Intraplate Proterozoic Magmatism in the Amazonian Craton Reviewed: Geochronology, Crustal Tectonics and Global Barcode Matches

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Abstract We review geochronological data including U-Pb baddelyite ages of Proterozoic mafic dyke swarms and sills of the Amazonian Craton, as well as their geochemical character and geological settings, in order to arrive at an integrated tectonic interpretation. The information together with the characteristics of coeval volcanic-plutonic suites indicates a cyclicity of the mafic-felsic activity through time and space. At least four LIP/SLIP events are apparent, and each one appears to accompany the stepwise accretionary crustal growth of Amazonia. The oldest two, the Orocaima (1.98–1.96 Ga) and Uatumã (c. 1.89–1.87 Ga) SLIPs, comprise calc-alkaline I-type and subordinate A-type plutonic and volcanic rocks. Synchronous mafic intraplate activity occurs across the Guiana and Central-Brazil Shields. These two events may be caused by interaction between subduction-related processes and mantle plumes with synchronous lithosphere extension during the two time periods. The Avanavero (1.79 Ga) LIP event mostly consists of mafic dykes and sills which are intrusive into the Roraima platform cover, in the Guiana Shield. They show tholeiitic chemistry and similarities with E-MORB and subcontinental lithospheric mantle-derived basalts, whereas the REE pattern suggests affinity with intraplate settings. The age of the Avanavero rocks is identical to the Crepori Diabase, located ca. 1800 km away to the south (Central-Brazil Shield). The youngest LIP event (1.11 Ga), the Rincón del Tigre-Huanchaca, has the Rio Perdido Suite as a component in the Rio Apa Terrane, which is ca. 300 km away from the Rincón del Tigre Complex, located in the SW portion of the Amazonian Craton. Furthermore, the Central-Brazil and Guiana Shields boasts widespread intraplate mafic activity, highlighted by the Mata-Matá (1.57 Ga),

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Salto do Céu (1.44 Ga) and Nova Floresta (1.22 Ga) mafic sills and the Cachoeira Seca Troctolite (1.19 Ga). Contemporaneous A-type, rapakivi granites with roughly similar ages also occur elsewhere. These particular episodes are extension specific steps of the Mesoproterozoic Amazonia, and the quite large distribution is consistent with LIP events. In a broader perspective, the intermittent Proterozoic intracratonic activity has a barcode that matches LIP/SLIP events in Columbia and Rodinia.

Keywords Amazonian craton · Proterozoic dykes and sills
Large Igneous Provinces · Intraplate magmatism · U-Pb geochronology

1 Introduction

As widely known, mafic dyke swarms are one of the key tectonic elements for understanding the geodynamic evolution of the Earth in the Precambrian time, including timing of assembly and breakup of supercontinents. Dyke swarms are particularly important in paleogeographic reconstructions and coupled paleomagnetic poles. Also, potential barcode matches may be found with LIP/SLIP events and/or mantle plume events on other continents through time (e.g., Halls 1982; Fahrig 1987; Halls and Fahrig 1987; Bleeker and Ernst 2006; Bryan and Ernst 2008a, b; Ernst et al. 2013; Ernst 2014; Peng 2015; Shumlyanskyy et al. 2016a, b; Antonio et al. 2017). In this regard, Amazonia/West Africa discloses coherent connections with Baltica and eastern Laurentia through the Paleo- and Mesoproterozoic time frame, supported by the paleomagnetic evidences, geologic correlation of the accretionary belts along the active margins, as well periods of intraplate magmatism (e.g., Rämö and Haapala 1995; Bettencourt et al. 1999; Åhäll et al. 2000; Dall'Agnol et al. 2012; Gower and Krogh 2002; Högdahl et al. 2004; Tohver et al. 2006; Cordani et al. 2010a; Cordani and Teixeira 2007; Johansson 2009, 2014; Bogdanova et al. 2013; Bispo-Santos et al. 2014a, b; D'Agrella-Filho et al. 2012, 2016; Teixeira et al. 2016).

Precambrian mafic dyke swarms and sills (and coeval plutons) like in most cratons are common in the Amazonian Craton, where they highlight a recurrent activity in association with alkaline complexes and A-type plutonic and volcanic rocks (e.g., Santos et al. 2002a; Klein et al. 2012; Teixeira et al. 2015). Furthermore, the Amazonian Craton hosts scattered Mesozoic mafic dykes, such as the c. 200 Ma Cassiporé dyke swarm which aligns with the CAMP Large Igneous Province (LIP) event (e.g., Priem et al. 1968; Amaral 1974; Sial et al. 1987; Gibbs 1987; Teixeira et al. 2018), and this not focused here.

Since the studies in the 1960s, achievements have been made on the geochronology, geochemistry and petrology of dykes and sills over the Amazonian Craton, such as synthetized by Teixeira (1978, 1990), Gibbs (1987), Sial et al. (1987), Santos et al. (2002a), among others. These studies have aimed to characterize the main geologic features of such igneous episodes and their tectonic significance. Further paleomagnetic studies have provided insights on the paleogeographic context of the Amazonian Craton (see for review D'Agrella-Filho et al. 2016). For most of the mafic dyke swarms, only K-Ar, $^{40}Ar/^{39}Ar$ and Rb-Sr ages have been used as estimates of crystallization ages (e.g., Snelling and McConnell 1969; Hebeda et al. 1973; Amaral 1974; Teixeira 1990). More recently an increasing number of U-Pb baddeleyite ages of dykes and sills and associated rocks have defined prominent magmatic episodes in time and space (e.g., Vasquez et al. 2002; Santos et al. 2002a; Klein et al. 2012; Reis et al. 2013a; Silva et al. 2016; Teixeira et al. 2015, 2016; Antonio et al. 2017).

This review deals with the Paleo- to Mesoproterozoic dyke swarms and associated rocks in the Amazonian Craton, whose ages, geochemical characteristics and geology are reassessed for an integrated tectonic interpretation. The roughly coeval plutonic-volcanic events (A-type and calc-alkaline affinity) associated with extensional settings through time are also considered. In addition, we emphasize the importance of U–Pb baddeleyite geochronology in mafic dykes for constraining the timing of recurrent intracratonic mafic activity and to understand its overall tectonic significance. To complete this review we compiled more than 300 published U-Pb ages (in a GIS database) of Precambrian dykes, sills, layered mafic-ultramafic intrusions and associated silicic rocks (e.g., A-type rapakivi complexes) to identify the geologic correlations (Teixeira and Albrez 2017).

2 The Amazonian Craton

The Amazonian Craton (Fig. 1) is a result of a long-lived crustal growth by addition of continental and/or oceanic arcs in Paleo- to Mesoproterozoic times to one or two Archean nuclei in the northeast. The accretionary regime possibly involved intervening older continental blocks such as the Imataca Block which accreted to the northern portion of the Craton (Guiana Shield) at the time of the Transamazonian orogeny (2.25–1.95 Ga), whereas the late Paleoproterozoic Paraguá and Rio Apa Terranes subsequently accreted to the SW portion of Amazonia around 1.35 and 1.00 Ga, respectively (Teixeira et al. 1989, 2010; Santos et al. 2000; Tassinari and Macambira 2004; Boger et al. 2005; Cordani and Teixeira 2007; Cordani et al. 2010b). According to Cordani and Teixeira (2007) the tectonic framework comprises the Central Amazonian (>2.6 Ga) province and the Maroni-Itacaiunas (2.45–1.95 Ga) province in the northeast, as well as four adjoining provinces to the SW, namely Ventuari-Tapajós (2.01–1.80 Ga), Rio Negro-Juruena (1.82–1.60 Ga), Rondonian-San Ignacio (1.59–1.30 Ga) and Sunsas-Aguapeí (1.20–0.95 Ga) (Fig. 1). Whereas this early model is roughly followed in the review, we take into account recent geophysical information, systematic U-Pb dating and geochemical and isotopic constraints that have shed more light on the internal organization of some provinces and the nature of particular tectonic-magmatic events (e.g., Bettencourt et al. 2010; Fernandes et al. 2011; Santos et al. 2004; Rizzotto et al. 2013, 2014; Kroonenberg et al. 2016; Scandolara et al. 2017).

The Amazonian Craton is the host of four LIP-scale magmatic events (see Fig. 1), discriminated by the Orocaima (1.98–1.96 Ga), Uatumã (1.89–1.87 Ga), Avanavero (1.79 Ga) and Rincón del Tigre (1.11 Ga) events, among other intraplate activity through time and space—to be dealt with here. In particular, the two oldest events have

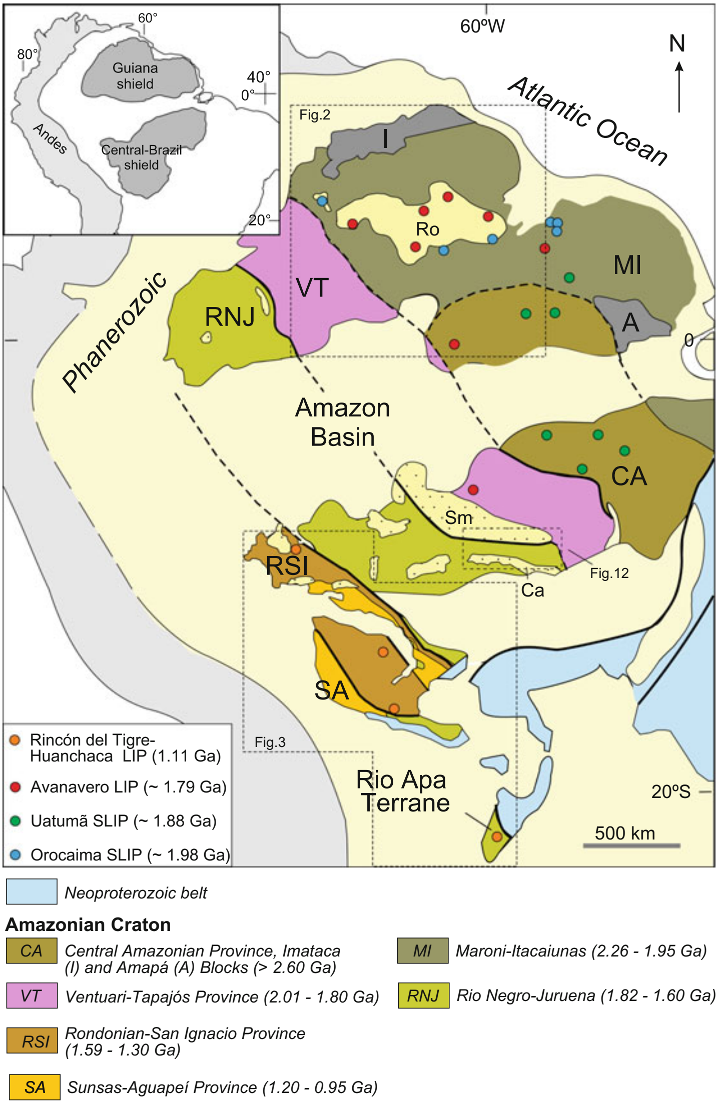

Fig. 1 Tectonic framework of the Amazonian Craton (adapted from Cordani and Teixeira 2007; Kroonenberg et al. 2016; Fraga et al. 2017). Proterozoic sedimentary covers (yellow doted domains): Ro (Roraima Supergroup), Sm (Sumaúma Supergroup; Cachimbo Graben), Cb (Caiabis Group; Caibis Graben). The distinct Proterozoic LIP/SLIP components (colourful dots) are also shown. See text for discussion

been termed with different names based on regional correlations with similar-looking volcanic-plutonic rocks. We summarize below the pertinent tectonic-geologic aspects of the Amazonian Craton that have important bearing for the scope of our review.

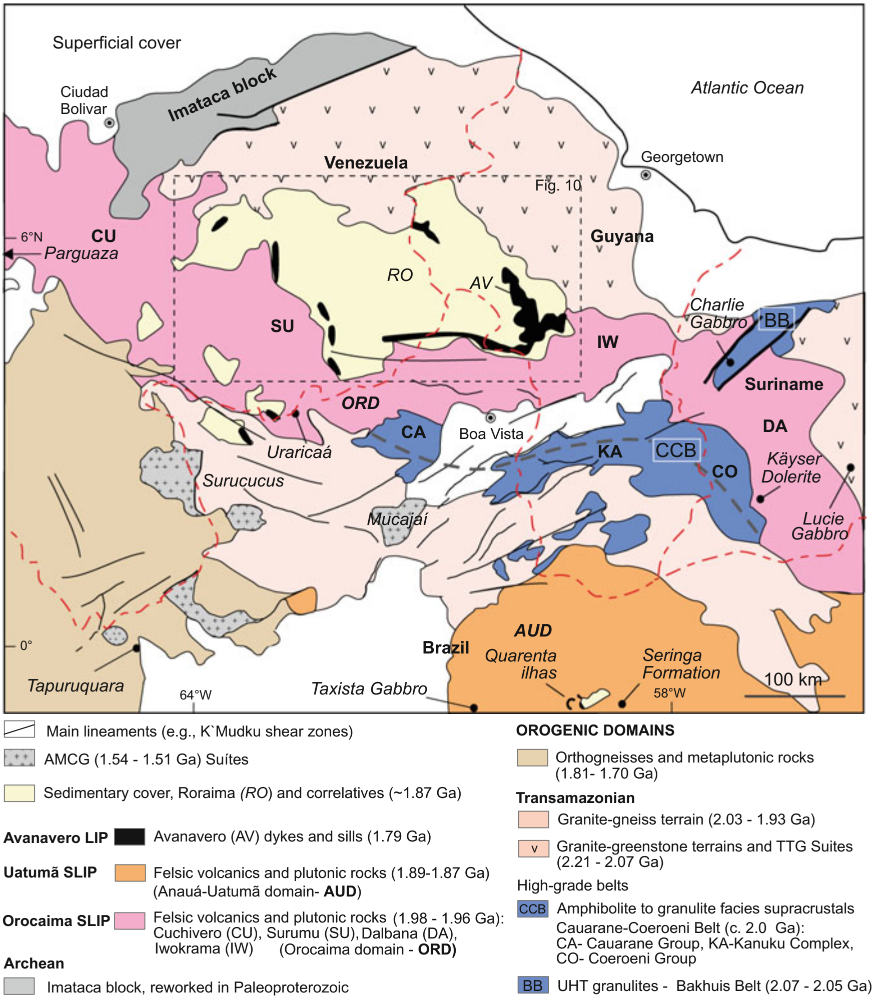

Fig. 2 Geologic outline of the central portion of the Guyana shield, including portions of the Imataca Block and the Central Amazonian, Maroni-Itacaiunas and Ventuari-Tapajos provinces. The distribution of the Orocaima and Uatumã SLIP and Avanavero LIP magmatisms are also shown. Adapted from Reis et al. (2017a, b) and Fraga et al. (2009, 2017). See text for details

The Maroni-Itacaiunas province (Fig. 2) where components of the Orocaima, Uatumã and Avanavero events occurred (see Sect. 4) is a product of successive accretionary arcs with later collision during the Orosirian. The most prominent tectonic components are the granite-greenstone and granite-gneissic terranes, as well as two roughly coeval high-grade metamorphic belts (e.g., Gibbs and Barron 1993; Delor et al. 2003; Cordani and Teixeira 2007; Vasquez et al. 2008; Fraga et al. 2009; Reis et al. 2004, 2013a). The granulitic belts in the Guiana Shield comprise: (i) the

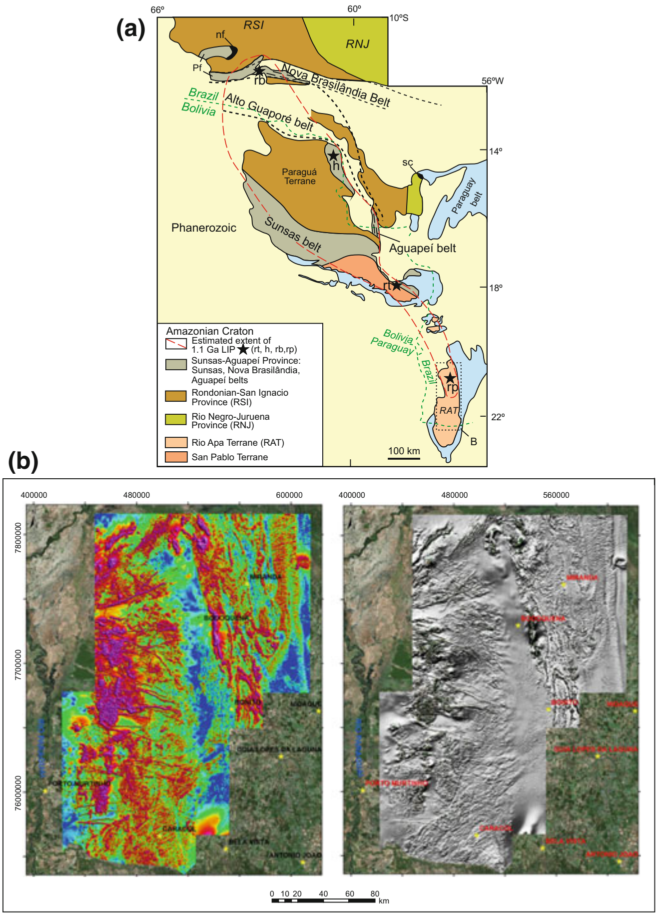

Fig. 3 **a** Tectonic outline of the SW portion of the Amazonian Craton, including parts of the Rio Negro-Juruena, Rondonian-San Ignacio and Sunsas-Aguapeí provinces. The possible correlative Rio Apa Terrane is also shown (adapted from Bettencourt et al. 2010; Rizzotto et al. 2013; Faleiros et al. 2016; Scandolara et al. 2017). Interpreted nodes of the 1.11 Ga Large Igneous Province are indicated by stars: rt (Rincón del Tigre), h (Huanchaca sill), rb (Rio Branco Suite in Mato Grosso), rp (Rio Perdido Suite), and its approximate outline indicated by the red dashed line. Other intraplate (≥1.20 Ga) mafic intrusions: Salto do Céu (sc) and Nova Floresta (nf) sills which is intrusive into the Palmeiral Formation (Pf) rift basin. Dashed black lines are inferred tectonic limits for the Nova Brasilândia and Alto Guaporé belts, respectively. **b** Aerogeophysical (total magnetic field) and radar image of a portion of the Rio Apa Terrane. The observed ~NW- and E-W trends highlight the orientations of the Rio Perdido Suite, supported by geologic mapping

2.07–2.05 Ga Bakhuis belt (fault bounded) whose granulites show peak conditions at 950–1050 °C and 8½–9 Kb (Kroonenberg et al. 2016 and references therein) and; (ii) the arcuate 2.01–1.98 Ga Cauarane-Coeroeni belt which is composed of amphibolite to granulite facies supracrustal rocks of Cauarane Group in Brazil, the

Kanuku Complex in Guyana and Coeroeni Group in Suriname (e.g., Fraga et al. 2009). The Paleoproterozoic crust is intruded in places by S-type granitic plutons (1.76–1.75 Ga), as well as by anorthosite-mangerite-charnockite-granite (AMCG) plutons (1.55–1.51 Ga), such as the Parguaza rapakivi batholith (1.51 Ga; Tassinari et al. 1996) and the 1.54 Ga Mucajaí anorthosite-mangerite-rapakivi granite (AMG) association (see Fig. 2) (Fraga et al. 2009). Restricted parts of the Maroni-Itacaiunas province are likely to be Archean (Amapá block; Fig. 1) and/or reclycled crust intruded by rich-K granites during the Orosirian times, such as in parts of the Imataca block (e.g., Tassinari et al. 2004; Tassinari and Macambira 2004; Cordani and Teixeira 2007; Kroonenberg et al. 2016; Fraga et al. 2017).

Large portions of the continental crust in the Central-Brazil Shield consolidated in Orosirian times, similar to the Maroni-Itacaiunas province. In particular, the southern portion (i.e., Tapajós region) of the Ventuari-Tapajós province accreted through the Tapajonic arcs, active between 2.01 and 1.90 Ga (Fernandes et al. 2011 and references therein). According to these authors these arcs involved northward flat subduction beneath the Archean/Paleoproterozoic continental margin, which eventually triggered nearby post-collisional activity over the already stable area, and linked with the Uatumã SLIP event to be discussed in Sect. 4.2.

After the consolidation of the Ventuari-Tapajós province, multiple orogenic belts subsequently accreted to the SW portion of the proto-Amazonian Craton. For instance, recent structural-tectonic studies, supported by geophysical interpretation (Scandolara et al. 2017) in the southern segment of the Rio Negro-Juruena province (Fig. 3a), characterized the Juruena accretionary orogeny (1.82–1.74 Ga). Contemporaneous calc-alkaline, granitic and (K-high) felsic volcanic rocks such as the Teles Pires Suite (1.78–1.76 Ga) occur within the adjoining portion of the Ventuari-Tapajós province, which in turn is age-equivalent to the Avanavero LIP event to be dealt with here. The Juruena orogenic belts underwent metamorphism at c. 1.69–1.63 and 1.42–1.37 Ga (Bettencourt et al. 2010; Scandolara et al. 2017). Furthermore the Rio Negro-Juruena province hosts several generations of A-type granitoids such as the Serra da Providência Suite (1.60–1.51 Ga; Table 2). Other A-type plutons with documented U-Pb ages from 1.40 to 1.31 Ga, as well as Mesoproterozoic tectonic basins are also present (Payolla et al. 2002; Bettencourt et al. 2010; Scandolara et al. 2013).

The Rondonian-San Ignacio province (Fig. 3a) is a result of a composite orogeny initiated at c. 1.59 Ga, which evolved through multiple arc accretion (e.g., 1.59–1.52, 1.51–1.48, 1.48–1.42 Ga), oceanic closure and final microcontinent–continent collision against the continental margin of the Rio Negro-Juruena province at c. 1.35 Ga (Cordani and Teixeira 2007; Bettencourt et al. 2010). As a matter of fact widespread reworking of the western portion of the Rio Negro-Juruena crust occurred during the time. The stepwise evolution was accompanied by intraplate mafic-felsic activity within the already stable parts of the proto-Craton (see Sects. 4 and 5).

The Alto Guaporé orogen (e.g., Rizzotto et al. 2014) which is the most prominent geologic-tectonic element of the Rondonian-San Ignacio province evolved in two steps, from 1.47–1.43 (accretionary phase) to 1.35–1.33 Ga (collisional phase). Strong magnetic anomalies and associated thrusts and shear zones highlight a WNW/ESE fossil suture zone preserved in the Alto Guaporé belt (see Fig. 3a), which is exemplified by syntectonic tonalitic-plagiogranitic plutons (c. 1.43 Ga) intruded into the ophiolites, marking the accretionary orogenic phase (Rizzotto et al. 2013 and references therein). The collisional phase marks the suturing of the Paraguá Terrane (1.82–1.66 Ga) against the proto-continental margin (i.e., Rio Negro-Juruena province) and eventually the consolidation of the Rondonian-San Ignacio province (e.g., Boger et al. 2005; Cordani and Teixeira 2007; Santos et al. 2008; Bettencourt et al. 2010; Rizzotto et al. 2014; Scandolara et al. 2017). The latter province is also the host of penecontempaneous late- to post-tectonic intraplate magmatism related to the collisional stage, exemplified by the 1.34–1.36 Ga Alto Candeias and the 1.31–1.30 Ga São Lourenço-Caripunas suites—as depicted in Table 3 (Bettencourt et al. 2010).

Finally, both the Rondonian-San Ignacio and the Rio Negro-Juruena provinces experienced later collision-related deformation which is considered to be late offshoots of the c. 1.10–1.00 Ga Sunsas orogeny, such as shear zones, tectonothermal overprints, metasedimentary belts (e.g., Nova Brasilândia), as well as magmatism. Post-tectonic to an orogenic stages took place after c. 1.00 Ga, evidenced by the occurrences of granites, pegmatites (0.99–0.97 Ga) (e.g., Rizzotto et al. 2002; Tohver et al. 2004, 2006; Teixeira et al. 2010). This orogeny which is the youngest and southwesternmost of the orogenic events recorded along the SW portion of the Amazonian Craton built the Sunsas-Aguapeí province (e.g., Teixeira et al. 2010; Bettencourt et al. 2010). This province hosts the 1.11 Ga Rincón del Tigre-Huanchaca LIP (Darbyshire 1979; Teixeira et al. 2015 and references therein) to be discussed in Sect. 4.4.

In particular, the Nova Brasilândia metasedimentary belt (see Fig. 3a) within the Rondonian-San Ignacio province (reworked portion of the Rio Negro-Juruena province; Bettencourt et al. 2010) originated in a precursor intracontinental rift setting (c. 1.35 Ga) which evolved to passive margin with narrow oceanic opening and subsequent crustal shortening and thrusting during which coeval bimodal magmatism (Rio Branco Suite) emplaced into the strata (Rizzotto et al. 2001, 2002). The Aguapeí metasedimentary belt (aborted rift) is roughly coeval with the Nova Brasilândia belt, as indicated by the comparable detrital zircon ages (<1230 and <1215 Ma), respectively (e.g., Teixeira et al. 2010 and references therein). During the onset of the Sunsas orogeny intraplate activity, reactivation of structures and tectonic basins occurred in places of the Central-Brazil and Guiana Shields. Specifically the Palmeiral rift basin which occurs in the Rondonian-San Ignacio province (Fig. 3) is intruded by 1.2 Ga mafic sills to be dealt with later.

3 Characteristics of the Paleo- to Mesoproterozoic Intraplate Activity

The most important Paleo- to Mesoproterozoic dyke swarms and sills, associated intraplate felsic volcanic-plutonic units and other mafic-ultramafic intrusions crop out in relatively low relief areas in the Guiana and Central-Brazil Shields, overlain by the

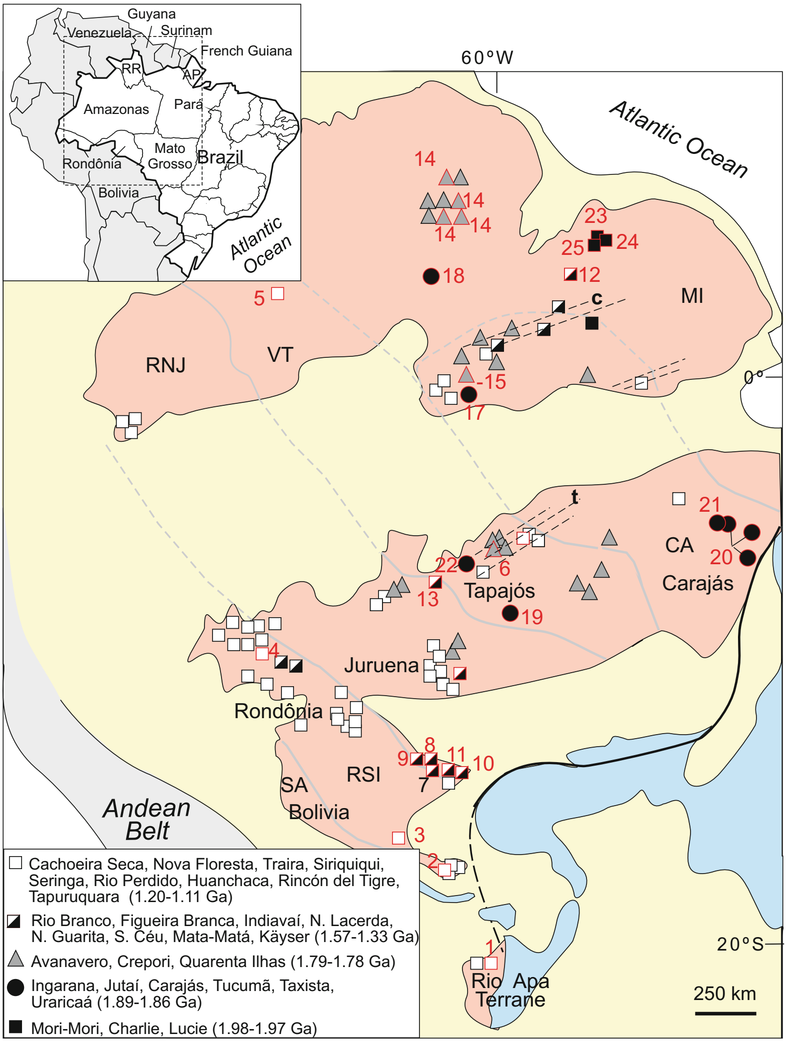

Fig. 4 Map of the Amazonian Craton, with symbols showing mafic dykes and sills and mafic-ultramafic complexes with published age determinations, grouped in different time groups (adapted from Teixeira 1990; Santos et al. 2002a). Some symbols represent multiple dated samples. Red frames (symbols) with numbers highlight key U-Pb ages used in the text. Boundaries between the tectonic provinces (abbreviations as in Fig. 1) are shown by gray dashes. 1. Major shear zones/lineaments are also outlined (black dashes): c = Cachorro; t = Tocantins. Inset: Brazilian Federal States (Amazon region): RR = Roraima, AP = Amapá, MT = Mato Grosso, RO = Rondônia, AM = Amazonas

Phanerozoic strata of the Amazon Basin. Within the Amazonian Craton the profuse mafic magmatic episodes of intracontinental setting are roughly contemporaneous with the Paleo- to Mesoproterozoic stepwise accretionary evolution of the tectonic

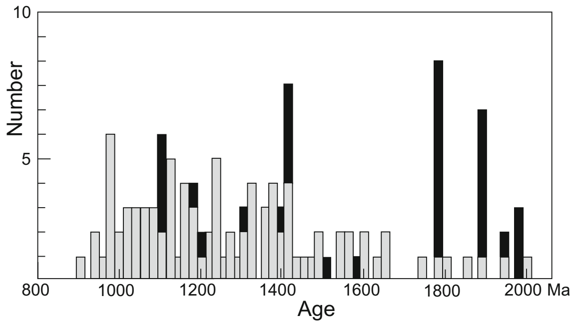

Fig. 5 Age-histogram (K-Ar, Ar-Ar and Rb-Sr ages: gray bars; U-Pb ages: black bars) of Proterozoic dykes and sills, and mafic-ultramafic complexes in the Amazonian Craton

provinces (see above). These rocks appear to be associated with major reactivated structures within the already stable parts of the craton (e.g., Cordani et al. 2010a and references therein). Specifically, the mafic activity comprises dykes, sills, flows and irregular bodies, to which alkaline complexes, rapakivi granites and (A- and I-type) volcanic-plutonic associations are related (e.g., Amaral 1974; Gibbs and Barron 1993; Teixeira 1978; Payolla et al. 2002; Santos et al. 2002a and references therein).

There is a systematic decrease in the radiometric ages of the intraplate activity towards the SW of the Amazonian Craton, as depicted in Fig. 4. The geochronologic data suggests an intermittent cratogenic mafic activity which is currently constrained in the time interval 2.00–0.90 Ga, on the basis of the different age methods (Fig. 5). However, we are aware that the K-Ar and Rb-Sr ages could be isotopically reset, and therefore their realiability are tested by newly published ages and the geologic correlation with associated rocks. Furthermore, the number of U-Pb ages (see Table 1 and Fig. 5) does not necessarily reflect the relative volume of the mafic magmas that originated during the magmatic pulses.

4 The Plutonic-Volcanic (LIP Scale) Events

At least four magmatic events (SLIP or LIP scale) occurred in the Amazonian Craton, well-defined by U-Pb ages, namely Orocaima (1.98–1.96 Ga), Uatumã (1.89–1.87 Ga), Avanavero (1.79 Ga) and Rincón del Tigre-Huanchaca (1.11 Ga), respectively (dots in Fig. 1). Their geologic-tectonic characteristics are overviewed, as suggested by the geochronologic and geochemical information. Morphology, dimension and geologic setting of each SLIP/LIP are discriminated when available from the literature, otherwise inferred by the integrated information.

The terminology of the lithostratigraphic units along the text follows the published information (e.g., suite, association, complex, swarm, mafic intrusion, Group, Formation) in a flexible way because of the review scope. However, we are aware that in some cases the standard classification may not have been strictly applied. Table 1 presents the available U-Pb ages for the mafic dykes, sills and mafic-ultramafic

Table 1 Compilation of U-Pb ages of intraplate activity (basaltic rocks and mafic-ultramafic complexes) in the Amazonian Craton

Stratigraphic unit (N)	Description	Location	U-Pb age (Ma)	References
Rio Perdido Suite (1)	Dykes (gabbros and diabases)	Rio Apa Block (SE Amazonia; Mato Grosso do Sul state)	[1]1111 ± 1 (b)	Teixeira et al. (2018)
Rincón del Tigre (2)	Layered complex (*granophyre*)	Bolivian Precambrian Shield	[1]*1110 ± 2* (b)	Teixeira et al. (2015)
Huanchaca Suite (3)	Gabbro sills and dykes	Bolivian Precambrian Shield (Paragua Terrane)	[1]1112 ± 2 (b)	Teixeira et al. (2015)
[a]Rio Branco Suite (4)	(Meta) leucogabbro	Rondonia-San Ignacio Province (Rondonia state)	[1]1110 ± 10 (z)	Rizzotto et al. (2002)
Tapuruquara Suite (5)	Elongated to semi-rounded stocks (*gabbro*)	Ventuari-Tapaós Province (NW Amazonas state)	[2]*1172 ± 8 (b)*	Santos et al. (2006)
Cachoeira Seca Troctolite (6)	Lacoliths and dykes of alkalic gabbro-troctolite	Ventuari-Tapaós Province (SW Para state)	[2]1186 ± 12 (b)	Santos et al. (2002a)
Nova Lacerda (7)	Mafic dykes of basaltic composition and tholeiitic affinity	Rio Negro-Juruena Province (Mato Grosso state)	[1]1387 ± 17 (b)	Teixeira et al. (2015)
Indiavaí Suite (8)	Mafic intrusion	Rio Negro-Juruena Province (Mato Grosso state)	[1]1416 ± 7 (b)	Teixeira et al. (2011)
Figueira Branca Suite (9)	Mafic-ultramafic layered complex and gabbroic stocks	Rio Negro-Juruena Province (Mato Grosso state)	[1]1426 ± 8 (b)	Teixeira et al. (2011)
Rio Branco Suite (10)	Mafic member (gabbro, tholeiitic dykes and porphyritic basalt). Felsic member (rapakivi granite)	Rio Negro-Juruena Province (Mato Grosso state)	[1]1423 ± 2 (z)	Geraldes et al. (2004)

(continued)

Table 1 (continued)

Stratigraphic unit (N)	Description	Location	U-Pb age (Ma)	References
Salto do Ceu Gabbro (11)	Tholeiitic, gabbro sills	Rio Negro-Juruena Province (Mato Grosso state)	[1]1439 ± 4 (b)	Teixeira et al. (2016)
Kayser Diabase (12)	Alkaline diabase dykes	Maroni-Itacaiunas Province (Suriname)	[3]1528 ± 2 (b)	De Roever et al. (2014)
Mata-Matá Gabbro (13)	Tholeiitic, diabase sill	Ventuari-Tapajós Province (SE Amazonas state)	[2]1576 ± 4 (b)	Betiollo et al. (2009)
[b]Avanavero Diabase (14)	Tholeiitic dykes, sills, ring structures: Pedra Preta, Cipo, Cotingo, Manga Brava (Brazil); Omai, Tumatumari (Guyana)	Central Amazonian Province (Roraima state; Venezuela, Guyana)	[1]1793 ± 1 (b); [1]1794 ± 2 (b); [1]1794 ± 2 (b, zr); [2]1787 ± 14 (b); [2]1782 ± 3 (b); [2]1786 ± 3 (b)	Reis et al. (2013a), Santos et al. (2004), Norcross et al. (2000)
Quarenta Ilhas Diabase (15)	Tholeiitic sill (elliptical cone sheet structures); Ring dyke	Central Amazonian Province (NE Amazonas state)	[2]1780 ± 3 (b)	Santos et al. (2003)
[b]Crepori Diabase (16)	Sills and dykes of tholeiitic gabbro, diabase, andesite and granophyre	Ventuari-Tapajós Province (SW Para state)	[2]1780 ± 7 (b)	Santos et al. (2002a)
[c]Taxista Gabbro (17)	Dyke intrusive into the Agua Clara granitoid	Central Amazonian Province (NE Amazonas state)	[2]1859 ± 15 (b)	Simões et al. (2015)
[a]Uraricaá Suite (18)	Gabbro, diabase, and minor hornblendite	Central Amazonian Province (NW Roraima state)	[2]1882 ± 4 (b)	Fraga et al. (2017)

(continued)

Table 1 (continued)

Stratigraphic unit (N)	Description	Location	U-Pb age (Ma)	References
Ingarana Suite (19)	Gabbro, anorthosite, diabase dykes, syenite: Ingarana, Jutaí	Ventuari-Tapajós Province (SW Para state)	[2]<1893 ± 10; 1879 ± 3; 1878 ± 9 (b-z)	Santos et al. (2000, 2001, 2002a)
[c]Tucumã (20)	Felsic and mafic dykes (bimodal), including those in Carajas	Central Amazonian Province (Para state)	[2]1881 ± 7; [2]1882 ± 9	Silva et al. (2016), Teixeira et al. (2018)
[c]Santa Rosa (21)	Rhyolite dyke	Central Amazonian Province (Para state)	[2]1895 ± 11 (z)	Antonio et al. (2017)
[c]Teodorico Diabase (22)	Tholeiitic gabbro dykes (Ingarana Suite?)	Ventuari-Tapajós Province (SW Para state)	[2]1893 ± 10 (z)	Santos et al. (2002a)
[d]Charlie Gabbro (23)	Gabbro	Maroni-Itacaiunas Province (Suriname)	[1]1971 ± 15 (b)	Klaver et al. (2016)
[d]Moi-Moi Gabbro (24)	(Meta)gabbro	Maroni-Itacaiunas Province (Suriname)	[2]1984 ± 4 (z)	Klaver et al. (2016)
[d]Lucie Gabbro (25)	Gabbro	Maroni-Itacaiunas Province (Suriname)	[3]1985 ± 4 (z)	Kroonenberg et al. (2016)

See text for explanation
U-Pb ages: [1]Isotopic dilution-thermal ionization mass spectrometer (TIM S); [2]sensitive high-resolution ion microprobe; [3]Kober method (single zircon Pb evaporation) 207/206 age. Components of LIP/SLIP events: [a]Rincón del Tigre-Huanchaca; [b]Avanavero; [c]Uatuma; [d]Orocaima. Age dating corresponding with particular rocks are shown in italics in lines 2 and 5 (see columns 2 and 4). Minerals: zircon (zr), baddeleyite (b)

complexes, used as key-time markers for the tectonic events. The accompanying Table 2 shows the age-equivalent plutonic-volcanic associations and plutonic rocks (selected) as well as their tectonic settings. The potential barcode matches between the Amazonian SLIP/LIP events and intraplate activity on other continental blocks through time are shown in Table 3.

Table 2 Compilation of U-Pb ages of selected plutonic rocks in the Amazonian Craton and their interpreted tectonic characteristics

Stratigraphic unit	Assemblage	U-Pb age (Ma)	Interpreted tectonic setting	References
Sunsas Granites	Taperas granite	1076 ± 18	Arogenic	1
Rio Branco Suite	Mafic to felsic members: gabbro, metagabbro, amphibolite, metadiabase, granite.	1110–1098	A-type, within-plate	2, 3
Santa Clara Suite	Monzogranite, syenogranite, granite	1082–1074	Anorogenic	4
Seis Lagos Complex	Carbonatite, carbonite breccia, siderite carbonatite	1154–1328	Anorogenic	5
Sao Lourengo-Caripunas Suite	Alkali-feldspar granite, syenogranite, quartz- syenite, and rhyolite porphyry	1314–1309	Post-collisional	4, 12, 17
Alto Candeias Suite	Monzogranite, syenogranite, charnockite and syenite	1346–1338	Late-tectonic	4, 12, 17
Rio Branco Suite	Felsic to mafic members: syenite, rapakivi granite, gabbro, diabase, basalt	1423 ± 2	Anorogenic	6, 7
Serra Grande Suite	Co-magmatic charnockites and rapakivi granites	1434–1425	Anorogenic	8
Mucajaí	Granite, mangerite, anorthosite (AMG) complex	1538 ± 5	Within-plate	9
Parguaza and Surucucus Suites	Rapakivi granites	1510;1551 ± 5	Anorogenic	4, 10, 11, 12
Serra da Providência Suite	Rapakivi granites, charnockitic/mangeritic granitoids, gabbronorite, gabbro	1600–1570, 1570–1560, 1550–1540; 1510	Anorogenic; within-plate	4, 12, 13
Teles Pires Suite	Granitic plutons and felsic volcanic rocks	1780–1760	A-type; post-collisional	14, 15, 16, 17
Madeira Suite	Albite-rich granite, per-alkaline granite	1839–1822	Post-collisional	18
Maloquinha Suite	Aluminous alkaline granites, syenogranites	1877–1865	A-type, post-collisional	19, 20
Parauari Suite	Calc-alkaline, monzogranite, granodiorite (mainly)	1883–1879	Post-collisional	19, 20

(continued)

Table 2 (continued)

Stratigraphic unit	Assemblage	U-Pb age (Ma)	Interpreted tectonic setting	References
Rio Pardo	Rapakivi granites, charnockites, enderbites and a gabbroic complex	1882–1860	Within-plate	21
Mapuera Suite	Granite, granodiorite, syenite, charnockite	1880–1871	Within-plate	22, 23
Kabalebo	Charnockites	1992–1984	Post-collisional	24
Pedra-Pintada-Surumu	Calc-alkaline (mainly), I-type plutonic and volcanic rocks	1985–1982	Post-collisional	25
Aricamã-Cachoeira da Ilha Suite	Syenogranite, K-feldspar granite, ignimbrite	1983 ± 4; 1973 ± 8	A-type, post-collisional	9, 25

Bold ages (Serra da Providência suite) are considered peak magmatism. See text for explanation
[1]Boger et al. (2005); [2]Rizzotto et al. (2001); [3]Tohver et al. (2004); [4]Bettencourt et al. (1999, 2010); [5]Rossoni et al. (2017); [6]Geraldes et al. (2004); [7]Teixeira et al. (2016); [8]Santos et al. (2011); [9]Fraga et al. (2009a); [10]Tassinari et al. (2006); [11]Santos et al. (2003); [12]Payolla et al.(2002); [13]Scandolara et al. (2013); [14]Santos et al. (2001); [15]Santos et al. (2008); [16]Neder et al. (2002); [17]Scandolara et al. (2014; 2017); [18] Bastos Neto et al. (2014); [19]Santos et al. (2000); [20]Vasquez et al. (2002); [21]Simoes et al. (2015); [22]Ferron et al. 2010; [23]Reis et al. (2017b); [24]Klaver et al. (2015); [25]CPRM (2010)

4.1 The Orocaima (1.98–1.96 Ga) Magmatism

The Orocaima volcanic-plutonic magmatism (Reis et al. 2003) is the oldest late Paleoproterozoic intraplate event of LIP scale across the Guiana Shield (Reis et al. 2003; Fraga et al. 2009 and references therein). The minimum areal extent of the Orocaima volcanic-plutonic magmatism is c. 200,000 km^2, only considering the exposure in the Guiana Shield.

The Orocaima rocks (e.g., Reis et al. 2004) mainly comprise high-K, calc-alkaline I-type rocks belonging to the Pedra Pintada-Surumi plutonicvolcanic association (1982 ± 3; 1984 ± 7; 1985 ± 1 Ma). This association is coeval with subordinate A-type volcanic rocks (Cachoeira da Ilha Formation) and rapakivi granites such as the Aricamã Suite (1986 ± 4 Ma; Fraga et al. 2009—see Table 2) in the Roraima block, northwestern portion of the Central-Amazonian province (Cordani and Teixeira 2007). This block is the host of the Roraima clastic sedimentary rocks, which is well-constrained in age to 1873 ± 3 Ma, on the basis of zircon U-Pb age determinations in interbedded tuff layers (Santos et al. 2003; Reis et al. 2017a). This sedimentary basin (Fig. 2) is intruded by mafic sills of the Avanavero Suite (Gibbs and Barron 1993; Reis et al. 2017a)—to be dealt with here.

The Surumu Group dominantly consists of ignimbrites with rhyolitic to andesitic composition, and subordinate subvolcanic intrusions and sedimentary layers (CPRM

Table 3 Potential barcode matches with the studied LIP/SLIP events. See pertinent sections for explanation

LIP/SLIP events	Potential Barcode matches	Paleotectonic connections
Rincón del Tigre–Huanchaca LIP (1.11 Ga)	Initiation of Keweenawan magmatism of Central Laurentia (Midcontinent Rift); Southwestern USA diabase province and its extent to northern Mexico (Tohver et al. 2006; Ernst et al. 2013; Stein et al. 2014; Bright et al. 2014); intraplate magmatism throughout the Kalahari, Congo and India cratons (Ernst 2014 and references therein)	Grenville Orogen
Avanavero LIP (1.79 Ga)	Ropruchey sills (Fedotova et al. 1999), Shosksha Formation (Pisarevsky and Sokolov 2001), Hoting gabbro (Elming et al. 2009) and Smaland-Varmland Intrusions in the Fennoscandia shield (Högdahl et al. 2004; Pisarevsky and Bylund 2010); Ultramafic-mafic dykes, coeval tholeiitic and jutonitic dykes and associated AMCG complexes in the Ukranian shield (Shumlyanskyy et al. 2016a, b, 2017); Xiong'er volcanics and Taihang dyke swarm in the North China Craton (Peng 2015)	Columbia
Uatumã SLIP (1.88–1.87 Ga)	Circum-Superior LIP of the Superior Craton (Jowitt and Ernst 2013); Widespread intraplate magmatism throughout the Slave Craton (Buchan et al. 2010; Ernst et al. 2013; Ernst 2014 and references therein). Dykes and sills in the Bastar and Dharwar, Siberia, Kaapvaal and Zimbabwe cratons (Ernst 2014)	Columbia
Orocaima SLIP (1.98–1.96 Ga)	Pechenga-Onega LIP of the Karelian-Kola Craton (Lubnina et al. 2016); Xiwangshan dyke swarm of the North China Craton (Peng 2015); Khajuraho-Jhansi dyke swarm of the Bhundelkhand Craton (Pradhan et al. 2012)	Columbia

2010 and references therein), mainly exposed in the Guiana Shield, Brazil (see Fig. 2). The correlative lithostratigraphic units occur in Venezuela (Cuchivero Group), Guyana (Iwokrana Group) and Suriname (Dalbana Group), and are predominantly composed of ignimbrites with varied composition similar to the Surumu rocks (e.g., Gibbs and Barron 1993; Delor et al. 2003 and references therein) (Fig. 6). However, we are aware that more robust geochronology coupled with petrologic studies is necessary to confirm the correlation between these lithostratigraphic associations. The fact that the Orocaima rocks are predominantly acid to intermediate in composition and their large geographic occurrence is consistent with a Silicic Large Igneous Province (SLIP) (cf. Bryan 2007; Bryan and Ernst 2008a, b).

Subordinate mafic activity (see Table 1) synchronous with the Orocaima SLIP event is apparent in Suriname, such as the Charlie gabbros and Moi-Moi metagabbros (1971 and 1984 Ma; see Table 1) which occur as km-sized bodies completely

Fig. 6 Field aspects of the Orocaima SLIP: **a** Lapilli-tuff (Surumu Formation, Brazil); **b** Ignimbrite (Iwokrama Formation, Guyana); **c** Dacitic Ignimbrite (Dalabana Formation, Suriname); **d** Aricamã rapakivi granite (Brazilian Roraima state) (photos by N. J. Reis)

enclosed by the Kabalebo charnockites (1984–1992 Ma), in the Bakhuis UHT granulitic belt (see Fig. 2). One anorthosite in the center of this belt was dated by zircon Pb evaporation at 1980 Ma, whereas the Lucie Gabbro in the eastern portion of Suriname yielded a similar zircon Pb evaporation age (1985 ± 4 Ma). These (ACG) rocks post-date the UHT event (Transamazonian orogeny) (Klaver et al. 2015, 2016 and references therein; Kroonenberg et al. 2016 and references therein).

The fact that the Orocaima volcanic-plutonic event roughly accompanies the arcuate exposure of the Cauarane-Coeroneni collisional belt (2.01–1.98 Ga) similarly suggests a connection between the orogen and extensional dynamics that gave rise to this particular event. Furthermore, the calc-alkaline characteristics of the volcanic-plutonic association are consistent with subduction-related arc magmatism, whereas the contemporaneous A-type volcanics, the Aricamã Suite (Roraima) and the ACG suites of Suriname (see above) are post-collisional in character (Reis et al. 2003, 2004; Delor et al. 2003; CPRM 2010; Klaver et al. 2015, 2016). Additional petrogenetic studies are needed for contraining the mantle and/or lithospheric sources from with the Orocaima rocks derived. Finally, from a global perspective the 1.98–1.96 Ga SLIP has potential age-equivalent units in many continental blocks, as summarized in Table 3.

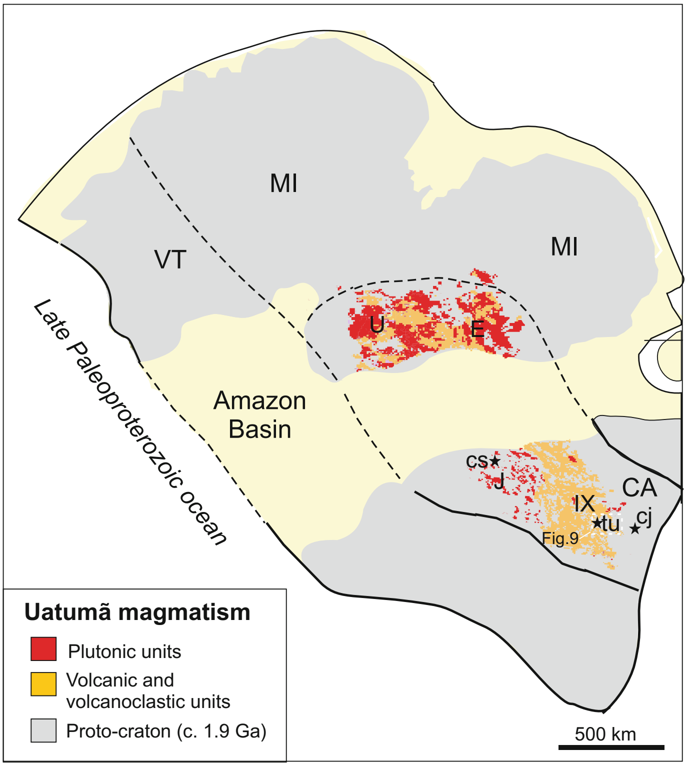

Fig. 7 Geologic cartoon showing the Uatumã SLIP in the proto-Amazonian Craton at c. 1.8 Ga. Tectonic domains within the Central Amazonian province: Anauá-Uatumã; E = Erepecuru-Trombetas; J = Jamanxim; I = Iriri-Xingu. Keys: Cachoeira Seca troctolite (cs); Tucumã bimodal swarm (tu), Carajás dykes (cj). Tectonic provinces (CA, MI and VT) are delineated as in Fig. 1

4.2 The Uatumã (1.89–1.87 Ga) Magmatism

The Uatumã SLIP (Klein et al. 2012 and references therein) has an estimated exposure of ~400,000 km^2 across the already stable continental crust of the Central Amazonian province, although part of the rocks within this area (Fig. 7) is possibly related to the older Orocaima magmatism. Similar to this, the Uatumã event is predominantly acid to intermediate, with peak ages between 1.89 and 1.87 Ga. This SLIP event has age match with the Uraricaá Suite (1882 ± 4 Ma; see Table 1 and Fig. 2) which is composed of low-Titanium tholeiitic gabbro with chemistry akin to basalts, basaltic-andesites and picrobasalts. Hornblendites are subordinate (Fraga et al. 2017). The A-type Rio Pardo Association (1882–1860 Ma; Table 2), which is composed of rapakivi granites, charnockites, enderbites and a gabbroic complex located in the Guiana Shield, is age equivalent with the Uatumã SLIP event (Simões et al. 2015). According to these authors, this particular A-type activity may include the spatially related Taxista Gabbro (1859 ± 15 Ma; see Table 1) which is hosted by the Água Branca granite (c. 1890 Ma) in the Anauá-Uatumã domain (see Fig. 2).

The Uatumã event, according to Klein et al. (2012), comprises an association of calc-alkaline I-type and A-type volcanic and plutonic rocks, as discriminated below:

(i) The effusive rocks where erupted rhyolites predominate. These rocks have been included into several stratigraphic units (Iriri and Iricoumé Groups; Bom Jardim, Sobreiro and Santa Rosa Formations) with different units exposed in different parts of the Central-Brazil Shield (Klein et al. 2012; Roverato et al. 2017; Antonio et al. 2017). The Iricoumé (1896–1882 ± 11 Ma; Santos et al. 2002a; Ferron et al. 2010) and Iriri (1870 Ma; Santos et al. 2001) groups have been correlated with similar-looking, dominantly silicic volcanic sequences in southern Guyana (Kuyuwini Group)—see Fig. 2 (Santos et al. 2004; Klein et al. 2012; Barreto et al. 2013; Silva et al. 2016; Fraga et al. 2017). Field aspects of the volcanic lithotypes of the Uatumã LIP are presented in Fig. 8.
(ii) The A-type (post-collisional and anorogenic) granitic plutons in the Central-Brazil Shield such as the Maloquinha Suite (1877–1865 Ma; Lamarão et al. 2005), as well as the I-type Água Branca Suite (1890–1980 Ma) and the Parauari Suite (1890–1870 Ma). Penecontemporaneous granitic intrusions occur in the Guiana Shield, such as the Mapuera (1880–1871 Ma) and Madeira Suites (1839–1822 Ma) in the Uatumã-Anauá Domain (Fig. 2), encompassed by the Iricoumé volcanics. The A-type granites are metaluminous to peralkaline, whereas the Parauari rocks show high-K, calc-alkaline affinity (e.g., Vasquez et al. 2002; Santos et al. 2002a; Lamarão et al. 2005; Dall'Agnol and Oliveira 2007; Ferron et al. 2010; Bastos Neto et al. 2014; Reis et al. 2017b).

The Uatumã SLIP event also includes the NW-oriented Tucumã bimodal dyke swarm (1881 ± 7 and 1882 ± 9 Ma; Silva et al. 2016 and references therein) (Fig. 9), as well as NW- and NW trending, mafic to intermediate dykes with identical ages (Teixeira et al. 2018); see Table 1) in the Carajás-Rio Maria region to the east. Locally these dykes form composite mafic-felsic bodies. All these dykes are correlated to the Uatumã SLIP on the basis of tight age match and similar intraplate setting (see Table 1).

According to Silva et al. (2016), the Tucumã swarm is comprised of three lithotypes, intrusive into the Archean granite-gneissic rocks and the associated greenstone belt (see Fig. 9): felsic (porphyritic rhyolites), mafic (basaltic andesites and subordinate basalts) and intermediate (andesite, dacite) rock. In particular, the rhyolites show porphyric, rapakivi-textures that suggest a close relationship with the nearby granitic plutons of the Maloquinha Suite (see Fig. 8e, f), intrusive into the Archean crust of the Central Amazonian province (e.g., Silva et al. 2016 and references therein). The felsic dykes are peraluminous to slightly metaluminous and akin to A2, ferroan and reduced granites (see Fig. 9 in Silva et al. 2016), whereas intermediate and mafic dykes are metaluminous and belong to the tholeiitic series. The emplacement of the Maloquinha plutons roughly follows the NW-SE general trend of the Tucumã dykes, whereas their sheeted-like geometry can be explained as a direct response to the extensional tectonic regime (Oliveira et al. 2008). The Tucumã dykes also have age

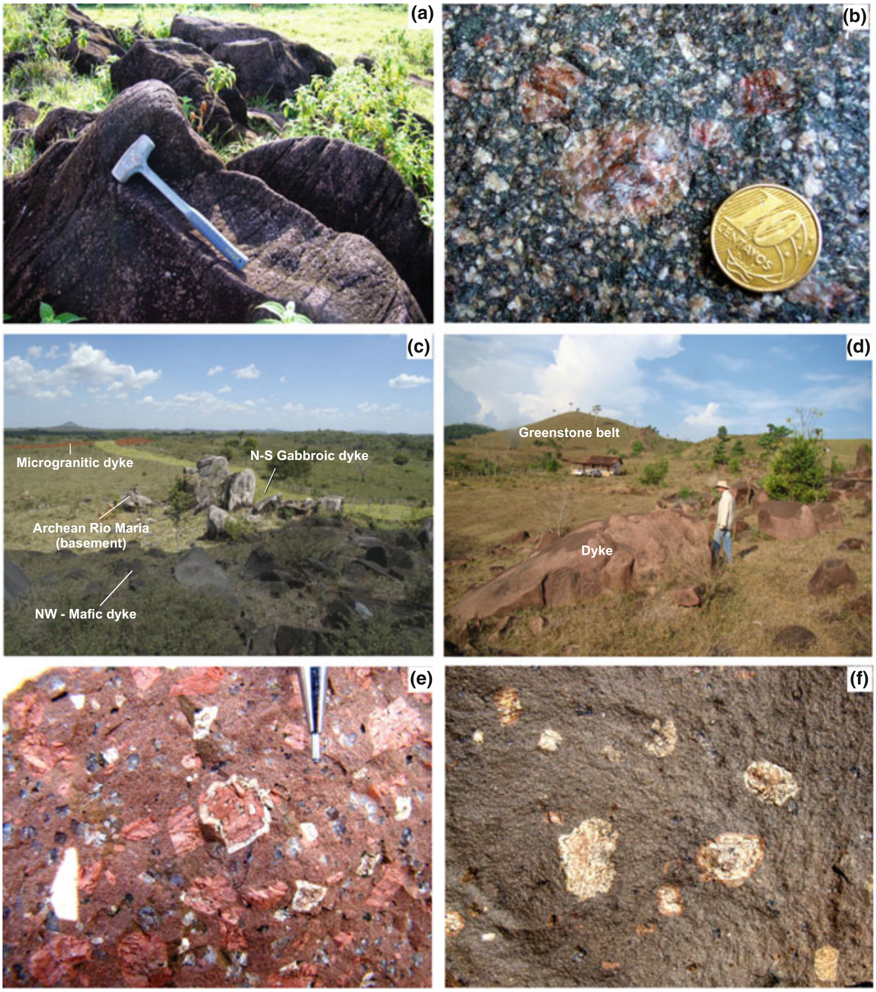

Fig. 8 Field aspects of the Uatumã SLIP: **a** Ignimbrite and rhyolitic tuff (Iricoumé Group) showing steeply dipping bedding; **b** Fine-grained porphyritic granite associated with rhyolites and tuffs of the Uatumã-Anauá domain (Photos by E. Klein); **c** Outcrop view of the Tucumã swarm (Photo by P. J. Antonio); **d** General view of one Tucumã dyke intrusive into local Archean greenstone belt sequence; **e** Macroscopic appearance of porphyritic rhyolitic dyke (Tucumã area) showing locally plagioclase mantled K-feldspar phenocrysts; **f** Dacitic dyke with K-feldspar phenocrysts (Tucumã area). See Fig. 7 for geographic location of the Tucumã swarm (Photos D. Oliveira)

match with some Au-bearing mafic intrusions that further west in the Central-Brazil Shield (Ventuari-Tapajós province), such as the Ingarana Suite (1881 ± 4 Ma; Santos et al. 2002a) which includes the Teodorico gabbro (1893 ± 10 Ma) and the Jutaí gabbro-anorthosite (1879 ± 7 Ma; Santos et al. 2001)—see Table 1. Nevertheless,

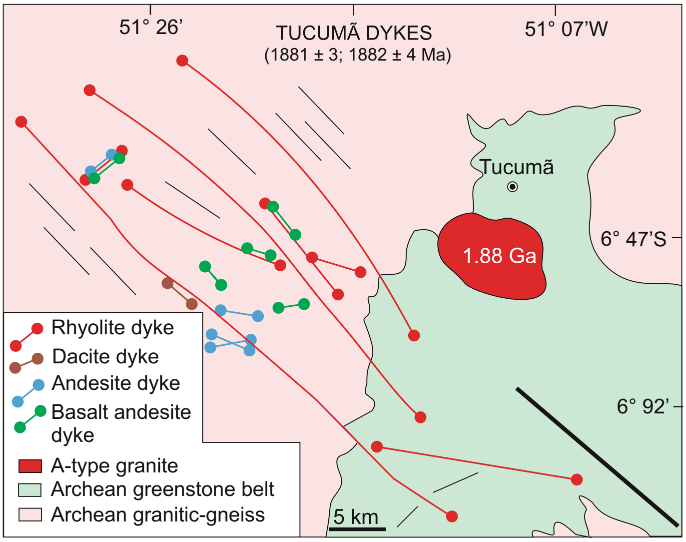

Fig. 9 Geologic sketch map of the Tucumã bimodal dyke swarm, intrusive into Archean lithostratigraphic units in the Central Amazonian province (after Silva et al. 2016). Uatumã SLIP component: 1.88 Ga granite. See Fig. 7 for geographic location of the Tucumã swarm and coeval dykes in the Carajás region

these particular intrusions may be more directly related to subduction going on in that area, and then not part of the Uatumã SLIP.

From a geodynamic perspective, the Uatumã SLIP event has been suggested to be related to thermal perturbations in the upper mantle and mafic underplating, of plume-like character (e.g., Silva et al. 2016). The felsic volcanic-plutonic activity (1.89–1.87 Ga) could have been derived by large crustal fusion, as suggested by available Nd-Sr isotopic constraints. The associated mafic magmatism should presumably be directly mantle-derived, as usually assumed for intraplate bimodal magmatic suítes (Silva et al. 2016; Fraga et al. 2017; Antonio et al. 2017). The Uatumã magmatism is also age-equivalent with the final stages (in a post-collisional setting) of the Tapajonic arcs (2.01–1.90 Ga; Fernandes et al. 2011) after which large portions of continental crust in the Central-Brazil Shield (e.g., Central-Amazonian and Ventuari-Tapajós provinces) consolidated as a stable landmass (see Sect. 2). According to Fernandes et al. (2011), the orogenic process included a northward flat subduction process beneath the Archean/Paleoproterozoic continental margin, which eventually triggered felsic plutonic intrusions (e.g., Parauari Suite; 1883 ± 4 to 1879 ± 3 Ma), as well as the c. 1.88 Ga Uatumã volcanic rocks in a back arc setting (e.g., Fernandes et al. 2011; Teixeira et al. 2017). This hypothesis is coherent with the geochemical signature of the 1.88 Ga basaltic and andesitic dykes of Carajás/Rio Maria, located to the east of the Tucumã dykes, which shows N-MORB and E-MORB characteristics with variable metasomatic effects (e.g., LREE and LILE enrichment with respect to HFSE; Rivalenti et al. 1998).

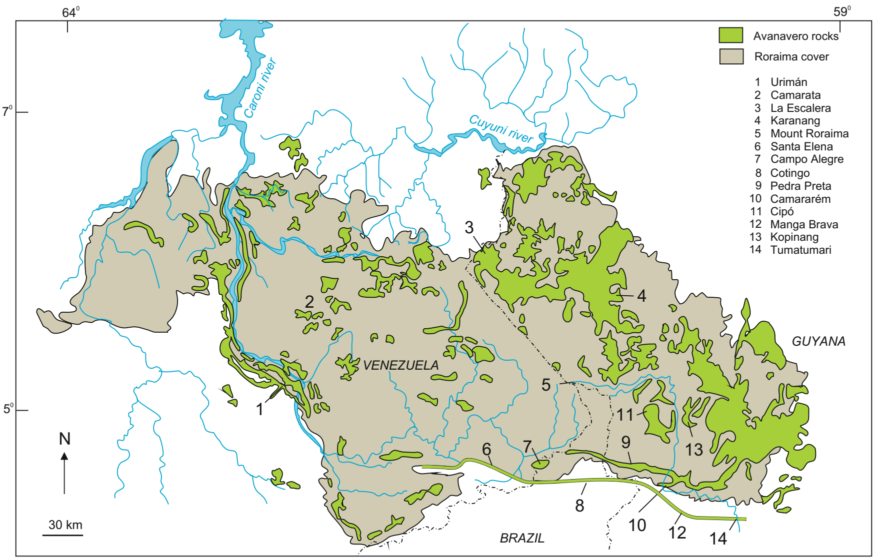

Fig. 10 Distribution of the Avanavero sills and dykes, emplaced into the Roraima cover within the Guiana shield (border area of Venezuela, Brazil and Guyana), northern Amazonian Craton. The dotted line indicates the country boundaries (after Reis et al. 2013a)

Noteworthy, the Uatumã SLIP event has economic importance, as shown by significant gold and tin deposits, in addition to tantalite-columbite and gemstones occurrences, and also has potential for Rare Earth Elements. Finally, Table 3 presents potential barcode matches (1.88–1.87 Ga) for this SLIP in the context of the Columbia supercontinent.

4.3 The 1.79–1.78 Ga Avanavero LIP Event

The Avanavero magmatism (Reis et al. 2013a) was active c. 100 my later than the Uatumã SLIP. It is the most widespread and voluminous intraplate mafic activity (Figs. 2 and 10) in the Guiana Shield, occurring over an extensive area (ca. 73,000 km^2) of Brazil, Venezuela and Guyana. The crystalline basement which hosts the Avanavero magmatism comprises distinct geological units developed during the Transamazonian orogeny, and is tectonically ascribed to the Maroni-Itacaiunas province (e.g., Gibbs and Barron 1993; Cordani and Teixeira 2007). However, much of the Avanavero magmatism is emplaced into the Roraima sedimentary cover (see Fig. 2) in at least four stratigraphic levels (Reis et al. 2013a; Beyer et al. 2015; Reis et al. 2017a and references therein).

Reis et al. (2013a) recently addressed the tectonic significance of the Avanavero LIP based on new and compiled U-Pb ages (see Table 1), geochemical data and geo-

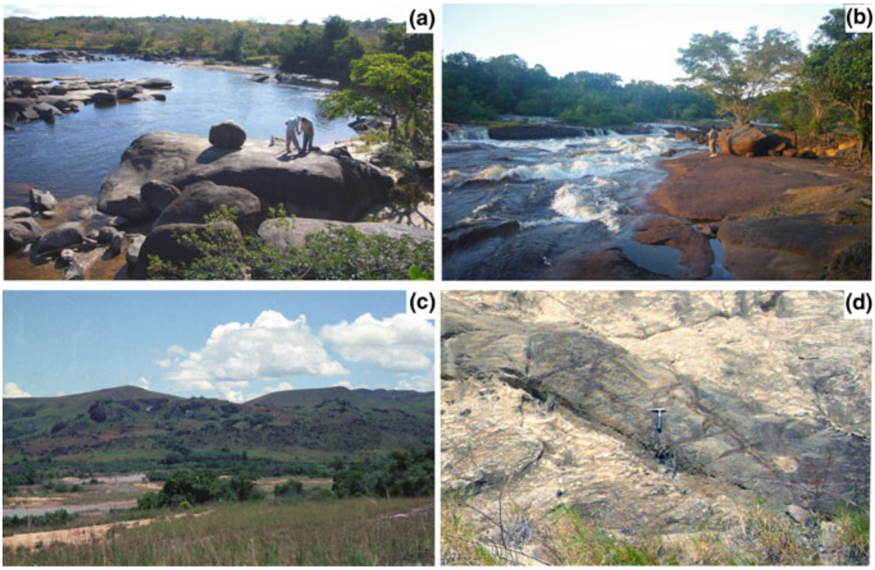

Fig. 11 Field aspects of the Avanavero mafic magmatism (photos by N. J. Reis). **a** The Pedra Preta sill along the Uailã river (Roraima Supergroup), northern portion of the Brazilian Roraima state; **b** The Pedra Preta sill along the Quinô river, northern portion of the Roraima state; **c** Landscape view of the Pedra Preta sill along the Quinô river, northern portion of the Roraima state, Roraima Basin; **d** The Cotingo dyke crosscuting the Orocaima volcanics (Orosirian in age), northern portion of the Roraima state

logic information. This LIP is dominated by widespread mafic sills such as the locally termed Cotingo, Kopinang, Tumatumari, Santa Elena, Cipó, and Monte Roraima sills that are emplaced into the Roraima cover (Figs. 2, 10 and 11). Sills can be as much as 400 m thick whereas the associated mafic dykes can be several of kilometers in length, sometimes showing branching or bifurcating forms.

Precise U-Pb baddeleyite ages for the Avanavero rocks in the Guiana Shield are: 1794 ± 2, 1782 ± 3 and 1786 ± 3 Ma (see Table 1), respectively (Reis et al. 2013a; Santos et al. 2003). These ages indicate a short-lived character for the Avanavero magmatism, and also imply that all previous published K-Ar and Rb-Sr ages are meaningless (Table 2 in Reis et al. 2013a). In the northeast portion of the Amazonas state, coeval mafic rocks form saucer shaped sills, the Quarenta Ilhas Diabase (see Fig. 2), intrusive into the Urupi Formation (Reis et al. 2013a). This diabase yielded U-Pb crystallization ages of 1793 ± 1 and 1780 ± 3 Ma (Reis et al. 2013a; Santos et al. 2003). These are 300–400 m.y. older that the previous K-Ar ages which reflect partial or total Ar loss due to much younger overprints.

Geochemically, the Avanavero rocks are tholeiitic in composition and are similar to E-MORB and subcontinental lithospheric mantle basalts, whereas the REE pattern indicates an intraplate character. In contrast, the low Nb/LREE ratios suggest lithospheric mantle sources modified by crustal contamination and/or by variable enrich-

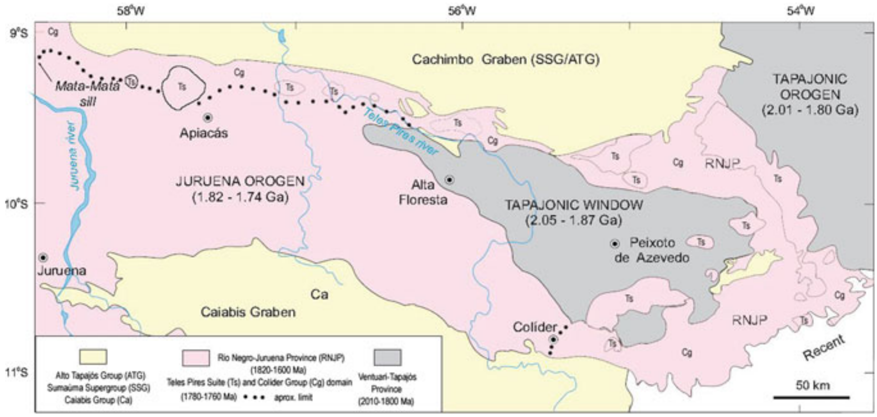

Fig. 12 Geologic outline of Teles Pires Suite and Colider Group (Alta Floresta Gold Province) in the southern portion of the Ventuari-Tapajós province (adapted from Cordani and Teixeira 2007; Scandolara et al. 2014; Bettencourt et al. 2016). See text and Fig. 1 for details

ment with slab fluids or melt from oceanic lithosphere (Reis et al. 2013a). According to these authors, such inherited chemical characteristics of arc-setting are genetically associated with the 1.98–1.95 Ga high-K calc-alkaline volcano-plutonism (Orocaima SLIP) whilst the mafic magmatism post-dates the evolution of the Maroni–Itacaiúnas Province as an intraplate activity.

Coeval rocks with the Avanavero magmatism occur elsewhere in the Amazonian Craton, as suggested by previous published U–Pb geochronology (e.g., Santos et al. 2002a and references therein). For instance, the Crepori Diabase (1780 ± 7 Ma; see Table 1) is ca. 1800 km away from the Avanavero-type area (see Fig. 4), discontinuously exposed 1.5–4.0 km south of the lower Crepori River in the Central-Brazil Shield. The documented U-Pb baddeleyite age is c. 200 my older than the previous K-Ar ages (see Santos et al. 2002a for review). The Crepori Diabase is composed of sills and dykes of tholeiitic gabbro and diabase, as well as differentiated rocks (andesite and granophyre). The sills and dykes stricking N55–75W and N10–15E are intrusive into the sedimentary rocks of the Palmares Group (<1.89 Ga) (Santos et al. 2001, 2002). From a chemical point of view (Almeida et al. 2000) the Crepori rocks are basalts, trachybasalts, tephrites and trachyandesites of alkaline affinity (alkali-basalts or alkali-olivine basalts).

The Crepori Diabase also has good age correlation with the Teles Pires Suite (1780–1760 Ma) which is located south of the Cachimbo Graben (Fig. 12). This suite consists of calc-alkaline granitic and (high-K) felsic volcanic rocks and unmetamorphosed volcanic-sedimentary rocks. The associated Colider Group is dominated by acid volcanics, showing medium- to high-K or shoshonitic calc-alkaline and subalkaline compositions, while the subordinate rocks with trachytic-rhyolitic composition and slightly alkalic (e.g., Santos et al. 2001, 2002b, 2004, 2008; Neder et al. 2002; Pinho et al. 2003; Bispo-Santos et al. 2008; Scandolara et al. 2014; CPRM 2014). The bulk plutonic-volcanic association continuously underlies the southern edge of the Cachimbo Graben (Figs. 1 and 12). These rocks contain significant Au-deposits in the mafic rocks (1.78–1.77 Ga), known as the Alta Floresta Gold Province (Bettencourt et al. 2016 and references therein).

The Cachimbo Graben comprises the basal Sumaúma Group, which is composed of two distinct lithostratigraphic units: the lower volcanosedimentary Vila do Carmo Group (1.76–1.74 Ga; rift phase) and the upper (>1.03 Ga; post-rift phase) sedimentary Beneficente Group (Reis et al. 2005, 2013b). The Vila do Carmo Group is intruded by the 1576 Ma (see Table 1) Mata-Matá gabbro sill (Betiollo et al. 2009), pointing to significantly younger intraplate activity than the Crepori Diabase within the southern portion of the Ventuari-Tapajós province. The Sumaúma Supergroup in turn is unconformably overlain by flat-lying, sedimentary strata of the Alto Tapajós Group (Paleozoic in age).

From a geodynamic perspective, the Teles Pires-Colider association has been considered to be subduction-related (Juruena orogeny) akin to a post-collisional (back arc) setting. The volcanic-plutonic rocks occur over the already stable tectonic environment east of the 1.81–1.74 Ga Juruena belt (i.e., southern border of the Ventuari-Tapajós province after Cordani and Teixeira 2007), similar as the tectonic setting of the older Uatumã rocks which occur east of the Ventuari-Tapajós province and are similarly considered to be subduction-related (see above). The age matches between the Teles Pires and Colider magmatisms with the Juruena accretionary orogeny are consistent with post-collisional manifestations (Scandolara et al. 2017). Whereas the Teles Pires and Colider rocks have similar ages with the Avanavero LIP, they may be rather formed by unrelated events because of the marked compositional and tectonic differences, as well as far distal exposures between them.

In summary, the 1.79 Ga Avanavero LIP likely marks a breakup attempt of the continental lithosphere due to mantle convection reorganization below the already stable Archean/late Paleoproterozoic continental lithosphere (proto-Amazonian Craton). This process occurred shortly after the cratonization of the Maroni-Itacaiunas province, and was resumed c. 100 my after the Uatumã SLIP event. The available ages for the mafic rocks of the Avanavero LIP suggest its evolution in two steps (1795–1780 Ma and c. 1780–1760 Ma), and therefore with a maximum life span of ~25 my (Reis et al. 2013a). This life span has been considered the result of a migrated mantle plume (Santos et al. 2002a), though it may be fortuitous due to the lack of more age data.

The potential barcode matches of the Avanavero LIP (see Table 3) around the world are consistent with many paleotectonic reconstructions which consider Amazonia, Baltica, Laurentia and West Africa possibly constituted a single landmass during much of the Proterozoic time (e.g., Zhao et al. 2004; Johansson 2009, 2014; Bispo-Santos et al. 2008; D'Agrella-Filho et al. 2016). From this paleogeographic perspective, there is also a plausible correlation between the Teles Pires Suite and Colider Group volcanics which occur along the Ventuari-Tapajós/Rio Negro-Juruena border (Proterozoic Amazonian proto-craton) and the Småland-Värmland Granitic-Porphyry Belt, particularly those which are roughly coeval to the TIB-1 phase (1.81–1.76 Ga) of the Transscandinavian Igneous Belt, and including the calc-alkaline c. 1.77 Ga Tving granitoids of Blekinge (see for review Högdahl et al. 2004; Pisarevsky and Bylund 2010). The latter rocks occupy a comparable position along the border between the Svecofennian and Gothian/Sveconorwegian provinces of Proterozoic Fennoscandia proto-craton, and are subduction-related (e.g., Johansson 2009), similar to the Teles Pires-Colider association. However, an extensional setting with mantle upwelling in a back-arc setting could also be envisaged for the Småland-Värmland rocks.

4.4 The 1.11 Ga Rincón del Tigre-Huanchaca LIP Event

Figure 3a outlines the geologic-tectonic framework of the SW portion of the Amazonian Craton, where the Rincón del Tigre-Huanchaca LIP occurs (Teixeira et al. 2015). This LIP has also a component (Rio Perdido Suite) in the distal Rio Apa Terrane, according to precise U-Pb age dating in baddeleyite (Teixeira et al. 2018). These LIP components can be characterized as follow: (i) mafic dykes and sills (Huanchaca and Rio Perdido Suites); (ii) the Rincón del Tigre layered Complex and; (iii) the Rio Branco Suite.

4.4.1 Huanchaca and Rio Perdido Suites

Mafic rocks of the Huanchaca Suite (Lima et al. 2012) crosscut the Paraguá Terrane (Bolivia; Fig. 3a) and the Huanchaca-Aguapeí sedimentary cover (1.17–1.15 Ga) (e.g., Litherland et al. 1986; Litherland and Powel 1989; Teixeira et al. 2010; Lima et al. 2012). The magmatism consists of large sills 50–200 m thick (trending N30 W; dipping ~10°SW) and associated (E-W oriented) dykes of ca. 150 km^2 (Fig. 13a, b). The sills have a documented U-Pb baddeleyite age of 1112 ± 2 Ma (Teixeira et al. 2015). Therefore all previously published K-Ar and $^{40}Ar/^{39}Ar$ ages between 1040 and 845 Ma (Litherland et al. 1986; Santos et al. 2002a; Lima et al. 2012) are isotopically reset. The Huanchaca Suite is classified as intraplate andesitic basalts of tholeiitic affinity and subalkaline character (Lima et al. 2012).

The Rio Perdido Suite (Faleiros et al. 2016 and references therein) comprises NW-SE and NWN-ESE oriented dykes (see Fig. 3a). One of these dykes (N85 W oriented; ~5 m thick) has a documented U-Pb baddeleyite age of 1110.1 ± 1.4 Ma (Teixeira et al. 2018). Subordinate E-W oriented dykes and NE-SW trending basaltic sills are also included in the Rio Perdido Suite, but for those we do not have any age constraints. The dykes (gabbros and diabases; Fig. 13c) are up to 30 m thick and crosscut mainly the southern exposure of the Rio Apa Terrane (1.95–1.72 Ga). The whole dyke swarm appears to be ca. 140 km wide with the traceable length as long as 200 km, according to aerogeophysical (total magnetic field) and radar images (Lacerda Filho 2015; Faleiros et al. 2016) (see Fig. 3b). Geochemical data suggest that the Rio Perdido dykes are andesitic basalts of tholeiitic affinity but with controversial

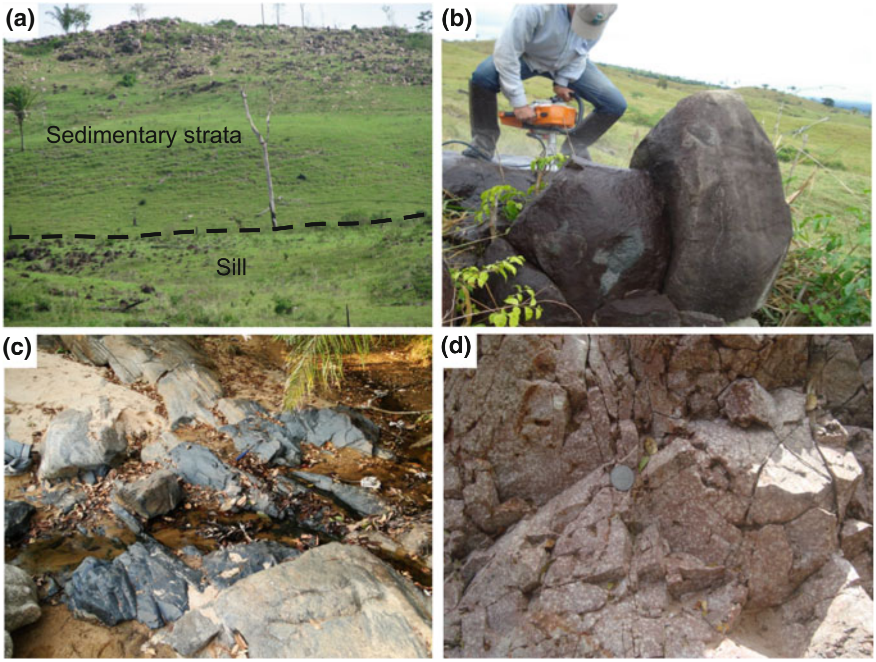

Fig. 13 Field aspects of the Huanchaca and Rio Perdido magmatism: **a** Landscape view of the Huanchaca sill (wheathered rock boulders in the foreground), intrusive into sedimentary strata of the Huanchaca-Aguapeí platform cover (top); **b** Block of mafic dyke (Huanchaca); **c** Rio Perdido dyke (Photos by A. S. Ruiz). **d** Outcrop view of fractured, pink granophyre (upper member of the Rincón del Tigre complex (Photo R. Matos))

signatures suggesting either intraplate (Lima 2016) or subduction-related magmatism (Remédio and Faleiros 2014).

The Rio Perdido dyke swarm is located ca. 300–1000 km SE from the other components of Rincón del Tigre-Huanchaca LIP (Teixeira et al. 2015) which implies a much larger scale for this LIP than previously thought. Furthermore, one may consider that distances could not be original because of the allochtonous character of the Rio Apa Terrane.

4.4.2 The Rincón del Tigre Layered Complex

This complex (e.g., Darbyshire 1979; Litherland et al. 1986 and references threrein) is a layered mafic-ultramafic sill (~4.8 km in thickness) within the Sunsas belt in Bolivia (see Fig. 3a). It consists of basal ultrabasic types (harzburgites, olivine bronzitites), intermediate gabbros and upper granophyres (Fig. 13d). The Rincón del Tigre Complex intruded along the contact between the Sunsas Group (below) and Vibosi Group (above), whose sedimentary strata experienced low-grade metamorphism and folding during the Sunsas collisional orogeny (e.g., Teixeira et al. 2010 and references therein)—see Sect. 2.

The Rincón del Tigre Complex is precisely dated at 1110 ± 2 Ma (see Table 1) by U-Pb baddeleyite age from the granophyres (Teixeira et al. 2015). There is a Ni-Cu-PGE ore potential for the Rincón del Tigre Complex, suggested by the geochemical anomalies and associated mineral occurrences. Specifically associated with the base of the magnetite gabbro portion, there occurs a precious metals zone with low grade sulfide and precious metals mineralization, 80–185 m thick (Prendergast 2000).

4.4.3 The Rio Branco Suite

The ~1.11 Ga Rio Branco magmatism (Brazilian state of Rondônia) is coeval with the crustal shortening/extension in the Nova Brasilândia belt (see Fig. 3a), contemporaneous with the Sunsas (Grenville) orogen (see Sect. 2) (e.g., Tohver et al. 2004, 2005, 2006). The magmatism comprises mafic and felsic plutonic and meta-plutonic intrusions: gabbro (1110 ± 8 Ma), metagabbro, amphibolite, metadiabase, and within-plate granite (1098 ± 10 Ma).

It is worth mentioning that roughly coeval mangerite-charnockite-rapakivi granite (MCG) plutonism is apparent in the state of Rondônia, SW portion of the Amazonian Craton (Fig. 12 in Bettencourt et al. 2016). For instance, the plutons of the Santa Clara Suite yields SHRIMP zircon U-Pb ages between 1082 and 1074 Ma (Bettencourt et al. 2010) (see Table 2). They are emplaced in major transpressional to extensional structures which transect the portion of the Rio Negro-Juruena province which was reworked at the time of the Sunsas collision (e.g., Bettencourt et al. 1999, 2016 and references therein).

Finally, the components of the 1.11 Ga Rincón del Tigre LIP broadly follow the arcuate structural trend of the Alto Guaporé and Sunsas belts (see Fig. 3a, and Sect. 2). This suggests a protracted causal relationship, controlled by a large-scale crustal weakness along the SW margin of the proto-Craton. The LIP components (intraplate character) have good age correlation with the timing of the Sunsas orogen, as illustrated in Fig. 14. From a geodynamic point of view, the nature of the Rincón del Tigre-Huanchaca LIP could involve the action of a subjacent mantle plume producing heat under the thickened crust—the stable foreland in relation to the Sunsas orogen. In a broader perspective this event has a remarkable match with prominent intraplate activity in other places around the world, as summarized in Table 3.

5 Other Mesoproterozoic Magmatism and Rifting

Intermittent magmatic episodes pre-dating the Rincón del Tigre LIP are apparent, mostly associated with basin tectonics and reactived structures in the SW portion of the Amazonian Craton (see Figs. 4 and 5). The intraplate activity can be tentatively grouped into two intervals, 1.57–1.37 and 1.20–1.17 Ga, given the age compilation,

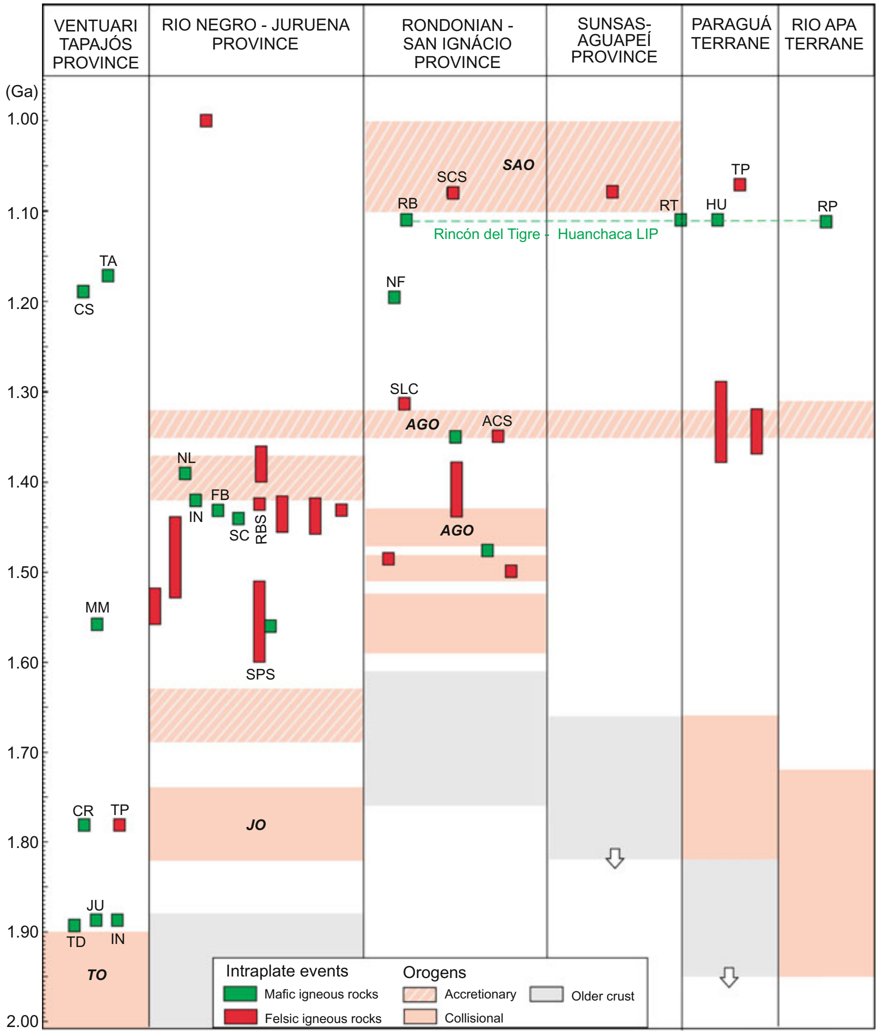

Fig. 14 Time-diagram comparing ages of anorogenic and post-collisional mafic and felsic magmatism in the Amazonian Craton with the timing of accretionary orogens along its active SW margin. Adapted from Bettencourt et al. (2010), Faleiros et al. (2016) and Scandolara et al. (2017). Green and red dots are individual U-Pb crystallization ages (data shown in Tables 1 and 2) of the intraplate (post-collisional and/or anorogenic) episodes. Mafic igneous rocks: RP = Rio Perdido Suite, HU = Huanchaca Suite, RT = Rincón del Tigre Complex, RB = Rio Branco Suite (Rondônia state), NF = Nova Floresta Gabbro, TA = Taparuquara Suite, CS = Cachoeira Seca Troctolite, NL = Nova Lacerda swarm, IN = Indiavaí Suite, FB = Figueira Branca Suite, SC = Salto do Céu Gabbro, MM = Mata Matá Gabbro, CR = Crepori Diabase, TD = Teodorico Diabase, Ingarana Suite (JU = Jutaí, IN = Ingarana). Felsic igneous rocks: TP = Teles Pires Suite, SPS = Serra da Providência Suite, SCS = Santa Clara Suite, SLC = São Lourenço-Caripunas Suite, TP = Taperas Suite. Other red bars: late- to post-orogenic and anorogenic granitic suites (data compiled from Fig. 5 in Bettencourt et al. (2010) and from Fig. 12 in Scandolara et al. (2017)). Shaded salmon bands: Proterozoic crustal growth events along the SW margin of Amazonia: SAO = Sunsas Orogen, AGO = Alto Guaporé Orogen, JO = Juruena Orogen, TO = Tapajonic Orogen. Older crust (gray bars): inferred from published Sm–Nd T_{DM} ages. See text for explanation

which can be compared to the accretionary evolution of the Rondonian-San Ignacio and Sunsas-Aguapeí provinces, respectively (see Table 1).

5.1 The 1.57–1.37 Ga Activity

This magmatism (e.g., dolerite dykes, bimodal magmatism, mafic-ultramafic complexes) is well-dated by U-Pb baddeleyite geochronology (Table 1). Representative examples are concentrated in the SE portion of the Rio Negro-Juruena province, as summarized below in three age groups:

(i) The Mata-Matá gabbro sill (1576 ± 4 Ma; Betiollo et al. 2009) is emplaced into the basal sedimentary strata (Vila do Carmo Group; Reis et al. 2013b) of the Cachimbo Graben (see Fig. 12) which is underlain by the c. 1790 Ma Teles Pires Suite and Colider Group volcanics (see Sect. 4.3). This sill is 250 m thick, cropping out as an elliptical exposure (~1 km^2) in the Aripuanã River (Brazilian state of Amazonas). The Mata-Matá sill could be tentatively related to some diabase dykes along the Iriri and Juruena rivers, which yielded minimum K-Ar ages in the 1470–1400 Ma range (Santos et al. 2002a; their Table 2). However, this remains to be proved by precise U-Pb geochronology.
There is a good age correlation between the Mata-Matá gabbro sill and the nearby Serra da Providência Suite, consisting of rapakivi granites, mangerites, charnockites and subordinate gabbronorite and gabbro (Payolla et al. 2002; Scandolara et al. 2013) (see Sect. 2 and Tables 1 and 2). This suite comprises four felsic phases based on the U-Pb ages (1600–1570, 1570–1560, 1550–1540 and 1530 Ma). The mafic representatives yielded $^{40}Ar/^{39}Ar$ ages of 1554 ± 6, 1552 ± 6 and 1558 ± 4 Ma (Bettencourt et al. 1999; Payolla et al. 2002). From a geochemical point of view the Serra da Providência (AMCG) Suite has been interpreted as A-type and within-plate type (Bettencourt et al. 1999; Payolla et al. 2002; Dall'Agnol et al. 2012), having a post-collisional character in relation to the Juruena orogeny (e.g., Scandolara et al. 2013).
The northwestern portion of the Guiana Shield similarly boasts ~1550–1510 Ma intraplate activity (see Table 2), such as the Parguaza and the Surucucus rapakivi granites in the Venezuela and Brazilian state of Roraima (e.g., Tassinari et al. 1996; Dall'Agnol et al. 2012; Santos et al. 2003. Cordani and Teixeira 2007 and references therein), as well as the Mucajaí mangerite/granite and the closely related Repartimento massive-type anorthosite in the Amazonas state (see Fig. 2). In a global scale, the Mata-Matá magmatism has a few barcode matches such as the Ålandand (buried) Riga rapakivi granites and Värmland dolerite intrusions in Fennoscandia and the Gawler Range event in Australia (Wahlgren et al. 1996; Fanning et al. 1988; Åhäll et al. 2000; Söderlund et al. 2005; Ernst 2014).

(ii) The Käyser NW-SE trending swarm of dykes occurs in southwestern Suriname (see Fig. 2), composed of olivine dolerites of alkaline character (Delor et al.

2003; De Roever et al. 2014 and references therein). The emplacement is precisely dated at 1528 ± 2 Ma (weighted mean $^{207}Pb/^{206}Pb$ age in baddeleyite), and is associated to major faults that crosscut the Paleoproterozoic crust of the Maroni-Itacaiunas province. The age of the Käyser Dolerite swarm provides an exact age match with the oldest dykes of the Essakane swarm of Burkina Faso, in the West African Craton (De Roever et al. 2014). According to these authors this barcode match supports that Amazonia and the West African Craton should be treated as a single crustal block at the time frame.

(iii) The Salto do Céu gabbro sill (1439 ± 4 Ma; Teixeira et al. 2016) is closely related with the anorogenic Rio Branco Suite (see Table 2), which comprises felsic members (syenites to rapakivi granites), and mafic members (gabbro, tholeiitic diabase dykes and porphyritic basalt). The gabbro sill (see Fig. 3a) is emplaced into a flat-lying platform sequence (<1.54 Ga) underlain by 1.82–1.79 Ga crystalline basement at the SE edge of the Rio Negro-Juruena province (e.g., Geraldes et al. 2004). In a regional perspective, this mafic event is roughly coeval with the syntectonic stage (1435 Ga) in the Alto Guaporé orogeny located to the west (see Sect. 2 and Fig. 3a). There is thus a coincidence in time between convergent-margin processes and the within-plate activity (i.e. Salto do Céu sill and coeval rocks) in the already stable parts of the SW Amazonian Craton. It is worth mentioning that similar-aged anorogenic activity is also present in the Guiana Shield, such as the 1.43–1.42 Ga co-magmatic charnockites and rapakivi granites of the Serra Grande Suite (Santos et al. 2011) which is ca. 2000 away from the Salto do Céu sill.

(iv) The Figueira Branca layered mafic–ultramafic Complex and the coeval Indiavaí gabbro and felsic-mafic plugs (1429 ± 3–1416 ± 7 Ma) occur the southwestern portion of the Rio Negro-Juruena province (Teixeira et al. 2011, 2016; D'Agrella-Filho et al. 2012). The age-equivalent NW-trending Nova Guarita dyke swarm (1418 ± 3 Ma; Bispo-Santos et al. 2012) composed of gabbro, microgabbro and diabase is located ca. 700 km northward in the Central-Brazil Shield. Contemporaneous anorogenic activity is also present within the Guiana Shield (such as the 1434–1425 Ma co-magmatic charnockites and rapakivi granites of the Serra Grande Suite (Santos et al. 2011). They are emplaced into the NW portion of the Central Amazonian province, ca. 2000 km away from the Figueira Branca Complex, suggesting therefore LIP scale magmatism.

(v) The NW-oriented Nova Lacerda dyke swarm (1387 ± 17 Ma) occurs not far from the Salto do Céu sill (Teixeira et al. 2011, 2016). The dykes likely derived from heterogenous mantle sources enriched by subduction-related metasomatism, according to the geochemical and isotopic data (Girardi et al. 2013). The Nova Lacerda swarm has age match with cratogenic granitic suites in the SW portion of the craton, such as the Alvorada, Teotônio, San Ramon and Santo Antônio plutons and associated dykes (Bettencourt et al. 2010 and references therein).

In summary, all these activities between 1.57 and 1.37 Ga can be considered as discrete extensional episodes within already stable parts, contemporaneous with the crustal growth steps along the active SW continental margin of Mesoproterozoic Amazonia. Figure 14 illustrates the potential age matches between the accretionary/collisional orogenies with the intraplate activity (felsic and mafic igneous events. The recurrent activity (Rb-Sr and K-Ar datings between 1.51 and 1.45 Ga, as well as few U-Pb ages; see Fig. 4), is particularly significant along reactived faults and/or shear zones (e.g., Cachorro and Tapajóslineaments). In addition, along the NW margin of the Amazonian Craton the recently dated Seis Lagos carbonatite Complex (1328–1154 Ma; Rossoni et al. 2017) is a further evidence of the within-plate magmatism. The carbonatite is emplaced into orthogneisses that are as old as 1.81–1.78 Ga (Almeida et al. 2007).

In a broader perspective, this intermittent Mesoproterozoic may have a linkage with global convergent dynamics, but could represent inboard extensional episodes within and overall convergent system. In this sense, the 1.57–1.37 Ga activity of Amazonia is roughly coeval with major intracontinental-related A-type felsic magmatism and mafic dykes (e.g., 1.47–1.42 Ga AMCG suites) such as in Eastern Laurentia and Fennoscandia, as well as in the West African Craton (e.g., Anderson and Bender 1989; McLelland 1989; Rämö and Haapala 1995; Åhäll et al. 2000; Gower and Krogh 2002; Högdahl et al. 2004; Brander and Söderlund 2009; Zariņš and Johansson 2009; Johansson et al. 2016). This particular Mesoproterozoic intraplate magmatism may be attempts of break-up in different parts of Columbia, penecontemporaneous with growing parts of the supercontinent (e.g., Rogers and Santosh 2002; Zhao et al. 2004; D'Agrella-Filho et al. 2016).

5.2 *The 1.20–1.17 Ga Activity*

Magmatic activity of this age range comprises mafic dykes and flows, laccoliths, anorthosite complexes with a regional distribution in the Amazonian Craton (see Figs. 4 and 5). This intraplate activity is associated with extension events (e.g., Teixeira 1990; Santos et al. 2002a) that also formed the Tonian rift basins such as in the SW portion of the Amazonian Craton (e.g., Palmeiral, Apiacás; see Figs. 3a and 12). The available ages of the mafic magmatism suggest a causal correlation between intraplate episodes and the Sunsas collision along the SW continental margin of the proto-Amazonian Craton (Tohver et al. 2006; Cordani et al. 2010a; Teixeira et al. 2010). Figure 14 illustrates the age correlation between the intraplate magmatism and orogenic events. The geodynamic scenario (1.10–1.00 Ga time frame) includes regional shearing and tectonic reactivation along crustal weakness zones such as the Ji-Paraná strike-slip shear network (1180–1150 Ma; Tohver et al. 2005) in Rondônia and the system of aborted rifts that evolved into the Huanchaca/Aguapeí basin in Bolivia (e.g., Teixeira et al. 2010 and references therein). Anorogenic granites, alkaline ring complexes, as well as pervasive isotopic resetting of the country rocks in some localized regions (e.g., K'Mudku tectonothermal episode in the Guiana Shield) are also reflective of the orogenic dynamics along the active SW margin of Amazonia (Cordani et al. 2010a for a review).

Mafic dykes with K-Ar ages in this range are concentrated in the SW edge of the Rio Negro-Juruena, Rondonian-San Ignacio and Sunsas-Aguapeí provinces, as shown in Fig. 4. This preferential geographic distribution is consistent with the general younging of the Amazonian Craton towards the southwest (current coordinates), with the dykes being related to inboard intraplate magmatism, according to the Cordani and Teixeira (2007) model. However, one may suspect that many K-Ar ages could have been reset (by Ar loss) due to the Mesoproterozoic polycyclic metamorphism and deformation, and thus they need to be confirmed by U-Pb dating. The representative examples of the 1.22–1.17 Ga intraplate mafic activity are summarized below:

The Nova Floresta sills (see Fig. 3a) display alkaline affinity and have documented $^{40}Ar/^{39}Ar$ ages of 1198 ± 3 to 1201 ± 2 Ma (Tohver et al. 2002). These ages are identical to a new U-Pb baddelyite dating age from a gabbro sill (M. Hamilton, written comm., 2017). The associated K-Ar ages are significantly younger, between 1118 and 1045 Ga (Santos et al. 2002a, see Table 2), reflecting Ar loss. Intraplate activity at c. 1.22 Ga is rare in the Amazonian Craton; one example could be the Canamã syenite (Rb-Sr age of c. 1217 Ma; Teixeira 1990), which occurs far north at the Cachorro lineament (Fig. 4) in the Guiana Shield. There are roughly coeval events like this globally, such as the Fraser Dyke Swarm in the Yilgarn Craton (Australia) and the dolerite dykes, associated syenites and granites along the Protogine Zone in Fennoscandia (e.g., Johansson 1991; Wingate et al. 2000; Pirajno and Hoatson 2012; Ernst 2014). The slightly older (c. 1.27 Ga) Mackenzie dyke swarm and associated sills and layered intrusions in Laurentia (e.g., Fahrig 1987), as well as the widespread 1.27–1.25 Ga Central Scandinavian Dolerite Group in north-central Sweden (Söderlund et al. 2005, 2006; Söderlund and Ask 2006) could be also associated.

The Cachoeira Seca lacoliths and dykes of troctolite and olivine gabbro crop out in Tapajós River region (Santos et al. 2002a), hosted by the Parauari Suite (1.89–1.87 Ga), which is tectonically ascribed to the Uatumã SLIP (see Sect. 4.2 and Fig. 7). The troctolite has a documented U-Pb baddeleyite crystallization age of 1186 ± 12 Ma (see Table 1). This age is c. 110–140 my older that the K-Ar ages for associated dykes (mean 1060 Ma). Potential contemporary mafic activity occurs elsewhere in the Central-Brazil Shield, as also suggested by a broad range of K-Ar ages from 1250 to 910 Ma (see Fig. 5). However, these dates need more precise age constraints. These mafic intrusions have dominantly tholeiitic affinity (e.g., Santos et al. 2002a and references therein).

The Cachoeira Seca magmatism also has age matches with the Tapuruquara Suite (see Fig. 2), comprised of several stocks of gabbros, as well as websterites and lherzolites, occurring far northward in the Guiana Shield (NW Amazonas state) (Reis et al. 2006). A representative gabbro from this suite yielded a SHRIMP baddeleyite age of 1172 ± 8 Ma, while two previous K-Ar datings gave 2250 and 2910 Ma ages, indicating excess Argon (Santos et al. 2006). The grabbroic rocks are high-alumina, showing strong subalkaline and silica-subsaturated character.

We also note that the Seis Lagos carbonatite Complex might be as young as 1187–1154 Ma (see previous section). If so there is a good age correlation with the nearby Tapuruquara mafic-ultramafic complex (1172 Ma; see Table 1). Both complexes could be related to the K'Mudku tectonothermal episode (e.g., Cordani et al. 2010a) that cut across the western portion of the Central Amazonian and Maroni-Itacaiunas provinces. In the Guiana Shield the alkaline sills and dykes of the Seringa Formation (see Fig. 2) have with minimum K-Ar ages from 1090 to 1080 Ma (Araujo Neto and Moreira 1976), but this needs to be confirmed by more robust geochronology.

Finally, the post-tectonic, A-type Taperas Granite (Sunsas Suite; see Table 2) which is intrusive into the Paraguá Terrane (see Fig. 3) yielded a zircon U-Pb age of 1076 ± 18 Ma (Boger et al. 2005). Whereas this granite is age-equivalent with the Cachoeira Seca troctolite, it could be associated with a particular extension episode within the Amazonian Craton that overlaps in time. Much younger occurrences of AMCG plutons (990–970 Ma) collectively known as the Rondônia Tin Province represent the anorogenic manifestations over in the Rio Negro-Juruena and Rondonian-San Ignacio provinces (Bettencourt et al. 1999; Payolla et al. 2002; Teixeira et al. 2010).

6 Summary and Conclusions

We have reviewed the geochronology, geochemistry and geologic setting of distinct mafic dyke swarms and sills and roughly coeval mafic and felsic plutonic and volcanic rocks in the Amazonian Craton. The conclusions and possible tectonic implications are summarized below:

- Four important and voluminous events of intracratonic magmatisms are apparent in the Amazonian Craton: the Orocaima (1.98–1.96 Ga) and Uatumã (1.89–1.87 Ga) SLIP events, and the Avanavero (1.79–1.78 Ga) and the Rincón del Tigre-Huanchaca LIP events (1.11 Ga).
- Both the Orocaima and Uatumã SLIP events consist of calc-alkaline I-type and subordinate A-type plutonic and volcanic rocks of widespread occurrence across the Central Amazonian and Maroni-Itacaiunas provinces. The Orocaima event has age matches with gabbros and associated charnockites and anorthosites which crosscut the Bakhuis belt, in Suriname. The Uatumã event likely includes the Tucumã bimodal swarm and nearby mafic to intermediate dykes and intraplate granites in the Central-Brazil Shield, given the age matches. It is also age-correlative to the Uraricaá Suite, the Rio Pardo rapakivi Association and some A-type and I-type plutons in the Guiana Shield.
- From a geodynamic point of view both the Orocaima and Uatumã SLIPs appears to be triggered by subduction-related processes with consequent extension of the continental lithosphere during these time periods. Their formation could be related to thermal perturbations in the upper mantle with associated mafic underplating, plume-like.
- The Avanavero event comprises mostly mafic sills and dykes with widespread occurrence in the Guiana Shield. Coeval dykes (Crepori Diabase) occur in the

Central-Brazil Shield, as well as other age-equivalent units such as the I-type, plutonic-volcanic Teles Pires Suite and the associated Colider Group in the Ventuari-Tapajós province. These suites with predominantly calc-alkaline composition have been related to a back-arc setting akin to the Juruena orogeny, as illustrated in Fig. 14.

- The 1.11 Ga LIP event previously defined in the SW portion of the Amazonian Craton (Huanchaca sills and dykes, Rio Branco Suite, Rincón del Tigre Complex) has tight age match with the Rio Perdido dyke in the distal Rio Apa Terrane. There is roughly contemporary anorogenic magmatism with this LIP elsewhere in the Amazonian Craton. In a broader scale this event is associated with the Grenville orogeny that consolidated the southwestern margin of the craton.
- Other intracratonic mafic activities are apparent in the main Craton, exemplified by the precisely dated: Mata-Matá sill (1.57 Ga), Käyser Dolerite (1.53 Ga), Salto do Céu (1.44 Ga) and Nova Floresta (1.22 Ga) sills, Cachoeira Seca Troctolite (1.19 Ga) and Tapuruquara Suite (1.17 Ga). These events could be associated in time and space with reativated structures and emplacement of A-type, rapakivi granites which largely occur in the SW portion of the Amazonian Craton. Taken together these 1.57–1.17 Ga episodes are also coeval with the long-lived accretion regime and convergent episodes that progressively built in Amazonia Mesoproterozoic times, as depicted in Fig. 14. The large scale of these events and the long-time period of magmatism are suggestive of a model coupling several plumes with distinct subduction-related processes through time. This is a key issue for understanding the relationship between intraplate magmatism (including that of LIP scale) with a convergent setting.
- The Paleo- to Mesoproterozoic intraplate activity of the Amazonian Craton has barcode matches with LIP events on other blocks in the context of the Columbia and Rodinia supercontinents, as summarized in Table 3.

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