013; Weber & Schulze, 2014; Weber et al., 2010), the Guichicovi Complex (Weber & Kohler, 1999; Weber & Schulze, 2014; Weber et al., 2010), the Huiznopala Gneiss (Lawlor et al., 1999; Weber & Schulze, 2014), and the Novillo Gneiss (Cameron et al., 2004; Weber & Schulze, 2014). This regionally coherent tectonothermal event has been interpreted as reflecting the climax of collisional metamorphism in the Putumayo/Oaxaquia margin during Amazonia's incorporation to Rodinia (Cardona et al., 2010; Cawood & Pisarevski, 2017; Cordani et al., 2005; Ibañez–Mejia et al., 2011, 2015; Li et al., 2008; Solari et al., 2003; Weber et al., 2010; among others).

Potential conjugate margins to the Putumayo/Oaxaquia margin based on recent tectonic reconstructions (Figure 3) are either the Grenville Orogen of Laurentia (e.g., Gower et al., 2008; McLelland et al., 1996, 2010) or the Sveconorwegian Orogen of Baltica (e.g., Bingen et al., 2008a; Bogdanova et al., 2008). In order to resolve this paleogeographic conundrum, possibly the best approach is to take the timing of regional tectonometamorphic events associated with collision in the Grenville and Sveconorwegian Orogens, and compare them with events identified in Putumayo/Oaxaquia in order to determine which margin is most likely to be its collisional conjugate.

In Laurentia, the major regional metamorphic event associated with continental collision took place during the 1.09–1.02 Ga interval and is locally known as the Ottawan Orogeny. This event, based on U–Pb dating of zircon (e.g., McLelland et al., 2001, 2004), U–Pb in monazite (e.g., Heumann et al., 2006), and U–Pb in titanite (e.g., Bonamici et al., 2015; Mezger et al., 1991) is thought to have attained its peak at ca. 1050 Ma before starting to cool slowly, presumably during exhumation and orogenic collapse. U–Pb zircon dates of an undeformed pegmatite dike in the Adirondack highlands (1034 ± 8 Ma; McLelland et al., 2001), and syn–kinematic granite injections associated with normal–fault displacement along the Carthage–Colton shear zone (1047 ± 5; Selleck et al., 2005) place a lower age limit of ca. 1047 Ma for Ottawan contractional deformation in this portion of the Grenville Orogen. The Ottawan event was followed by a phase known as the Rigolet phase, which lasted from 1011 to 980 Ma and is commonly associated with ubiquitous extensional deformation and channel–flow in the front of the Grenville orogenic plateau, marking widespread orogenic collapse (Rivers, 2008).

In Baltica, following the arc–accretion–related orogenesis of the Arendal phase, the main continent–continent collisional episode is thought to have taken place in the interval from 1.05 to 0.98 Ga and is locally known as the Agder phase (Bingen et al., 2008a; Bogdanova et al., 2008). This event induced metamorphism and magmatism in the Idefjorden and Telemarkia Terranes, with high–pressure (1.0–1.5 GPa) amphibolite– to granulite–facies conditions affecting the Idefjorden and moderate pressure (0.6–0.8 GPa) amphibolite– to granulite–facies conditions and penetrative deformation affecting Telemarkia (Bingen et al., 2008b). Following the regionally extensive Arendal tectonometamorphic event, Sveconorwegian deformation migrated towards the foreland, to affect primarily the so–called 'Eastern Segment' during an event known as the Falkenberg phase. This event is associated with local eclogite and regional high–P granulite–facies metamorphism with peak pressures of ca. 1.5 GPa and 'clockwise' P–T paths, presumably reflecting deep burial of Fennoscandian crust due to overthrusting of the Sveconorwegian hinterland (Johansson et al., 2001; Möller, 1998). Following this final phase of convergence, the Sveconorwegian Orogen entered a phase of extensional deformation during tectonic relaxation and gravitational collapse; this phase is locally known as the Dalane phase, and is marked by post–collisional magmatism in the time interval from 0.97 to 0.90 Ga (Bingen et al., 2008a; Bogdanova et al., 2008). During this period, rapid exhumation of high–pressure metamorphic rocks took place at ca. 960 Ma in the footwall of the mylonite zone (Möller, 1999), shallow plutons were emplaced in a brittle regime between 0.97 and 0.93 Ga (e.g., Hellstrom et al., 2004), and, finally, between 0.93–0.92 Ga, voluminous plutonic rocks including AMCG complexes, such as the Rogaland Complex (e.g., Westphal et al., 2003), were emplaced, marking the end of the Sveconorwegian Orogeny.

Using a compilation of the available geochronologic data from the Grenville, Sveconorwegian, Sunsás–Aguapeí, Oaxaquia, and Putumayo, and particularly from observations regarding the timing of peak metamorphism described above, Ibañez–Mejia et al. (2011) concluded that the Sveconorwegian is a more likely conjugate margin to explain the timing of collisional deformation of the Putumayo Orogen and Oaxaquia than the Grenville. In this framework, the Sunsás–Aguapeí Orogen was developed by early oblique collision between Amazonia and the Llano segment of the Grenville Province (Tohver et al., 2002, 2005) and thus reflects the onset of collisional incorporation of Amazonia into an assembling Rodinia, but not final supercontinent amalgamation. The hypothesis of a frontal Amazonia–Baltica collision to explain the Arendal and Falkenberg phases of the Sveconorwegian Orogen had previously been suggested by Bogdanova et al. (2008), based on other paleogeographic and paleomagnetic arguments (see section 3), but the new geochronologic data that has since emerged from the Putumayo Orogen has not only re–affirmed such correlations but also significantly improved our understanding of the tectonic processes and dynamics that led to Rodinia assembly in this complex orogenic 'triple–junction'.

4.7. Collapse of the Orogenic Plateau and Supercontinent Breakup (<0.97 Ga)

It is thought that through the major collisional events that occurred along the Grenville, Putumayo, and Sveconorwegian margins, the core of Rodinia was fully assembled (Cawood &

Pisarevski, 2017; Li et al., 2008), and a large, high–standing orogenic plateau akin to the Tibetan Plateau in the India–Asia collision zone (Dewey et al., 1988; Royden et al., 2008) developed in the Rodinian orogenic hinterland (e.g., Rivers, 2008, 2012). This feature has been suggested to set the Grenville–Sveconorwegian–Putumayo Orogen apart from all older orogens associated with pre–Rodinian supercontinents (i.e., Nuna/Columbia and Superia/Sclavia; Hawkesworth et al., 2013), in that this represents the first known occurrence of a long–lived, possibly high–standing orogenic plateau in the geological record. If true, this apparently simple feature marks a dramatic shift in the geologic evolution of our planet, given the strong impact that plateau development has in modulating continental weathering and tectonic forcing of global climate (Edmond, 1992; Garzione, 2008; Raymo & Ruddiman, 1992).

Following the lithospheric thickening that occurs along collisional orogens by rapid structural shortening, advective thinning of the thermal boundary layer in the lower lithosphere, coupled with isotherm relaxation, inevitably leads to extensional orogenic collapse (Dewey, 1988). In NW South America, units belonging to the Putumayo Orogenic Cycle yield biotite, hornblende, feldspar, and phlogopite Ar–Ar (plateau) cooling dates ranging mainly from ca. 970 to 870 Ma (Baquero et al., 2015; Cordani et al., 2005; Fournier et al., 2017; Restrepo–Pace et al., 1997), indicating that significant exhumation and cooling of the lower crustal orogenic roots took place within this time interval. Older cooling dates in the range from 1007 and 1045 Ma (Ar–Ar plateau ages from biotite and hornblende) occur exclusively in the Florencia Migmatites unit of the eastern Garzón Massif (Margaritas Gneiss of Cordani et al., 2005), which is consistent with an early onset of their exhumation associated with the 1.05 to 1.02 Ga metamorphism by arc–continent collision (see section 4.4) rather than orogen–wide extensional collapse.

To this date, little is known about the ultimate demise of the Putumayo Orogen and events associated with the onset of Iapetus Ocean opening in NW South America. In the Grenville and Sveconorwegian margins, opening of the Iapetus Ocean is constrained by ca. 570 Ma rift–related structures and magmatism in the Newfoundland margin (Cawood et al., 2001), and emplacement of the Egersund dike swarm in southern Norway at ca. 616 Ma (Bingen et al., 1998). The best constraints from the Amazonia side of this rift come from: (1) Plume-related dikes intruded into the Novillo Gneiss in northern Oaxaquia, dated to 619 ± 9 Ma using U–Pb in micro–baddeleyite (Weber et al., 2019); and (2) El Triunfo Complex in the Chiapas Massif of southern Mexico (González–Guzmán et al., 2016; Weber et al., 2018), where amphibolite layers with E–MORB geochemical characteristics are found within the Ediacaran Jocote metasedimentary unit and in Oaxaca–type orthogneiss and anorthosite (Weber et al., 2018); and (3) metamorphic zircon overgrowths ca. 600 Ma in Oaxaquian anorthosites from the Chiapas Massif, which Cisneros de León et al. (2017) suggested were formed due to anorthosite reheating during intra–plate rifting and mafic magma intrusions. These observations unambiguously indicate a Neoproterozoic age for rift–related magmatism on the Oaxaquian (Amazonian) margin of the Iapetus rift zone. Further efforts focused on finding the evidence of orogenic collapse and supercontinent break–up in the exposed basement inliers of the northern Andes and autochthonous Putumayo basement is an important target for future research.

5. The P–T–t History of Continent–Continent Collisions

Reconstructing the pressure–temperature–time (P–T–t) paths of metamorphic rocks is key for understanding the rates and mechanisms of orogenic development and reconstructing the tectonic history of metamorphic belts throughout the geologic record (Brown & Johnson, 2018; England & Thompson, 1984; Thompson & England, 1984). Quantitative P–T estimates (e.g., using mineral thermodynamics) of Putumayo–related metamorphic assemblages in NW South America remain limited, restricted to the works of Jiménez–Mejia et al. (2006), Altenberger et al. (2012), and Ibañez–Mejia et al. (2018). Jiménez–Mejia et al. (2006) applied multi–equilibrium thermodynamic calculations to samples from El Vergel Granulites and Florencia Migmatites of the Garzón Massif, using the TWQ software and thermodynamic database of Berman (1991). These authors determined peak conditions around 750 ºC and 0.6 GPa for a charnockitic gneiss of El Vergel unit, and conditions between 680–830 ºC and 0.6–0.9 GPa for the Florencia unit. These results are broadly indicative of metamorphism having taken place at ca. 22–30 km depths and under upper–amphibolite to granulite–facies conditions. On the other hand, based on exsolution textures in feldspars and pyroxenes and Ti–in–quartz thermometry, Altenberger et al. (2012) suggested that El Vergel unit was metamorphosed at (or near) ultra–high temperature (UHT) conditions ca. 900–1000 ºC. These authors hypothesized that the UHT metamorphic event in El Vergel unit must have resulted from high heat–flow provided by an episode of arc magmatism and back–arc extension that shortly pre–dated continental collision, in agreement with the tectonic history of the Putumayo Orogen as described in the previous sections (e.g., potentially in association with AMCG–related magmatism). One sample from the Florencia Migmatites studied by Altenberger et al. (2012) yielded lower peak temperatures ca. 760 ºC, in agreement with the results of Jiménez–Mejia et al. (2006) for the same unit.

Of all the samples analyzed for geothermobarometry by Jiménez–Mejia et al. (2006) and Altenberger et al. (2012), only sample Gr–15 of Jiménez–Mejia et al. (2006) from the Florencia Migmatites has been dated using U–Pb geochronology of metamorphic zircon overgrowths, yielding a mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1015 ± 8 Ma (Cordani et al., 2005), and a two–point garnet–whole rock Sm–Nd isochron (1034 ± 6 Ma; Cordani et al., 2005). Thus, the general disconnect that exists between the currently available thermobarometric and geochronologic datasets precludes using most of the existing P–T data to robustly constrain the time–temperature history of events within the Putumayo Orogenic Cycle. Nevertheless, from a qualitative standpoint, based on regional mapping and petrographic observations made by Kroonenberg (1982), Restrepo–Pace et al. (1997), Jiménez–Mejia et al. (2006), Altenberger et al. (2012), and Ibañez–Mejia et al. (2011, 2015), two generalizations can be made: (1) it seems likely that (volcano)–sedimentary units that in the field appear as stromatic metatexites were metamorphosed during the early orogenic episode at ca. 1.05–1.02 Ga and dominantly recrystallized under upper–amphibolite to granulite facies conditions, and (2) the massive felsic and mafic granulites were dominantly recrystallized during the main collisional event at ca. 1.0 to 0.95 Ga. In the Garzón Massif, amphibolite–facies stromatic metatexites are found both within the Florencia Migmatites and El Vergel Granulites units (e.g., Altenberger et al., 2012; Ibañez–Mejia et al., 2015) whereas massive granulites seem to be restricted to El Vergel Granulites unit only (as mapped by Rodríguez et al., 2003).

More recently, Ibañez–Mejia et al. (2018) performed a detailed high–temperature thermochronologic study of a metasedimentary granulite with migmatitic textures from La Rastra–1 well of the Putumayo Basin basement. The chemical composition of co–existing garnet, orthopyroxene, and plagioclase in the melanosome indicated peak P–T conditions of approximately 680 ºC and 0.62 GPa, by simultaneously solving the net–transfer GAPES geobarometer of Eckert et al. (1991) and the garnet–orthopyroxene Fe–Mg exchange geothermometer of Ganguly et al. (1996). Garnets in contact with biotite exhibit conspicuous retrograde Fe–Mg zoning profiles, which were used to determine an initial cooling rate of ca. 5 K/my from peak conditions using diffusion–based geospeedometry (Lasaga, 1983) and a numerically optimized solution to the 1–D diffusion equation (after Ganguly et al., 2000). Garnets with a narrow grain–size distribution of 100 ± 20 μm in diameter where hand–picked and analyzed for their Sm–Nd and Lu–Hf isotopic compositions (Figure 7a, 7b), resulting in a five–point Sm–Nd isochron of 1007.0 ± 2.9 Ma (2σ, MSWD = 1.3) and a six–point Lu–Hf isochron of 1070.8 ± 5.6 Ma (2σ, MSWD = 0.84). This discrepancy in apparent ages was explained by Ibañez–Mejia et al. (2018) in terms of the different diffusivities of Sm–Nd and Lu–Hf in garnets (determined experimentally by Bloch et al., 2015, 2020; Ganguly et al., 1998; Tirone et al., 2005; van Orman et al., 2002), and was solved numerically to invert a time–temperature history that satisfied the thermobarometry, initial cooling rate, grain–size–age relation of Sm–Nd and Lu–Hf isochrons, and a garnet Sm–Nd bulk closure temperature of 560 ºC independently calculated using the analytical formulations of Ganguly & Tirone (1999). The results of this numerical inversion are shown graphically in Figure 7c, which represents what is currently the best (and only) estimate for the time–temperature history of the metamorphic basement of the Putumayo Basin. Comparison of this T–t history with trajectories reconstructed for metasedimentites of the Great Himalayan Sequence in the India–Asia collision zone are in good agreement (Figure 7d), thus indicating that the tectonic processes resulting in metamorphism of La Rastra–1 well basement were likely similar to those operating in modern collisional orogenic settings (see Ibañez–Mejia et al., 2018 for further discussion).

Other garnet Sm–Nd dates for samples from the Colombian cordilleran inliers have been published by Cordani et al. (2005) and Ordóñez–Carmona et al. (2006). These studies obtained two–point (garnet–whole–rock) isochron dates for two samples of the Florencia Migmatites in the Garzón Massif (1034 ± 6 Ma and 990 ± 8 Ma; Cordani et al., 2005), two samples of El Vergel Granulites in the W Garzón Massif (935 ± 5 Ma and 925 ± 7 Ma; Cordani et al., 2005), and one sample of Los Mangos Granulites in the Sierra Nevada de Santa Marta (971 ± 8 Ma; Ordóñez–Carmona et al., 2002, 2006). Nevertheless, these ages –and their assigned uncertainties– must be interpreted cautiously, as two–point isochrons are not always reliable and the uncertainties associated to linear regressions through only two points are rarely an accurate approximation of the true geological uncertainty of an isochron age. Qualitatively, however, these results appear to agree with an early metamorphic event for metasedimentites from the Florencia Migmatites unit (Sm–Nd dates between 1.05 and 0.99 Ga), and a younger cooling of higher–grade units such as El Vergel and Los Mangos granulites (e.g., during exhumation after the 0.99 Ga peak metamorphism). Nevertheless, neither of these two studies obtain peak T conditions of the dated samples, cooling rates, or described the dimensions of the garnets that were analyzed. Without such data, it is not possible to calculate the effective closure temperature of the Sm–Nd system in the analyzed garnets, and thus these dates cannot be utilized to quantitatively constrain the T–t path of the studied units.

In summary, considering the reconstruction of the Putumayo Orogen as presented in section 4 of this chapter and the numerically modeled peak metamorphic date for La Rastra–1 basement (i.e., 1035 +8/–6 Ma; Figure 7c), it is possible that the basement drilled by the La Rastra–1 well represents a slice of metasedimentites underthrusted to mid–crustal depths and exhumed during arc–terrane accretion (Figure 4e), but that subsequently sat at a structural level that did not experience significant burial during continent–continent collision (unlike the basement of the Payara–1 well). Nevertheless, discerning the significance of La Rastra–1 thermal path within the tectonic history of the Putumayo remains mostly hypothetical until additional studies combining thermobarometry and high–temperature thermochronology are performed throughout the orogen. Particularly, units yielding ca. 990 Ma zircon U–Pb ages,

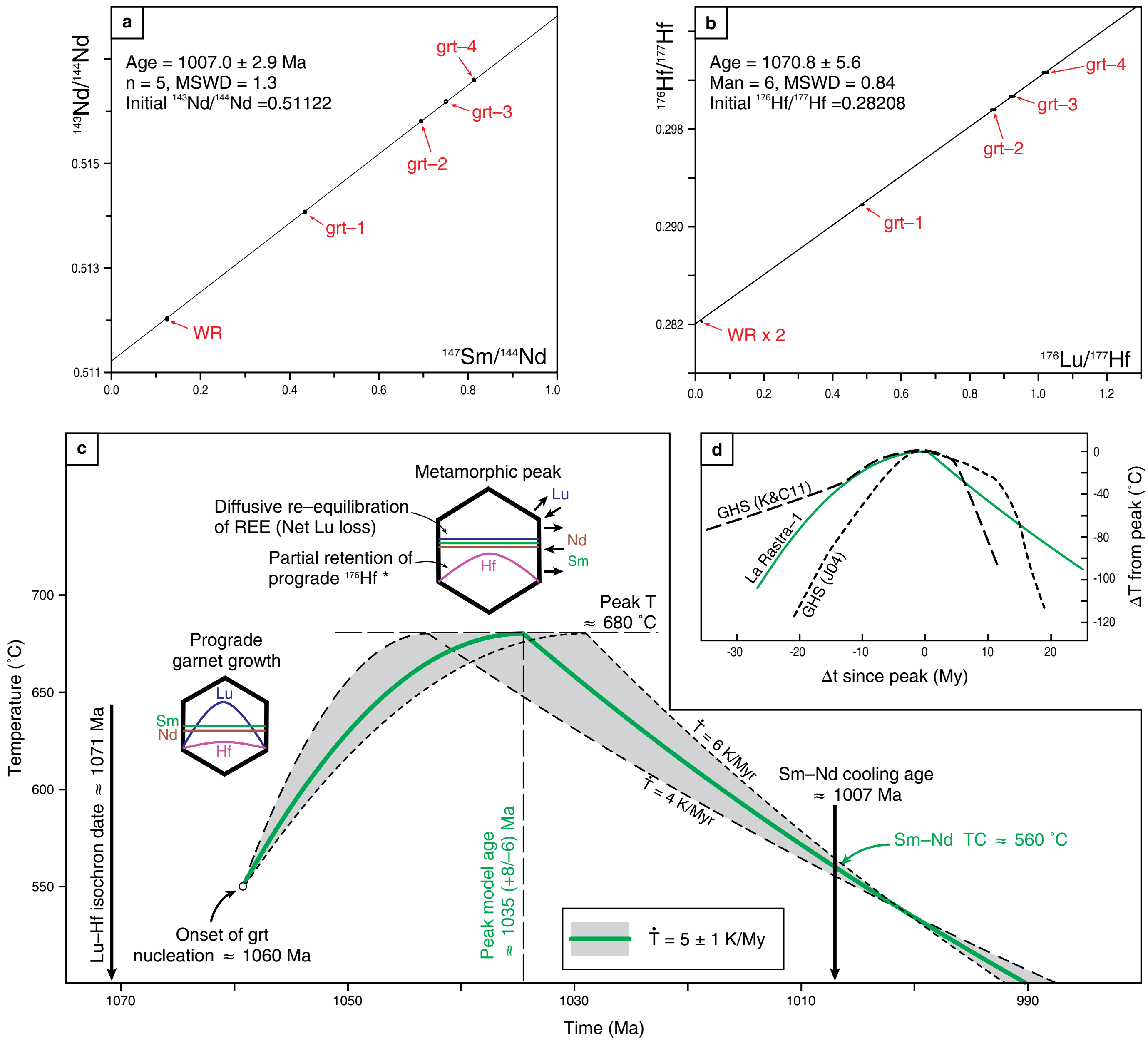


Figure 7. (a) Sm–Nd, **(b)** Lu–Hf internal isochron diagrams and calculated dates for analyzed garnet and whole–rock fractions of La Rastra–1 basement. **(c)** Time–temperature (T–t) evolution model reconstructed for the basement of La Rastra–1 well in the Putumayo Basin by Ibañez–Mejia et al. (2018). Hexagons present a conceptual representation of the Lu–Hf diffusive decoupling issue in prograde garnet crystals; see text and Ibañez–Mejia et al. (2018) for further details. **(d)** Comparison of the (idealized) T–t path reconstructed for La Rastra–1 with paths reconstructed for the Greater Himalayan Sequence (GHS) of the Indo–Asian collision zone by means of titanite U–Pb thermochronology and Zr thermometry (K&C11 curve, after Kohn & Corrie, 2011), and thermo–mechanical numerical modeling (J04 curve, after Jamieson et al., 2004). See Ibañez–Mejia et al. (2018) for further details. Figures reproduced from Ibañez–Mejia et al. (2018), with permission of Elsevier.

such as El Vergel Granulites, are an important target for future high–temperature thermochronology studies. Beyond allowing a more complete P–T–t reconstruction of the Putumayo Orogen to be achieved, such studies will be crucial for better understanding the structural role that the Amazonian cratonic margin played in the series of collisional events leading to the assembly of Rodinia.

6. Outstanding Challenges and Future Outlook

Despite significant advances made over the last two decades in understanding the Meso–Neoproterozoic orogenic events that took place in (modern) NW South America during Amazonia's incorporation into Rodinia, the existing geochronologic, thermochronologic, and thermobarometric databases remain limited. This is due to multiple factors, but particularly problematic are the limited exposure (i.e., most of the Putumayo Orogen is buried under younger Andean hinterland and foreland cover), and the difficulty of access to many regions where portions of this orogenic belt are exposed. Nevertheless, recent developments in micro–analytical techniques for the geochemical and isotopic study of geological samples are constantly expanding the spectrum of information that can be gleaned from the tiniest mineral fragments, and even small samples can now be investigated to extract a wealth of chronologic and thermal history information (e.g., Ibañez–Mejia et al., 2018). Further applications of state–of–the–art analytical techniques for studying the Proterozoic basement of NW South America and southern Mexico have the potential to provide a wealth of new information that will certainly improve and/or modify the ideas presented throughout this chapter.

In particular, some key outstanding issues and therefore aspects where further research could be deeply transformative for the ideas presented here are:

1. Although the probability of finding extensive outcrops of Putumayo–related rocks in the westernmost exposed Guiana Shield in Colombia is rather low (see Ibañez–Mejia & Cordani, 2020 in this volume), the possibility that even limited outcrops can be found remains plausible. Such exposures could be located in proximity of the serranía de La Macarena and San José del Guaviare uplifts (Figure 2), where the thickness of the Llanos and Putumayo Andean Foreland Basins tapers and basement rocks are exposed.
2. The existing geochronologic database is, for most practical purposes, devoid of a robust petrologic context. For instance, thermobarometric information of dated samples remains scarce, and no trace element data for zircon domains dated by U–Pb methods yet exist, therefore precluding linking these (re)crystallization dates with the petrologic history of their host rocks (e.g., DesOrmeau et al., 2015; Kohn et al., 2015). Further application of methods that allow linking metamorphic temperatures and/or phase assemblages with dates (e.g., Engi et al., 2017; Ibañez–Mejia et al., 2018; Kohn, 2016) will allow more robust time–temperature histories for the different phases of the Putumayo Orogenic Cycle to be reconstructed.
3. In detail, structural models of the Grenville–Putumayo–Sveconorwegian collision remain relatively poorly developed. For instance, it remains unclear which margins were underthrusted or thrusted–on–top–of other(s) during collision, and petrologic studies from the Grenville, Putumayo, and Sveconorwegian have generally resulted in conflicting hypotheses as to which margin acted as a 'lower plate' during collision (e.g., Bingen et al., 2008a; Gower et al., 2008; McLelland et al., 1996; Weber et al., 2010). Further thermobarometric, geochemical, and geo–thermochronologic work from all three margins is necessary to arrive at a plausible structural configuration that explains the P–T trajectories and thermal histories of these orogenic belts.
4. Although most lines of paleogeographic and geochronologic evidence suggest that the Putumayo and Sveconorwegian margins collided near the end of the Stenian and beginning of the Tonian Periods, recent studies have challenged the collisional nature of the Sveconorwegian Orogen (Coint et al., 2015; Slagstad et al., 2013a, 2017), a scenario which would render the collisional model between Amazonia and Baltica as depicted in Figure 3a–c inaccurate. Although debate still persists regarding the nature and causes of the contractional deformation within tectonic units of the Sveconorwegian (e.g., Bingen & Viola, 2018; Möller et al., 2013; Slagstad et al., 2013b), resolving this discrepancy will have a major impact on reconstructions of Rodinia and the Putumayo Orogen.
5. The apparent lack of voluminous AMCG–type intrusives in the Colombian cordilleran inliers contrasts with their widespread occurrence in Oaxaquia. This stark difference not only requires further explanation in order to validate the hypothesis that Oaxaquia was integral part of the Putumayo Orogen (as suggested in this chapter), but the petrologic and tectonic significance of the Oaxaquian AMCG massifs, emplaced just prior to continent–continent collision, remains to be better understood.
6. The paleo–latitude of the Guiana Shield in the Meso– and Neoproterozoic remains, strictly speaking, almost entirely unconstrained. All of Amazonia's paleomagnetic poles in this time period with a quality factor (Q) of 4 or greater, and robust age constrains, namely the Guadalupe (1.53 Ga; Bispo–Santos et al., 2012), Rio Branco (1.54 – 1.44 Ga; D'Agrella–Filho et al., 2016b), Salto do Céu (1.44 Ga; D'Agrella–Filho et al., 2016b), Nova Guarita (1.42 Ga; Bispo–Santos et al., 2012), Indiavaí (1.42 Ga; D'Agrella–Filho et al., 2012), Nova Floresta (1.2 Ga; Tohver et al., 2002), and Fortuna (1.15 Ga; D'Agrella–Filho et al., 2008) poles, have been obtained from localities in the Central Brazil Shield (see recent review by D'Agrella–Filho et al., 2016a). Therefore, obtaining robust paleomagnetic information from Meso– Neoproterozoic units of the Guiana Shield is a most needed objective in order to better constrain its position during the Meso– and Neoproterozoic and further corroborate (or challenge) the ideas presented here and the concept of a unified 'Amazonia'.

7. Summary

Significant advances in the geologic and geochronologic knowledge of NW South America's basement over the last 15 years have, in concert with the growing paleomagnetic database, allowed for a better understanding of: (1) the timing and nature of the Meso– Neoproterozoic orogenic events that have affected the westernmost Guiana Shield, and (2) the role that Amazonia played prior to, and during, the amalgamation of the supercontinent Rodinia. These reconstructions have led to the idea of a 'Putumayo Orogen', underscoring the importance that these series of tectonic events have in our understanding of the geologic evolution of Amazonia.

The Putumayo Orogenic Cycle, as summarized here, records a protracted (ca. 400 my) history of convergence and arc–related magmatism and sedimentation along the leading margin of Amazonia, prior to continent–continent collision at the heart of an assembling Rodinia. Therefore, continuing to refine the timing and physical conditions of the events described herein will continue to provide insights for reconstructing the tectonic history of the Putumayo Orogen, the westernmost Guiana Shield, and perhaps more crucially, for refining the paleogeographic role of Amazonia in global tectonic reconstructions of the Proterozoic Earth. Lastly, notwithstanding the lack of widespread AMCG magmatism in NW South America during the late Mesoproterozoic, the congruence in geologic histories between the Putumayo Basin basement, the north Andean Proterozoic basement inliers, and Oaxaquia, suggests that the latter is an integral part of the Putumayo Orogen.

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Explanation of Acronyms, Abbreviations, and Symbols:

AMCG	Anorthosite–Mangerite–Charnockite–Granite
CHUR	Chondritic uniform reservoir
E–MORB	Enriched–mid ocean ridge basalt
FM	Florencia Margin
GAPES	Garnet–Pyroxene–Plagioclase–Quartz geobarometer of Eckert et al. (1991)
GHS	Greater Himalayan Sequence
GLOOS	Global subducting sediments
LA–ICP–MS	Laser ablation–inductively coupled plasma–mass spectrometry
LIP	Large igneous province
RNJ	Río Negro–Juruena
RSI	Rondonian–San Ignacio
SAMBA	South America Baltica
SIMS	Secondary ion mass spectrometry
SM	Solita Margin
TIMS	Thermal ionization mass spectrometry
TWQ	Software and thermodynamic database of Berman (1991)
UHT	Ultra–high temperature
VM	Vergel Margin

Author's Biographical Notes

Mauricio Ibañez–MEJIA graduated as a geologist from the Universidad Nacional de Colombia, Bogotá, in 2007. He obtained MS (2010) and PhD (2014) degrees in petrology and geochemistry from the University of Arizona, USA, followed by two years as a W.O. Crosby postdoctoral fellow in the Massachusetts Institute of Technology in Cambridge, USA, and four years as an assistant professor in the Department of Earth and Environmental Sciences at University of Rochester, USA. He is currently an assistant professor in the Department of Geosciences at the University of Arizona, USA. His main research interests are in the fields of isotope geochemistry, geochronology, petrology, and crustal evolution.