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Fragments of 1.79-1.75 Ga Large Igneous Provinces in reconstructing Columbia (Nuna): a Statherian supercontinent-superplume coupling?

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Supported on available paleomagnetic data, a new Columbia (Nuna) supercontinent reconstruction is proposed based on matching U-Pb-dated 1.79-1.75 Ga Large Igneous Province (LIP) mafic unit fragments and particularly on linking their dykes into radiating systems. Information from the literature is augmented with the herein dated 1762 Ma (U-Pb) Januária dyke swarm from the São Francisco Craton (Brazil). In this reconstruction, three major LIPs would be restored. The first one (1.79 Ga Hart-Carson LIP), would consist of the Hart sills and Carson volcanics, and the Pebbair mafic dyke swarm. The second one (1.79-1.78 Ga Avanavero-Xiong'er LIP), would be composed of Avanavero sills and dykes, Taihang and Xiong'er dykes along with volcanics, Pará de Minas-1 dykes, Uruguayan/Florida dykes, Tomashgorod-Belokorovich dykes and related intrusives, Oskarshamn dykes, and Libiri dykes. The third one (1.76-1.75 Ga Tipton LIP), would comprise the Tipton radiating swarm, Newer dolerites, Januária dykes, Kédougou dykes, Tagragra of Akka dykes, Vestfold Hills-3 dykes, Kivalliq suite, Subbottsy-Nosachev dykes and intrusives, and Pugachevka-Fedorovka dykes and intrusives. Additionally, it is suggested that the model of supercontinent-superplume coupling (previously applied to Rodinia and Pangea supercontinents) represents a possible geodynamic framework for Columbia (Nuna) during the beginning of the Statherian Period.

Introduction

The Archean to Proterozoic continental cores consist of cratonic masses, which represent independent blocks that have separated and reconnected over the geological time through plate tectonic process. The reconstruction of Precambrian supercontinents depends on the matching details in continental geology from one craton to the next and on comparing paleomagnetic data for units on different blocks

that match in age. Many of the key units used for paleomagnetic study are mafic dykes and sills, which are particularly well-behaved paleomagnetically (Evans, 2013; Pisarevsky et al., 2014). They can be part of the plumbing system of Large Igneous Provinces (LIPs) (Ernst, 2014). After Bryan and Ernst (2008), LIPs are dominantly mafic magmatic provinces (that also can have significant ultramafic and silicic components), with areal extents >0.1 Mkm², igneous volumes >0.1 Mkm³ and maximum lifespans of ~50 Myr that have intraplate tectonic settings or geochemical affinities, and are characterised by igneous pulse(s) of short duration (~1–5 Myr). An important new tool in reconstructing ancient supercontinents is based on dating and matching LIPs fragments (mafic dykes, sills, volcanics) from different cratonic blocks, also restoring the primary geometry of radiating and linear dyke swarms (Ernst et al., 2013). Mafic dykes are important fragments of LIPs that radiate from a magma center commonly associated to mantle plume activity (Ernst, 2014).

Concerning models of a Paleo-Mesoproterozoic supercontinent, Hoffman (1997) suggested the concept of global-scale 1.8 Ga supercontinent referred to as NUNA, after an Inuktitut word for “the lands bordering the northern oceans and seas”. Rogers and Santosh (2002) introduced the name COLUMBIA, because the hypothetical relationship between eastern India and the Columbia region of North America. Zhao et al. (2002, 2004) and Hou et al. (2008) proposed different reconstructions for Columbia.

The geologic and paleomagnetic probability of a proto-SWEAT (SW of United States of America and Eastern Antarctica) and connection between western Laurentia and variably-rotated portions of the Australian cratons between 1.75 and 1.59 Ga have been recognized by Betts et al. (2008) and Payne et al. (2009). India has been tentatively positioned near Australian segments of Columbia (Zhang et al., 2012). The SAMBA juxtaposition of cratons assumed the long-lived assembly of the Amazonia craton in South America, and Baltica, together with West Africa, as a coherent body from terrane unification at 1.8 Ga (Johansson, 2009; Bispo-Santos et al., 2014; D'Agrella-Filho et al., 2016). As an alternative to SAMBA, Pisarevsky et al. (2014) suggested that India was positioned adjacent to Baltica during the Mesoproterozoic Era, and Amazonia and West Africa were banished together into the ocean as a separately drifting block.

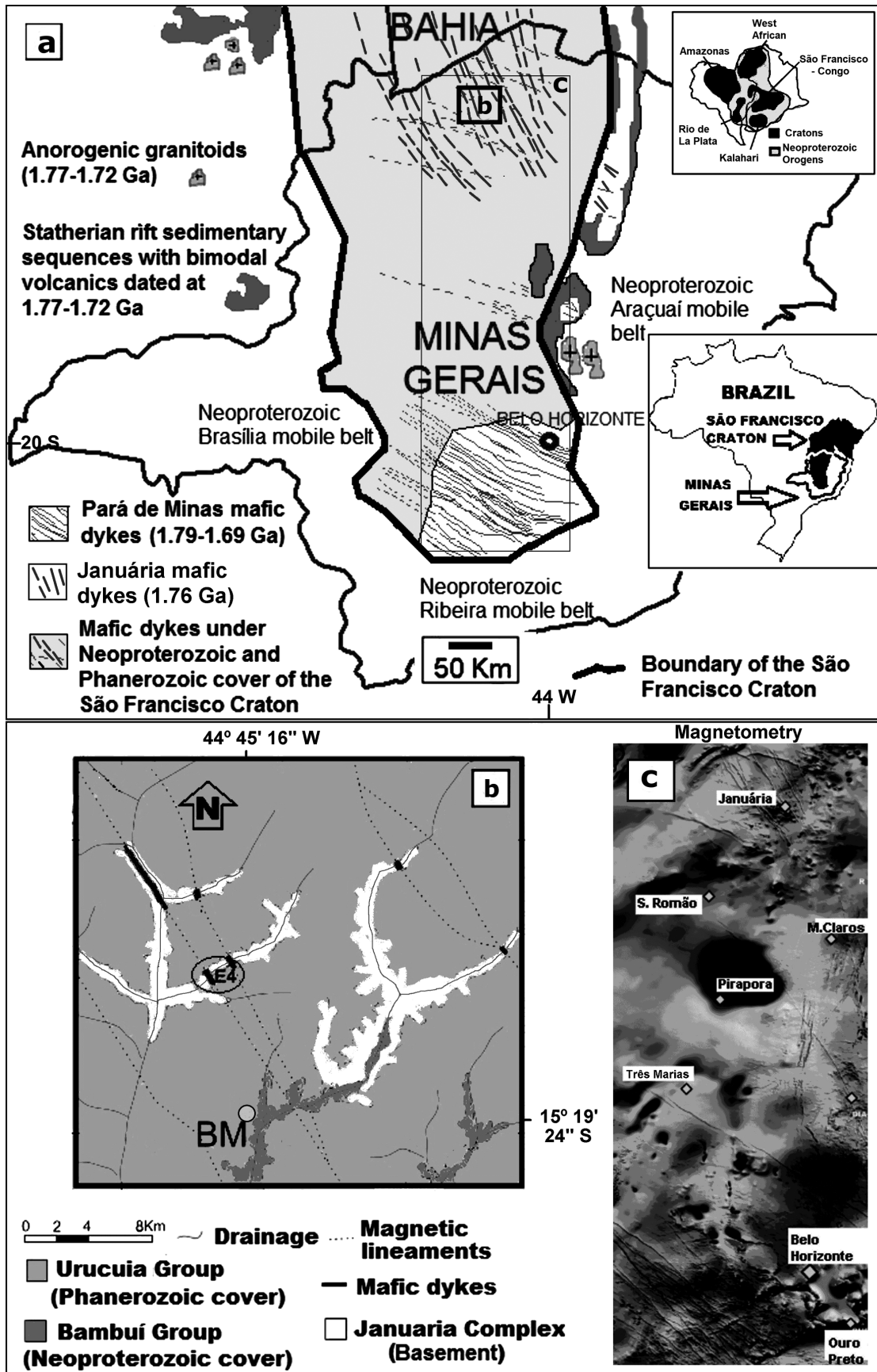


Figure 1. (a) NW Pará de Minas and NNW Januária mafic dyke swarms of the São Francisco Craton in the Brazilian State of Minas Gerais. (b) Geological context where E4 Januária dyke sample was collected. Mafic dykes of NNW Januária swarm are represented by the NNW-SSE lineaments. (c) Magnetometric map (CPRM and CODEMIG, 2014). BM = Bonito de Minas town.

A location of North China near Baltica and Amazonia was preferred by Bispo-Santos et al. (2008) in a regional reconstruction at 1.77 Ga and this was incorporated by Rogers and Santosh (2009) in their updated Columbia model. Furthermore, paleomagnetic data of Pesonen et al. (2012) supported placing North China near Baltica and Amazonia. A location of North China near Baltica and Amazonia was also favored by D'Agrella Filho et al. (2012). India has been tentatively positioned near Australia (Zhang et al., 2012; Pesonen et al., 2012). By using paleomagnetism and anisotropy of magnetic susceptibility (AMS) of the Xiong'er volcanics, Xu et al. (2017) positioned North China craton between São Francisco/Congo, Siberia and Rio de la Plata cratons in the Statherian period.

Pesonen et al. (2012) and Rogers and Santosh (2002) indicated that maximum packing of the Columbia (Nuna) supercontinent likely occurred around 1.5 Ga. However, Zhao et al. (2004) and Zhang et al. (2012) point out its final assembly around 1.8 Ga. On the other hand, Meert and Santosh (2017) argued that only the available paleomagnetic data are unsatisfactory to fully test Columbia (Nuna) configurations for any extended interval of the Paleo-Mesoproterozoic range from ~1.8 to 1.3 Ga.

By using available paleomagnetic data and existing U-Pb-dated 1.79–1.75 Ga LIP fragments represented by mafic sills, volcanics and particularly dykes from crustal blocks around the world, including the herein dated Januária dyke swarm from the São Francisco craton (SE Brazil), the aim of this paper is to propose a new Columbia (Nuna) reconstruction. In order to matching events between blocks the trends of dykes are reconstructed into primary radiating and linear patterns. As a final point, the supercontinent-superplume coupling model (developed by Li and Zhong, 2009, for Rodinia and Pangea) is proposed as a geodynamic framework for Columbia (Nuna) during the beginning of the Statherian Period.

U-Pb Dating of a Mafic Dyke of the Januária swarm (São Francisco craton)

Sample E4, a diabase (dolerite) with preserved phaneritic subophitic igneous texture, was collected from a 30 m wide, NW trending mafic dyke of the Januária swarm in the northern area of Minas Gerais State (Brazil), at the central part of the São Francisco craton. The Januária swarm is only exposed in a small area but can be traced under cratonic cover and the overall extent of the swarm is estimated as 500 km by 250 km based on aeromagnetic maps (Figs. 1a, 1b, 1c). Sample E4

Table 1. U-Pb TIMS data of the baddeleyite crystals from Januária dyke

Analysis no. (number of grains)	U/Th	Pbc/Pbtot ¹⁾	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²³⁵ U	± 2s % err	²⁰⁶ Pb/ ²³⁸ U	± 2s % err	²⁰⁷ Pb/ ²³⁵ U	± 2s	²⁰⁶ Pb/ ²³⁸ U	± 2s	²⁰⁷ Pb/ ²⁰⁶ Pb	± 2s	Concordance
			raw ²⁾	[corr] ³⁾		[age, Ma]								
Bd-1 (3 grains)	6.3	0.091	688.0	4.6145	1.11	0.31118	1.09	1751.9	9.2	1746.5	16.6	1758.4	6.4	0.993
Bd-2 (5 grains)	8.5	0.062	964.8	4.5855	0.51	0.30864	0.49	1746.6	4.3	1734.0	7.4	1761.8	3.2	0.984
Bd-3 (3 grains)	10.8	0.050	1294.0	4.5713	0.68	0.30753	0.67	1744.1	5.7	1728.5	10.1	1762.7	3.9	0.981

¹⁾ Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).

²⁾ Measured ratio, corrected for fractionation and spike.

³⁾ Isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (0.5 pg Pb and 0.05 pg U), and initial common Pb. Initial common Pb corrected with isotopic compositions from the model of Stacey and Kramers (1975) at the age of the sample.

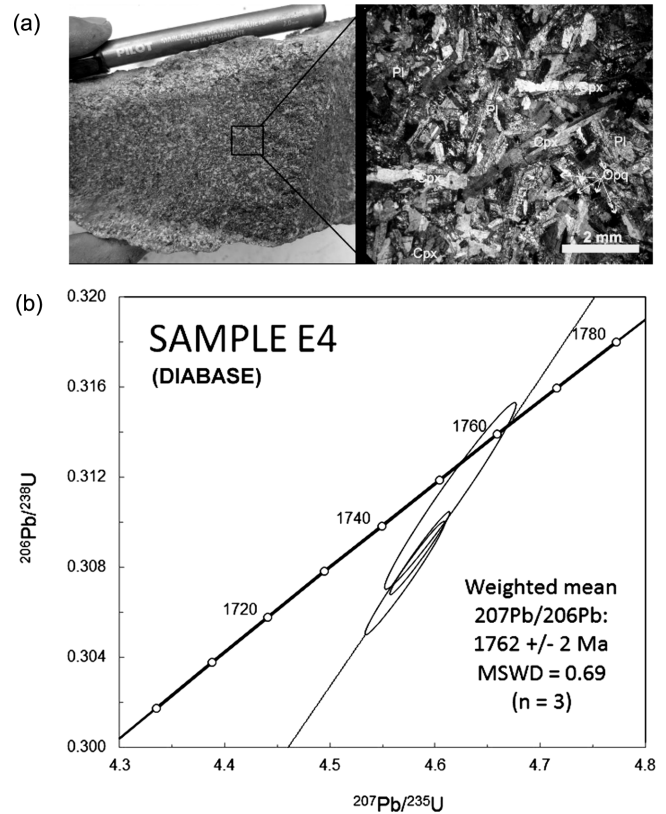


Figure 2. (a) Macroscopic (weathered rim) and microscopic aspects of the sample E4 (Pl – plagioclase, Cpx – Clinopyroxene, Opq – Opaque mineral). (b) Concordia diagram showing U-Pb data points from analyses of baddeleyite crystals of the Januária diabase dyke.

(Fig. 2a) was prepared for U-Pb geochronology at the Department of Geology at Lund University. Mass spectrometric analyses of its baddeleyite crystals were performed at the Laboratory of Isotope Geology (LIG) at the Natural History Museum of Stockholm, following the same procedures as described in Cederberg et al. (2016), which also present the age calculation routine.

The analytical results are presented in Table 1 and Fig. 2B. The weighted mean ²⁰⁷Pb/²⁰⁶Pb age obtained for Januária dyke of the São Francisco craton is 1762 +/- 2 Ma.

A revised Columbia (Nuna) Reconstruction Consistent with Available Paleomagnetism and the Distribution of 1.79-1.75 Ga Large Igneous Provinces

Paleomagnetic data provide the only quantitative method for reconstructing supercontinents (Meert, 2017). Geological processes linked to the existence of supercontinents include, among others, concepts such as mantle superplume events, LIPs and fragmentation of continental dyke swarms (Ernst, 2014), matching of conjugate orogenic belts (Hoffman, 1991) and major rifts (Dalziel, 1999), and the concept of true polar wander (Evans, 2003). A revised Columbia (Nuna) reconstruction, supported on available paleomagnetic data of Pesonen et al. (2012) and Xu et al. (2017) and based on matching of 1.79–1.75 Ga LIP fragments (mafic dykes, sills, volcanics) from different cratonic blocks, is presented in this section. Remnants of LIPs and associated rift sequences are used on repositioning of three Statherian plume centers in Columbia (Nuna).

Paleomagnetism

The SAMBA reconstruction in the Columbia (Nuna) supercontinent (Johansson, 2009), includes Laurentia, Baltica, Amazonia and West Africa, and is based on geological correlations without using paleomagnetic data. Pisarevsky et al. (2014) argue that the SAMBA reconstruction is paleomagnetically permissible, but still doubtful at 1790 Ma. Bogdanova and Pisarevsky (2015) not only found several geological mismatches between Amazonia and Baltica, but also sustain that available Mesoproterozoic paleomagnetic data from Baltica and Amazonia does not support the connection of these cratons and they are not connected in the revised Columbia (Nuna) reconstruction presented in the Fig. 3a. The West Africa craton is often placed close to the Amazonian craton (Zhao et al., 2002, 2004; Hou et al., 2008; Zhang et al., 2012). However, in the paleomagnetic continental reconstruction of Pesonen et al. (2012), West Africa is omitted for lack of reliable paleomagnetic data at 1.78 Ga. In the absence of reliable paleomagnetic data in this time for the West Africa block, then in Fig. 3a West Africa craton and Amazonia have been reconstructed in separate locations that best satisfy the 1790 and 1750 Ma radiating dyke swarm patterns. In this position, the West Africa is tentatively anchored between Siberia, Laurentia and Baltica (Fig. 3a). Kouyaté et al. (2013) mentioned the existence of a possible 2.05 Ga continental block, which included the West Africa and northern Laurentia.

Pesonen et al. (2012) used reliable paleomagnetic data from Laurentia, Baltica, North China, Amazonia, Australia, India and Kalahari to propose the 1.78 Ga configuration of these blocks presented in Fig. 3c and followed in the Fig. 3a. These continents remained at low to intermediate latitudes during 1.88–1.77 Ga (Pesonen et al., 2012). The Trans-North China orogen formed at 1.85 Ga possibly represent the same orogenic event as the orogens in Baltica and Amazonia (Pesonen et al., 2012). The 2.0–1.8 Ga Ventuari-Tapajós and 1.8–1.45 Ga Rio Negro-Juruena orogenic belts of Amazonia are coeval with the 1.9–1.8 Ga Svecofennian orogenic belt and ca. 1.8–1.7 Ga Transscandinavian Igneous Belt (TIB) of Baltica, and with the corresponding 1.8–1.7 Ga Yavapai belt in Laurentia (Zhao et al., 2004). According to the reconstruction of Betts et al. (2008), at 1.78 Ga Australia is located slightly

apart from Laurentia. Pesonen et al. (2012) positioned Australia together with its possible counterparts India and Kalahari (Fig. 3c), based on paleomagnetic data.

After Xu et al. (2017), a comparison of geological and paleomagnetic results from Statherian mafic dykes and volcanics suggests the positioning of the North China craton between São Francisco-Congo, Rio de la Plata and Siberia (Fig. 3d) in the Nuna/Columbia supercontinent. This arrangement of blocks is followed in the Fig. 3a. Xu et al. (2017) also reported the results of anisotropy of magnetic susceptibility (AMS) of the 1.79 Ga Xiong'er volcanic rocks. The inferred magma flow directions from the AMS results revealed a radial flow pattern with an eruption center located near Xiong'er Mountain on the south margin of the North China craton. Xu et al. (2017) results support a co-genetic relationship between the mafic dykes and the Xiong'er volcanic rocks, with the former as the intrusive counterpart of the latter and comprising a LIP, which is plume-related (Peng, 2010).

1.79 Ga Hart-Carson LIP/plume

The Carson Volcanics outcrop throughout the lower part of the Kimberley Basin and are associated with volcanoclastic and sedimentary rocks (Pirajno and Hoatson, 2012). The volcanic rocks consist mainly of tholeiitic basalt. The Hart dolerite rocks of the Kimberley region in the northern Australia craton comprise a series of dykes and massive sills. Zircon from a dolerite sill was dated with the SHRIMP U-Pb method and gave an age of 1790 ± 4 Ma (Pirajno and Hoatson, 2012), which can be considered the age of the Hart-Carson LIP from Australia/East Antarctica block. Mafic-ultramafic intrusions of Hamersley (West Australia), Mt. Isa (North Australia) and Gawler (South Australia) are also parts of this LIP (Pirajno and Hoatson, 2012).

Pesonen et al. (2012) have suggested a nearest neighbor relationship between India and Australia at 1.78 Ga. It is therefore possible that Pebbair dykes from India, dated at 1788 ± 12 Ma (U-Pb in baddeleyite - Demirel, 2012) can be linked as part of the 1.79 Ga Hart-Carson LIP, radiating from a plume center located in North Australia (Kimberley region – see respective star of Fig. 3a). Tyler et al. (1998) previously suggested that the generation of mafic melts of the Hart-Carson LIP could be related to a mantle plume, with the plume head located somewhere north of the present-day position of the Kimberley province, based on paleocurrents in sandstones of the Kimberley sedimentary sequence. Eruption of the Carson Volcanics was followed by deposition of these sandstones of the upper Kimberley Basin (Pirajno and Hoatson, 2012), which are rocks probably related to the rifting triggered by plume activity. The Hart-Carson plume formed soon after 1.80 Ga orogenesis developed along the Southern Australian margin and which is also recorded in the Arunta Inlier and the Rudall Complex of the northern margin of the West Australian craton (Betts et al., 2008) (Fig. 3a).

1.79-1.78 Ga Avanavero-Xiong'er LIP/plume

The 1.79-1.78 Ga Avanavero suite represents the most important Paleoproterozoic mafic magmatism event in the Guiana Shield, northern Amazonian craton (Reis et al. 2013). It comprises voluminous dykes and sills, the latter intruded into regional sedimentary cover successions such as the Roraima Supergroup. Both the Ilhas sill (1793

± 1 Ma) in the northern part of the Amazonia craton and the Pedra Preta dolerite sill (1795 ± 2 Ma) near the Venezuelan border have matching U-Pb ages (Reis et al., 2013). Other units connected to the Avanavero event include the Crepori dolerite in the southern part of the Amazonia craton (1780 ± 7 Ma), and the Quarenta Ilhas dolerite (1780 ± 3 Ma) and Cipo dolerite (1778 ± 12 Ma) in the northeastern part of the Amazonia craton (Santos et al., 2002).

Bispo-Santos et al. (2008) have suggested a location for the North China craton between Baltica and Amazonia at 1.77 Ga. D'Agrella Filho et al. (2012) and Pesonen et al. (2012) incorporated this idea in their 1.78 Ga models, and this configuration is used in Fig. 3a. The NNW-SSE Taihang dyke swarm and associated sills are distributed throughout the North China Craton and are dated at 1.78 Ga using the U-Pb method on both baddeleyite and zircon (Peng et al., 2010). The Taihang dyke swarm has been suggested to have a connection with the Xiong'er volcanics (the extrusive counterpart of this swarm) and a plume tectonic model has been proposed for this Taihang-Xiong'er association (Peng, 2010). However, the tectonic setting of the Xiong'er volcanic rocks is controversial. Some authors argue that the Xiong'er volcanic rocks represent a continental margin arc bordering the southern margin of the North China craton because these volcanic rocks are dominated by andesites and dacites with minor basaltic andesites and rhyolites (He et al., 2008, 2009, 2010; Zhao et al., 2009). There are massive volcanic flows correlated over large areas and a giant fanning dyke swarm with plume geochemical signature and a radiating geometry that is compatible with the Xiong'er rift developed in an extensional intraplate setting. These features suggest that the plume tectonic model of Peng (2010) seems to be more suitable.

It is here proposed that Avanavero magmatic suite and Taihang-Xiong'er mafic (-intermediate) magmatism belongs to the single reconstructed 1.79–1.78 Ga Avanavero-Xiong'er LIP, which would also include additional fragments dispersed in different continental blocks such as Rio de la Plata, Baltica, West Africa, and São Francisco-Congo (see respective star and LIP fragments of the Fig. 3a). A matching ca. 1795 Ma (U-Pb baddeleyite age) has been found for NW-SE trending Pará de Minas-1 dykes from São Francisco craton (Cederberg et al., 2016). Chaves and Neves (2005) attributed these Pará de Minas dykes to Statherian mantle plume activity and they may represent a branch of the Avanavero-Xiong'er LIP. Cederberg et al. (2016) have suggested a nearest neighbor relationship between Xiong'er and Pará de Minas-1 rocks at 1.80 Ga. The inferred plume center here suggested for the Avanavero-Xiong'er LIP could be constrained between Amazonia, North China and São Francisco-Congo blocks, and the reconstruction of the Fig. 3a was adjusted to allow the Pará de Minas-1 dykes to trend toward this plume center. This reconstruction satisfies the anisotropy of magnetic susceptibility (AMS) data, which indicate that some dykes of the 1795 Ma Pará de Minas -1 swarm were emplaced with subhorizontal magma flow and a flow direction from NW to SE (Raposo et al., 2004; Chaves and Neves, 2005). Metasedimentary rocks of the Arai, Espinhaço and Chapada Diamantina basins record Statherian rifting in São Francisco craton (Brito Neves et al., 1995) following the Avanavero-Xiong'er LIP event. This huge rifting took place simultaneously to the Xiong'er rifting and both reinforce the positioning of the Avanavero-Xiong'er plume center presented in Fig. 3a.

In the Rio de la Plata craton, the ENE Uruguayan (Florida) mafic

dyke swarm has been dated by U-Pb on baddeleyite at 1790 ± 5 Ma (Halls et al., 2001) and paleomagnetically studied by Teixeira et al. (2013), who suggest a “upside down” reconstruction of this craton between Amazonia and Baltica. Such a position is here accepted for Fig. 3a. The Uruguayan (Florida) swarm (Rio de La Plata craton) could be proposed as a fragment of the Avanavero-Xiong'er LIP that proceeds from the Avanavero-Xiong'er plume center toward Sarmatia and Fennoscandia regions of the Baltica block. The NNW Tomashgorod dyke in the northwestern Ukrainian shield of the Sarmatia was dated yielding a precise U-Pb baddeleyite age of 1791 ± 5 Ma (Bogdanova et al., 2013). After Bogdanova et al. (2013), the Volgo-Sarmatia and Fennoscandia parts of the Baltica block should be considered as independent blocks in pre-1.75 Ga paleogeographic reconstructions, with the final assembly of Baltica only occurring after 1.75 Ga by docking of Volgo-Sarmatia and Fennoscandia. Pisarevsky and Bylund (2010) describe 1780 Ma Oskarshamn mafic dykes in Fennoscandia, which probably represent the end of the Avanavero-Xiong'er LIP branch also formed by Uruguayan (Florida) dykes (Rio de La Plata craton) and Tomashgorod dykes (Sarmatia) (Fig. 3a).

The central branch of the 1.79–1.78 Ga Avanavero-Xiong'er LIP starts with the Taihang dykes of the North China craton and probably proceeds to the West Africa block (Fig. 3a). ID-TIMS U-Pb age has been obtained on baddeleyite for the NS Libiri dyke swarm from Leo Man craton (Niger), yielding an age of ca. 1790 Ma (Baratoux et al., 2018).

1.76–1.75 Ga Timp-ton LIP/plume

Gladkochub et al. (2010) point to the existence of a 1750 Ma giant radiating dyke swarm (Timp-ton LIP) in Siberian craton possibly related to a mantle plume centered in the respective star of the Fig. 3a. 1.73 Ga rifting of the Siberian craton along its southern margin (Gladkochub et al., 2006), followed by rifting both to the east and west of the Anabar Shield (Milanovskiy, 1996), supports the positioning of the Timp-ton plume center. As shown in the Fig. 3 reconstruction, additional LIP fragments can be linked to the 1750 Ma Timp-ton LIP/plume, from many additional 1.76–1.75 Ga units (LIP fragments) dispersed in different continental blocks such as Laurentia, West Africa, Baltica, India and São Francisco-Congo.

The ca. 1.75 Ga Cleaver - Hadley Bay - Nuelin dykes and sills (and felsic magmatism) of the Kivalliq suite from Laurentia (Ernst et al., 2013; Peterson et al., 2015), along with the 1.75 Ga Tagragra of Akka of the Anti Atlas Inliers of West Africa (Youbi et al., 2013) and 1.76 Ga Kédougou dykes from southern West Africa craton (Baratoux et al., 2018), the 1.76 Ga Subbottsy-Nosachev and Pugachevka-Fedorovka dykes and mafic intrusions from Sarmatia (the SW segment of Baltica) (Bogdanova et al., 2013), the 1.76 Ga Newer Dolerites from the Singhbhum craton of India (Shankar et al., 2014), the 1.75 Ga Vestfold Hills-3 dykes from East-Antarctica (Ernst et al., 2013) and the 1.76 Ga Januária dykes (this study) from São Francisco portion of the Sao Francisco-Congo craton, could be all considered as fragmented portions of the 1.76–1.75 Ga Timp-ton LIP (Fig. 3a).

U-Pb ages of the fragments from 1.79 Ga Hart-Carson LIP, 1.79–1.78 Ga Avanavero-Xiong'er LIP, and 1.76–1.75 Ga Timp-ton LIP, globally distributed in several ancient crustal blocks, are summarized in Table 2. The 1.75 Ga Columbia model of Fig. 3a is supported by the recon-

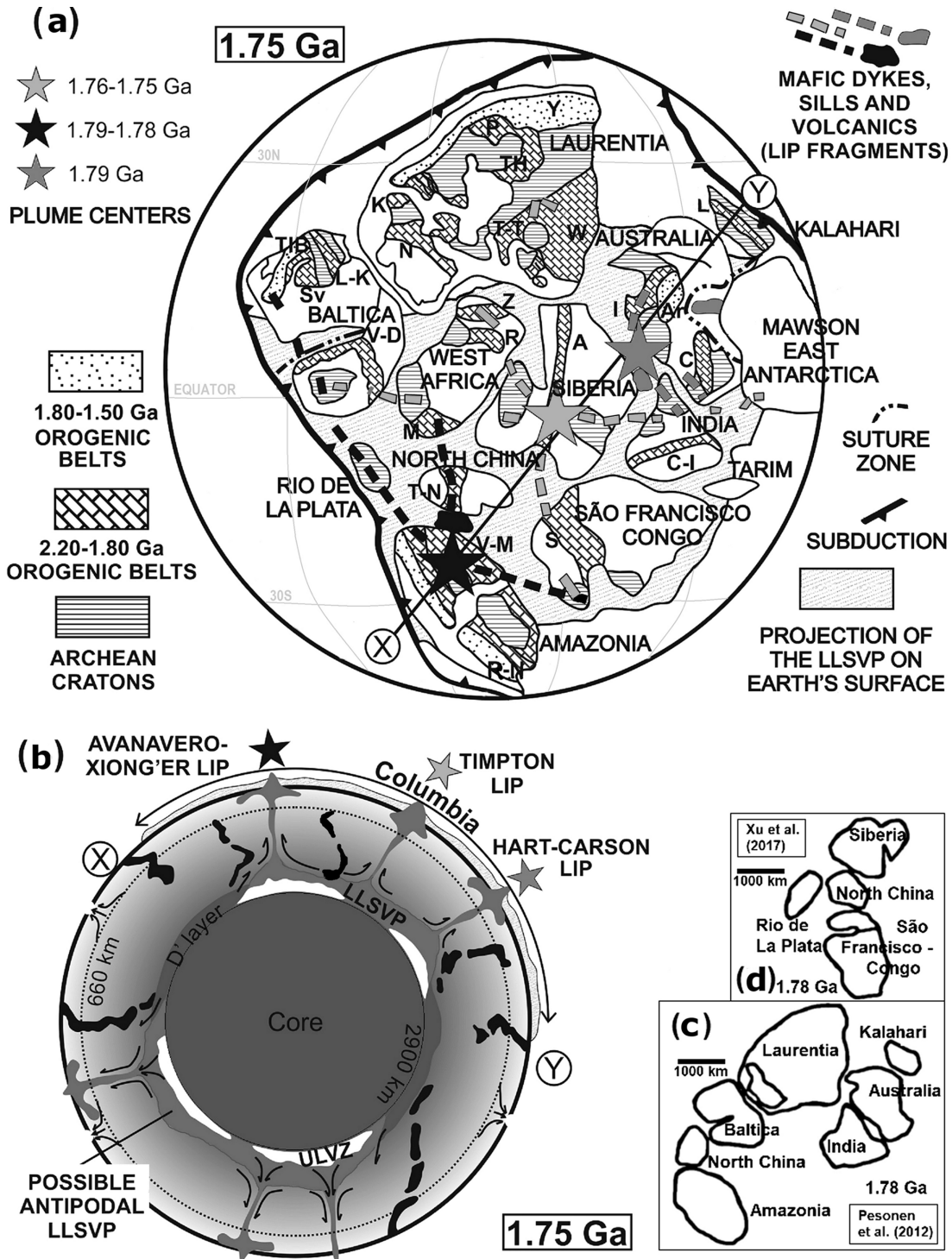


Figure 3. (a) 1.75 Ga Columbia (Nuna) reconstruction model derived from matching 1790-1750 Ma ages of LIP fragments on different cratonic pieces. Stars: centers of the 1.79 Ga Hart-Carson LIP, 1.79-1.78 Ga Avanavero-Xiong'er LIP, and 1.76-1.75 Ga Tipton LIP. The orogenic belts shown in dark green and black are: LAURENTIA: Nagssugtoqidian (N), Ketilidian (K), Torngat (T), Trans-Hudson (TH), Penokean (P), Wopmay (W), Taltson-Thelon (T-T), Yavapai (Y); BALTICA: Lapland-Kola (L-K), Svecofennian (Sv), Volga-Don (V-D), Transscandinavian Igneous Belt (TIB); AMAZONIA: Ventuari-Tapajos/Maroni-Itacaiunas (VM), Rio Negro-Juruena (R-N); NORTH CHINA: Trans-North China (TN); SIBERIA: Akitkan (A), WEST AFRICA: Leo Man (M), Reguibat (R), Zenaga (Z); SÃO FRANCISCO/ CONGO: Salvador (S); INDIA: Central Indian tectonic zone (C-I); AUSTRALIA: Capricorn (C), Mt. Isa (I), Arunta (Ar); KALAHARI: Limpopo (L). (b) Supercontinent-superplume coupling suggested for Columbia (Nuna), adapted from that for Pangea and Rodinia developed by Li and Zhong (2009). LLSVP = large low shear velocity provinces, ULVZ = ultra-low velocity zones, SUPERPLUME = cluster of mantle plumes starting from a LLSVP. (c) 1.78 Ga positioning of the India, Australia, Kalahari, Laurentia, Baltica, North China and Amazonia blocks after Pesonen et al. (2012). (d) Statherian positioning of the North China, Rio de la Plata, São Francisco/Congo and Siberia blocks after Xu et al. (2017).

struction of LIP fragments like mafic dyke swarms, sills and volcanic rocks, which suggest that maximum packing of the supercontinent likely occurred around 1.75 Ga, in agreement with the suggestion of Zhao et al. (2004) and Zhang et al. (2012).

Examination of the Superimposition of 1.79-1.78 Ga and 1.76-1.75 Ga LIP Units on Previous Alternative Columbia (Nuna) Reconstructions

Restoration of the radiating or linear primary geometry of mafic dyke swarms (the plumbing system of LIPs) offers a supercontinent reconstruction criterion (Ernst et al., 2013). Based on this proposition, 1.79–1.78 Ga and 1.76–1.75 Ga LIP fragments (not only mafic dykes, but also sills and volcanics) of the Table 2 have been plotted on previous alternative Columbia (Nuna) reconstructions (Fig. 4).

In the 1.8 Ga Columbia reconstructions of Rogers and Santosh (2002, 2009) and Zhao et al. (2002, 2004), there was no restoration of the 1.79–1.78 Ga mafic dykes neither as radiating nor linear in the far end regions of the supercontinent (Figs. 4a and 4b), making difficult the connection of cratonic pieces as suggested by them. Although 1.76–1.75 Ga mafic dykes have been plotted in Figs. 4a and 4b, they

should not be analyzed due to their ages are not matching with the age of the reconstruction.

Hou et al. (2008) presented a 1.8 Ga Columbia reconstruction very similar to Zhao et al. (2002, 2004). The main difference was placing North China and India side by side with Laurentia, where they show that the overall pattern exhibited by the 1.8 Ga mafic dykes appears to constitute a giant radiating swarm, with a piercing point between the Cuddapah rift in South India and the Xiong'er aulacogen in North China (Fig. 4c). However, mafic dykes from India used by them in such reconstruction were not dated by U-Pb to constrain their model.

By using SAMBA conjunction of cratons proposed by Johansson (2009), Zhang et al. (2012) considered the West Africa craton close not only to the Amazonian and Baltica cratons, but also to the Siberia in their 1.74 Ga Nuna (Columbia) reconstruction. Unfortunately, the branches of the 1.76 Ga Timpton radiating swarm from Siberia do not find prolongations with 1.76 Ga dyke swarms of West Africa, Baltica, Laurentia, India, and East Antarctica when superimposed over the Zhang et al. (2012) reconstruction (Fig. 4d). Due to difference in ages, older 1.79–1.78 Ga mafic dykes were not analyzed over such 1.74 Ga reconstruction.

In the 1.77 Ga Pisarevsky et al. (2014) Nuna (Columbia) recon-

Table 2. Available U-Pb ages of the Statherian LIP fragments, including the new U-Pb age of the Januária dyke swarm

Large Igneous Province	Continental Block	Name of the LIP fragments	U-Pb Age (Ga)	LIP fragments	References
Hart-Carson	Australia/East Antarctica	Hart, Carson, Hamersley-Mt.Isa-Gawler	1.79	Sills and dykes/volcanics/mafic-ultramafic intrusions	Pirajno and Hoatson (2012)
	India	Pebbair	1.79	WNW dyke	Demirer (2012)
Avanavero-Xiong'er	Amazonia	Avanavero	1.79	Sills/NE dykes	Reis et al. (2013)
	Amazonia	Creporei	1.78	Sill	Reis et al. (2013)
	North China	Taihang	1.78	NNW dykes	Peng (2010)
	North China	Xiong'er	1.78	Volcanics	Peng (2010)
	São Francisco/Congo	Pará de Minas (first generation)	1.79	NW dykes	Cederberg et al. (2016)
	Río de la Plata	Uruguayan (Florida)	1.79	ENE dykes	Teixeira et al. (2013)
	Baltica (Sarmatia)	Tomashgorod-Belokorovich	1.79	NNW dykes	Bogdanova et al. (2013)
	Baltica (Fennoscandia)	Oskarshamn	1.78	ENE dykes	Pisarevsky and Bylund (2010)
	West Africa	Libiri	1.79	NS dykes	Baratoux et al. (2018)
Timpton	Siberia	Timpton	1.75	Radiating dykes	Gladkochub et al. (2010)
	India	Newer dolerites	1.76	WNW dykes	Shankar et al. (2014)
	East Antarctica	Vestfold Hills-3	1.75	NE dykes	Ernst et al. (2013)
	São Francisco/Congo	Januária	1.76	NNW dykes	Chaves et al. (this study)
	West Africa	Kédougou	1.76	NE dykes	Baratoux et al. (2018)
	West Africa	Tagragra of Akka	1.75	NW dykes	Youbi et al. (2013)
	Laurentia	Kivalliq (Cleaver-Hadley Bay-Nueltin)	1.75	Dykes and sills	Ernst et al. (2013)
	Baltica (Sarmatia)	Subbottsy-Nosachev	1.76	ENE dykes/mafic intrusions	Bogdanova et al. (2013)
	Baltica (Sarmatia)	Pugachevka-Fedorovka	1.76	NE dykes/mafic intrusions	Bogdanova et al. (2013)

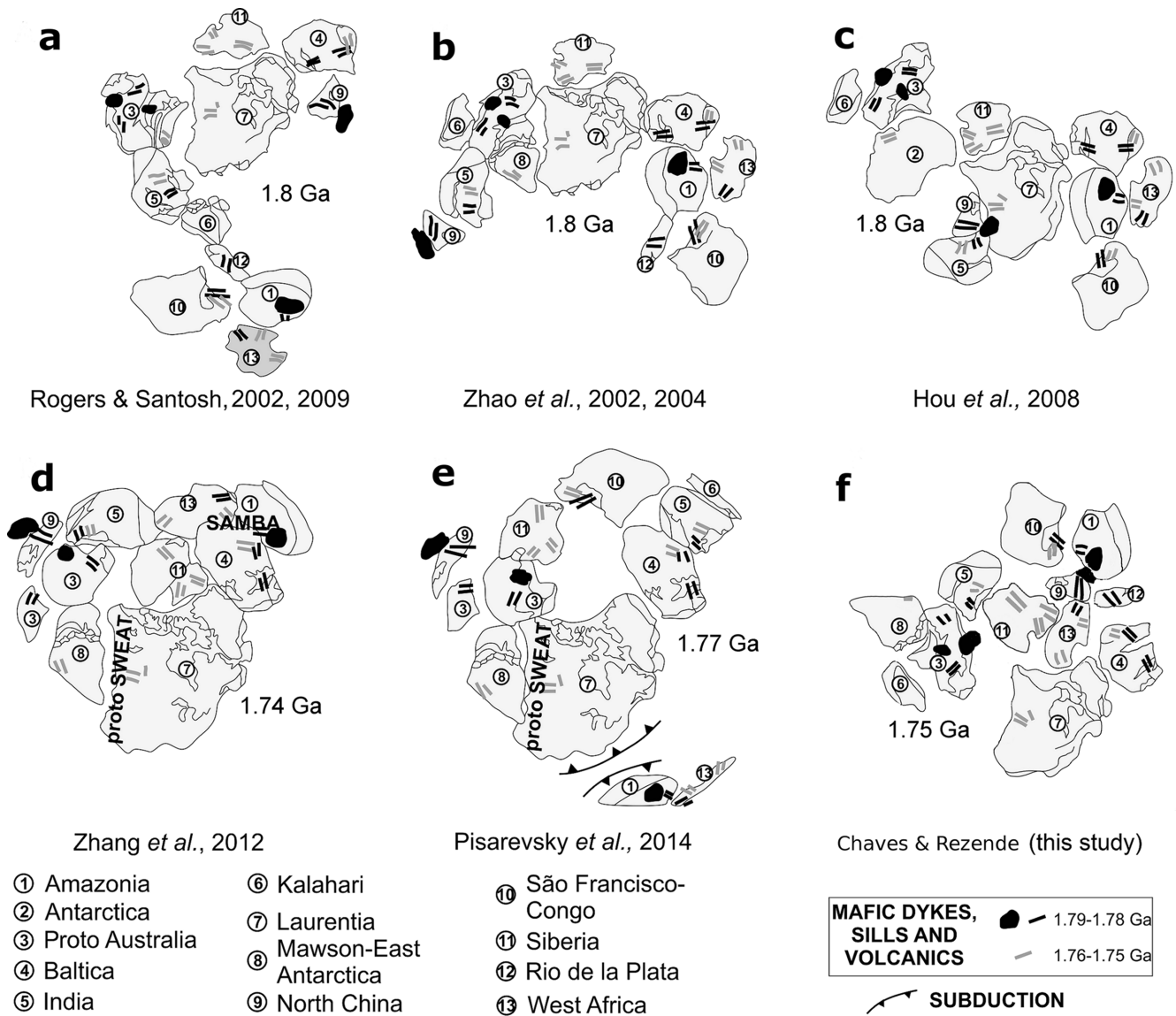


Figure 4. 1.79–1.78 Ga and 1.76–1.75 Ga LIP fragments superimposed on five configurations (a–e) of the supercontinent referred to as Columbia (a–c) or Nuna (d–e), for the late Paleoproterozoic (modified from Evans, 2013). a – Rogers and Santosh (2002), b – Zhao *et al.* (2002, 2004), c – Hou *et al.* (2008), d – Zhang *et al.* (2012), and e – Pisarevsky *et al.* (2014). F – Chaves *et al.* (this study).

struction, there is an apparent radiating pattern of 1.79–1.78 Ga dykes from Baltica, India and São Francisco-Congo blocks (Fig. 4e). However, this pattern is debatable due to the fact that dykes of the 1795 Ma Pará de Minas -1 swarm keep a subhorizontal magma flow direction from NW to SE (Raposo *et al.* 2004; Chaves and Neves, 2005) in their present position inside São Francisco craton. This observation undoes the possibility of a focal point to a radiating swarm in such reconstruction.

Hence, the configuration of the radiating mafic dykes of 1.79 Ga Hart-Carson, 1.79–1.78 Ga Avanavero-Xiong'er, and 1.76–1.75 Ga Tipton LIPs shown in Fig. 4f (and Fig. 3a), supported by robust paleomagnetic data of Xu *et al.* (2017) and Pesonen *et al.* (2012) from Statherian period, presented in Figs. 3c and 3d respectively, seems to be more suitable in reconstructing Columbia (Nuna) supercontinent than previous reconstructions.

Discussion

Columbia (Nuna) Younger LIPs as Additional Support to the Proposed Reconstruction

Mafic dykes are LIP fragments that radiate from a magma center commonly associated to mantle plume activity (Ernst, 2014). When younger LIPs represented by 1.64–1.68 Ga mafic dykes and volcanics, 1.52–1.51 Ga mafic dykes, and 1.38 Ga volcanics, mafic dykes and sills are restored on the proposed Columbia (Nuna) reconstruction shown in Fig. 3a, it is observed that their mafic dykes really converge to respective plume centers (Fig. 5), supporting the proposed Columbia (Nuna) reconstruction. These plume centers are located near continental margins, which represent the locations of rifting attempt of the Columbia

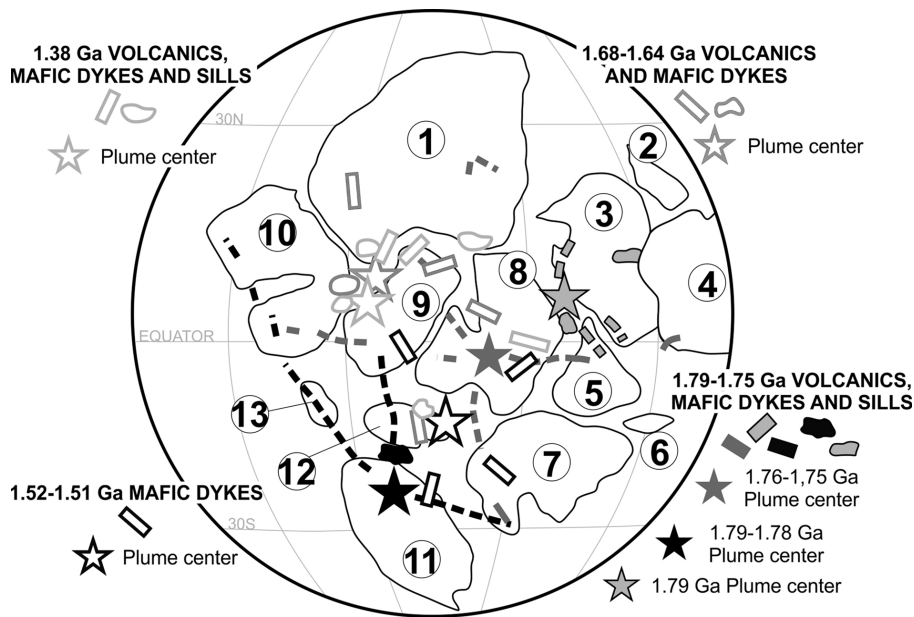


Figure 5. 1.64–1.68 Ga, 1.51–1.52 Ga, and 1.38 Ga LIPs restored on the Columbia (Nuna) reconstruction proposed in this paper, with their respective possible plume centers. Ages of LIP fragments are from Kouyaté et al. (2013) and references therein, Peng (2015), Baratoux et al. (2018), Ernst et al. (2008), Silveira et al. (2013), El Bahat et al. (2013) and references therein. 1.75–1.79 Ga LIPs of the Figure 3 are also presented here. (1) Laurentia; (2) Kalahari; (3) Australia; (4) Mawson East Antarctica; (5) India; (6) Tarim; (7) São Francisco-Congo; (8) Siberia; (9) West Africa; (10) Baltica; (11) Amazonia; (12) North China; (13) Rio de la Plata.

(Nuna) supercontinent.

After Bogdanova et al. (1996), Paleo- to Mesoproterozoic rifting and sediment accumulation began in the easternmost Baltica, around 1.65 Ga ago. This applies both to the Peri-Uralian troughs and the Pachelma rift system. The Volhyn-Orsha/Central Russian rift system and the interior rifts of Fennoscandia (e.g., the Ladoga and Bothnian rifts) began to develop later, at ca. 1.4–1.3 Ga. Such rifting events should be associated to 1.64–1.68 Ga and 1.38 Ga LIP events of the Fig. 5. 1.56 Ga rhyolitic tuff bed was discovered inside Gaoyuzhuang Formation of the Yan-Liao rift in the northern margin of the North China craton (Peng, 2015 and reference therein), possibly recording Mesoproterozoic extensional setting related to the 1.52 Ga LIP of the Fig. 5.

Possible Links Between Subduction, Large Low Shear Velocity Provinces / Ultra Low Velocity Zones, Plumes / Superplumes, LIPs, and Supercontinent Breakup

Plumes of hot upwelling rock rooted in the deep mantle have been proposed as a possible origin of hotspot and LIPs magmatic activity and deep mantle seismic tomography has shown the occurrence of mantle plumes (Zhao, 2001; Nolet et al., 2006). After Li and Zhong (2009), a cluster of mantle plumes can be named as a superplume. There is a correlation of hotspots and LIPs locations with the large low shear velocity provinces (LLSVPs - characterized by slow shear wave velocities) at the base of the mantle (Thorne et al., 2004). Furthermore, based on geodynamic modelling, McNamara et al. (2010) suggest that hotspots might preferentially occur above ultralow velocity zones (ULVZs) located in the lowermost mantle (Fig. 3b) close to

the core-mantle boundary (CMB).

French and Romanowicz (2015) describe the use of a whole-mantle seismic imaging technique - combining accurate wavefield computations with information contained in whole seismic waveforms - that reveals the presence of broad (not thin tails), quasi-vertical, long-lived thermochemical conduits beneath many prominent present-day hotspots around the world. These conduits extend from the CMB to about 1,000 kilometres below Earth's surface, where some are deflected horizontally, as though entrained into more vigorous upper-mantle circulation. At the base of the mantle, these conduits (individual plumes) are rooted in patches of greatly reduced shear velocity that correspond to the locations of ULVZs located below the LLSVPs. This correspondence establishes a continuous connection between ULVZs, LLSVPs and mantle plumes (McNamara et al., 2010).

Steinberger and Torsvik (2012) modelling supports that mantle plumes are more intimately linked to plate tectonics than usually assumed. After these authors, not only can plumes cause continental breakup, but also conversely subducted plates may trigger plumes at the margins of LLSVPs near the CMB.

A supercontinent-Superplume Coupling at 1.79–1.75 Ga?

Taking into account available paleomagnetic data and precise U-Pb ages of LIP fragments, three regions of possible incidence of mantle plume activity can be recognized in Fig. 3a, recorded by 1.79 Ga Hart-Carson LIP/plume, 1.79–1.78 Ga Avanavero-Xiong'er LIP/plume and 1.76–1.75 Ga Tipton LIP/plume. Following not only the suggestions of Li and Zhong (2009) concerning the correlations between Rodinia and Pangea supercontinents and their associated subduction zones and LLSVP-related superplumes, but also the Steinberger and Torsvik (2012) plume modelling, it is suggested here that a LLSVP (with possible associated ULVZs) beneath Columbia (Nuna) would have triggered the three separate mantle plumes (collectively representing a superplume). These would have resulted from prior arrival of 2.2 Ga to 1.8 Ga subducting slabs in the lowermost mantle. Fig. 3b shows such a scenario (note older 2.20–1.80 Ga slabs under Columbia different from the younger 1.80–1.50 Ga circum-supercontinent subducting slabs) at 1.75 Ga with respect to the X-Y section of the Fig. 3a. The first attempt at Columbia (Nuna) breakup manifested as a rift system would have initially started in the regions consisting of 1.79 Ga Hart-Carson and Avanavero-Xiong'er LIPs, and subsequently at the 1.76 Ga Tipton LIP, centered above the plume conduits. In fact, the spatial coincidence between the probable 1.79–1.75 Ga LLSVP and such LIPs implicates a geodynamic relationship between the long-term subduction processes (2.2–1.8 Ga) related to Columbia (Nuna) assembly and the formation of plumes rooted in a LLSVP, whose projection on Earth's surface is shown in Fig. 3a.

Shear wave velocity anomalies were detected near the core-mantle

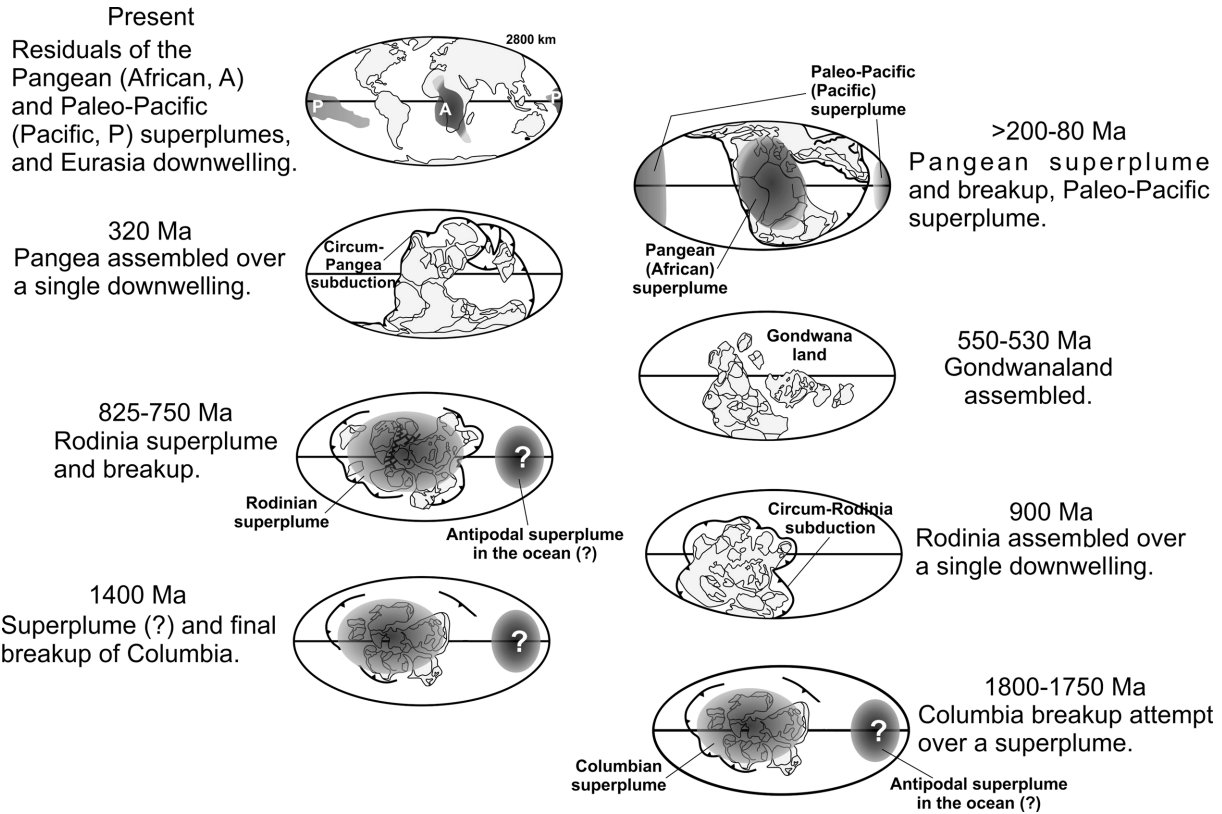


Figure 6. Illustration of supercontinent-superplume coupling in the past 1800 Ma (modified from Li and Zhong, 2009). Superplumes are projected on the Earth's surface.

boundary (Becker and Boschi, 2002), illustrating the location and lateral extent of the present antipodal African (A) and Pacific (P) superplumes (Fig. 6). Li and Zhong (2009) have speculated that circum-supercontinent subduction (single downwelling) leads to the formation of antipodal superplumes corresponding to the positions of the

supercontinents. The superplumes could bring themselves and the coupled supercontinents to equatorial positions through true polar wander events, and eventually lead to the breakup of the supercontinents like Pangea and Rodinia.

Zhao et al. (2004) and Zhang et al. (2012) pointed out Columbia (Nuna) final assembly around 1.8 Ga. Following this scenario, it is proposed here that a Columbia (Nuna) supercontinent-superplume coupling initially took place at 1.79–1.75 Ga, which led to the first breakup attempt of the supercontinent (Fig. 6). Despite the breakup attempts recorded by successive LIP events (Fig. 5), Columbia (Nuna) probably remained as a supercontinent for nearly 400 Ma and did not fully breakup until 1380 Ma, when a huge event recorded on almost all of Earth's continental blocks (Fig. 7) would mark its final breakup (Ernst et al., 2008).

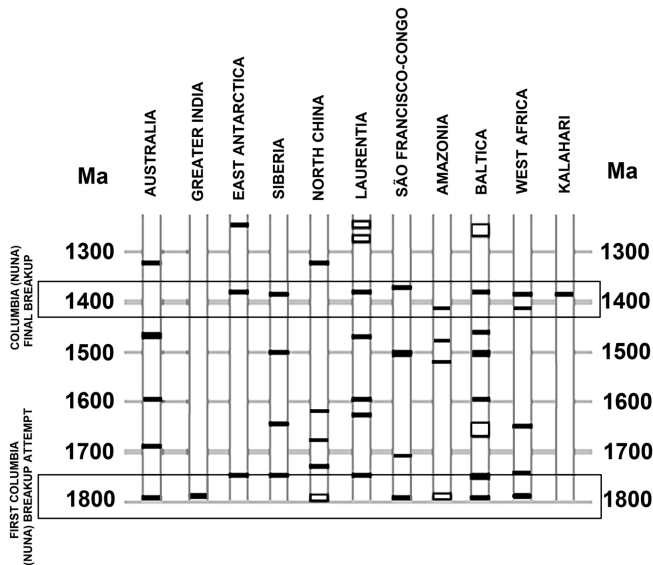


Figure 7. LIP barcode diagram for cratonic blocks grouped in the time interval relevant to Columbia (Nuna) reconstruction. A bar indicates a single pulse. A box can enclose multiple pulses for a single event (modified from Ernst et al., 2013, and with updates of Peng, 2015; D'Agrella-Filho et al., 2016).

Conclusion

A new Columbia (Nuna) supercontinent reconstruction, supported by available paleomagnetic data, is proposed based on restructuring U-Pb-dated LIP fragments, mainly their mafic dykes (with their radiating trends, and including the additional U-Pb 1762 Ma age of the Januária dyke from São Francisco Craton), but also their sills and volcanic rocks from cratonic blocks around the world. The 1.79–1.76 Ma units were assembled into three reconstructed LIPs (Hart-Carson, Avanavero-Xiong'er, and Tipton) presented in Fig. 3a, which shows cratonic blocks connected in a single supercontinent. It is suggested that these LIPs were emplaced above a LLSVP. A supercontinent-

superplume geodynamic setting is proposed to be linked to the formation of these LIPs in Columbia (Nuna) in the beginning of the Statherian Period. The same LIP units were superimposed on previous alternative Columbia (Nuna) reconstructions, but no radiating or linear dyke patterns could be restored to justify cratonic connections in a single supercontinent.

Three additional younger Proterozoic LIPs can be restored on the proposed Columbia (Nuna) reconstruction shown in Fig. 3a and their mafic dykes converge to respective plume centers (Fig. 5), supporting the proposed Columbia (Nuna) reconstruction.

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References

- Baratoux, L., Söderlund, U., Ernst, R.E., de Roever, E., Jessell, M.W., Kamo, S., Naba, S., Perrouty, S., Metelka, V., Yatte, D., Grenholm, M., Diallo, D.P., Ndiaye, P.M., Diouf, E., Courrière, C., Benoit, M., Baratoux, D., Youbi, N., Rousse, S., and Bendaoud, A., 2018, New U-Pb baddeleyite ages of mafic dyke swarms of the West African and Amazonian Cratons: implication for their configuration in supercontinents through time. In: Srivastava, R.K., Ernst, R.E., Peng, P. (eds.) *Dyke Swarms of the World – A Modern Perspective*. Springer, Singapore, pp. 263–314. (in press)
- Becker, T.W. and Boschi, L., 2002, A comparison of tomographic and geodynamic mantle models. *Geochemistry Geophysics Geosystems* 3, doi:10.1029/2001GC000168.
- Betts, P.G., Giles, D., and Schaefer, B.F., 2008, Comparing 1800–1600 Ma accretionary and basin processes in Australia and Laurentia: Possible geographic connections in Columbia. *Precambrian Research*, v. 166, pp. 81–92.
- Bispo-Santos, F., D'Agrella-Filho, M.S., Pacca, I.I.G., Janikian, L., Trindade, R.I.F., Elming, S-Á., Silva, J.A., Barros, M.A.S., and Pinho, F.E.C., 2008, Columbia revisited: Paleomagnetic results from the 1790 Ma Colíder volcanics (SW Amazonian Craton, Brazil). *Precambrian Research*, v. 164, pp. 40–49.
- Bispo-Santos, F., D'Agrella-Filho, M.S., Trindade, R.I.F., Janikian, L., and Reis, N. J., 2014, Was there SAMBA in Columbia? Paleomagnetic evidence from 1790 Ma Avanavero mafic sills (northern Amazonian Craton). *Precambrian Research*, v. 244, pp. 139–155.
- Bogdanova, S.V., Pashkevich, I.K., Gorbatshev, R. and Orlyuk M.I., 1996, Riphean rifting and major Palaeoproterozoic crustal boundaries in the basement of the East European Craton: geology and geophysics. *Tectonophysics*, v. 268, pp. 1–21.
- Bogdanova, S.V., Gintov, O.B., Kurlovich, D.M., Lubnina, N.V., Nilsson, M.K.M., Orlyuk, M.I.O., Pashkevich, I.K., Shumlyansky, L.V., and Starostenko, V.I., 2013, Late Palaeoproterozoic mafic dyking in the Ukrainian Shield of Volgo-Sarmatia caused by rotation during the assembly of supercontinent Columbia (Nuna). *Lithos*, v. 174, pp. 196–216.
- Bogdanova, S.V. and Pisarevsky, S.A., 2015, Were Amazonia and Baltica connected in Nuna and Rodinia? AGU Fall Meeting. American Geological Society, San Francisco, T13A–2966.
- Brito Neves, B.B., Sá, J.M., Nilson, A.A. and Botelho, N.F., 1995, A tafrogênese estateriana nos blocos paleoproterozóicos da América do Sul e processos subsequentes (Statherian taphrogenesis in Paleoproterozoic blocks of South America and subsequent processes). *Geonanos*, v. 3(2), pp. 1–21.
- Bryan, S.E. and Ernst, R.E., 2008, Revised definition of Large Igneous Provinces (LIPs). *Earth-Science Reviews*, v. 86, pp. 175–202.
- Cederberg, J., Söderlund, U., Oliviera, E.P., Ernst, R.E., and Pisarevsky, S.A., 2016, U-Pb baddeleyite dating of the Proterozoic Pará de Minas dyke swarm in the Sao Francisco craton (Brazil)-implications for tectonic correlations with Siberia, Congo and North China cratons. *Journal of the Geological Society of Sweden (GFF)*, v. 138, pp. 219–240.
- Chaves, A.O. and Neves, J.M.C., 2005, Magmatism, rifting and sedimentation related to Late Paleoproterozoic mantle plume events of Central and Southeastern Brazil. *Journal of Geodynamics*, v. 39, pp. 197–208.
- CPRM, Serviço Geológico do Brasil and CODEMIG, Companhia de Desenvolvimento Econômico de Minas Gerais., 2014, Mapa Geológico do Estado de Minas Gerais, Escala 1:1.000.000.
- D'Agrella-Filho, M.S., Trindade, R.I.F., Elming, S-Á., Teixeira, W., Yokoyama, E., Tohver, E., Geraldés, M.C., Pacca, I.I.G., Barros, M.A.S., and Ruiz, A.S., 2012, The 1420 Ma Indivaí Mafic Intrusion (SW Amazonian Craton): Paleomagnetic results and implications for the Columbia supercontinent. *Gondwana Research*, v. 22, pp. 956–973.
- D'Agrella-Filho, M.S., Bispo-Santos, F., Trindade, R.I.F., and Antonio, P.Y.J., 2016, Paleomagnetism of the Amazonian craton and its role in paleocontinents. *Brazilian Journal of Geology*, v. 46, pp. 275–299.
- Dalziel, I.W.D., 1999, Global paleotectonics: reconstructing a credible supercontinent. In *Geological Society of Australia Abstracts. Geological Society of Australia*, vol. 59, 114p.
- Demirer, K., 2012, U-Pb baddeleyite ages from mafic dyke swarms in Dharwar craton, India – links to an ancient supercontinent. Master's thesis, Department of Geology, Lund University, 25 p.
- El Bahat, A., Ikenne, M., Söderlund, U., Cousens, B., Youbi, N., Ernst, R., Soulimani, A., El Janati, M., and Hafid, A., 2013, U-Pb ages and geochemistry of dolerite dykes in the Bas Draa Inlier of the Anti-Atlas of Morocco: newly identified 1380 Ma event in the West African Craton. *Lithos*, v. 174, pp. 85–98.
- Ernst, R.E., Wingate, M.T.D., Buchan, K.L., and Li, Z.X., 2008, Global record of 1600–700 Ma Large Igneous Provinces (LIPs): implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents. *Precambrian Research*, v. 160, pp. 159–178.
- Ernst, R.E., Bleeker, W., Söderlund, U., and Kerr, A.C., 2013, Large Igneous Provinces and supercontinents: toward completing the plate tectonic revolution. *Lithos*, v. 174, pp. 1–14.
- Ernst, R.E., 2014, *Large Igneous Provinces*, 1-653. Cambridge University Press, Cambridge. 653 p.
- Evans, D.A.D., 2003, True polar wander and supercontinents. *Tectonophysics*, v. 362, pp. 303–320.
- Evans, D.A.D., 2013, Reconstructing pre-Pangean supercontinents. *Geological Society of America Bulletin*, v. 125, pp. 1735–1751.
- French, S.W. and Romanowicz, B., 2015, Broad plumes rooted at the base of the Earth's mantle beneath major hotspots. *Nature*, v. 525, pp. 95–99.
- Gladkochub, D., Pisarevsky, S.A., Donskaya, T., Natapov, L.M., Mazukabzov, A., Stanevich, A., and Silkyarov, E., 2006, Siberian craton and its evolution in terms of Rodinia hypothesis. *Episodes*, v. 29(3), pp. 169–174.
- Gladkochub, D.P., Pisarevsky, S.A., Donskaya, T.V., Ernst, R.E., Wingate, M.T.D., Söderlund, U., Mazukabzov, A.M., Sklyarov, E.V., Hamilton, M.A., and Hanes, J.A., 2010, Proterozoic mafic magmatism in Siberian craton: An overview and implications for paleocontinental reconstruction. *Precambrian Research*, v. 183, pp. 660–668.
- Halls, H.C., Campal, N., Davis, D.W., and Bossi, J., 2001, Magnetic studies and U-Pb geochronology of the Uruguayan dyke swarm, Rio de la Plata craton, Uruguay: paleomagnetic and economic implications.

- Journal of South American Earth Sciences, v. 14, pp. 349–361.
- He, Y.H., Zhao, G.C., and Sun, M., 2008, Geochemistry of the Xiyanghe volcanics at the southern margin of the North China Craton: Petrogenesis and tectonic implications. *Lithos* 102, pp. 158–178.
- He, Y.H., Zhao, G.C., Sun, M., and Xia, X.P., 2009, SHRIMP and LA-ICP-MS zircon geochronology of the Xiong'er volcanic rocks: implications for the Paleo-Mesoproterozoic evolution of the southern margin of the North China Craton. *Precambrian Research* v. 168, pp. 213–222.
- He, Y.H., Zhao, G.C., and Sun, M., 2010, Geochemical and isotopic study of the Xiong'er volcanic rocks at the southern margin of the North China Craton: Petrogenesis and tectonic implications. *Journal of Geology*, v. 118, pp. 417–433.
- Hoffman, P.F. 1991, Did the breakout of Laurentia turn Gondwana inside out? *Science*, v. 252, pp. 1409–1412.
- Hoffman, P.F., 1997, Tectonic genealogy of North America, In: van der Pluijm, B.A., and Marshak, S., (Eds), *Earth Structure: An Introduction to Structural Geology and Tectonics*: New York, McGraw-Hill, p. 459–464.
- Hou, G., Santosh, M., Qian, X., Lister, G.S., and Li, J., 2008, Configuration of the Late Paleoproterozoic supercontinent Columbia: Insights from radiating mafic dyke swarms: *Gondwana Research*, v. 14, pp. 395–409.
- Johansson, Å., 2009, Baltica, Amazonia and the SAMBA connection: 1000 million years of neighbourhood during the Proterozoic? *Precambrian Research*, v. 175, pp. 221–234.
- Kouyaté, D., Söderlund, U., Youbi, N., Ernst, R., Hafid, A., Ikenne, M., Soulaïmani, A., Bertrand, H., El Janati, M., and R'kha Chaham, K., 2013, U-Pb baddeleyite and zircon ages of 2040Ma, 1650Ma and 885 Ma on dolerites in the West African Craton (Anti-Atlas inliers): Possible links to break-up of Precambrian supercontinents. *Lithos*, v. 174, pp. 71–84.
- Li, Z.-X., and Zhong, S., 2009, Supercontinent–superplume coupling, true polar wander and plume mobility: Plate dominance in whole-mantle tectonics: *Physics of the Earth and Planetary Interiors*, v. 176, pp. 143–156.
- McNamara, A.K., Garnero, E.J., and Rost, S., 2010, Tracking deep mantle reservoirs with ultra-low velocity zones. *Earth and Planetary Science Letters*, v. 299, pp. 1–9.
- Meert, J.G. and Santosh, M., 2017, The Columbia supercontinent revisited. *Gondwana Research*, v. 50, pp. 67–83.
- Milanovskiy, E.E., 1996, *Geologiya Rossii i blizhnego zarubezh'ya (Severnaya Evraziya)*. Geology of Russia and Near Abroad, North Eurasia. Izd. Mosc. Univ., Moscow.
- Nolet, G., Karato, S.-I., and Montelli, R., 2006, Plume fluxes from seismic tomography. *Earth and Planetary Science Letters*, v. 248, pp. 685–699.
- Payne, J.L., Hand, M., Barovich, K.M., Reid, A., and Evans, D.A.D., 2009, Correlations and reconstruction models for the 2500–1500 Ma evolution of the Mawson Continent. In: Reddy, S.M., Mazumder, R., Evans, D.A.D., Collins, A.S., (Eds), *Palaeoproterozoic Supercontinents and Global Evolution*: Geological Society of London Special Publication, v. 323, pp. 319–355.
- Peng, P., 2010, Reconstruction and interpretation of the giant mafic dyke swarms: a case study of 1.78 Ga magmatism in the North China Craton. *Special Publication of Geological Society of London*, v. 338, pp. 163–178.
- Peng, P., 2015, Precambrian mafic dyke swarms in the North China Craton and their geological implications. *Science China Earth Sciences*, v. 58(5), pp. 649–675.
- Pesonen, L.J., Mertanen, S., and Veikkolainen, T., 2012, Paleo-Mesoproterozoic Supercontinents – A paleomagnetic view. *Geophysica*, v. 48, pp. 5–47.
- Peterson, T.D., Scott, J.M.J., LeCheminant, A.N., Jeerson, C.W., and Pehrsson, S.J., 2015, The Kivalliq Igneous Suite: anorogenic bimodal magmatism at 1.75 Ga in the western Churchill Province, Canada. *Precambrian Research*, v. 262, pp. 101–119.
- Pirajno, F., and Hoatson, D.M., 2012, A review of Australia's Large Igneous Provinces and associated mineral systems: implications for mantle dynamics through geological time. *Ore Geology Reviews*, v. 48, pp. 2–54.
- Pisarevsky, S.A. and Bylund, G., 2010, Paleomagnetism of the 1780–1770 mafic and composite intrusions of the Smaland (Sweden): implications for the Mesoproterozoic supercontinent. *American Journal of Science*, v. 310, pp. 1168–1186.
- Pisarevsky, S.A., Elming, S.-Å., Pesonen, L.J., and Li, Z.-X., 2014, Mesoproterozoic paleogeography: Supercontinent and beyond. *Precambrian Research*, v. 244, pp. 207–225.
- Raposo, M.I.B., Chaves, A.O., Lojkasek-Lima, P., D'Agrella-Filho, M.S., and Teixeira, W., 2004, Magnetic fabric and rock magnetism of Proterozoic dike swarm from the southern Sao Francisco craton, Minas Gerais state, Brazil. *Tectonophysics*, v. 378, pp. 43–63.
- Reis, N.J., Teixeira, W., Hamilton, M.A., Bispo-Santos, F., Almeida, M.E., and D'Agrella-Filho, M.S., 2013, Avanavero mafic magmatism, a late Paleoproterozoic LIP in the Guiana Shield, Amazonian Craton: U-Pb TIMS baddeleyite, geochemical and paleomagnetic evidence. *Lithos*, v. 174, pp. 175–195.
- Rogers, J.J.W., and Santosh, M., 2002, Configuration of Columbia, a Mesoproterozoic supercontinent: *Gondwana Research*, v. 5, pp. 5–22.
- Rogers, J.J.W. and Santosh, M., 2009, Tectonics and surface effects of the supercontinent Columbia. *Gondwana Research*, v. 15, pp. 373–380.
- Santos, J.O.S., Hartmann, L.A., McNaughton, N.J., and Fletcher, I.R., 2002, Timing of mafic magmatism in the Tapajos Province (Brazil) and implications for the evolution of the Amazon craton: Evidence from baddeleyite and zircon U–Pb SHRIMP geochronology. *Journal of South American Earth Sciences*, v. 15, pp. 409–429.
- Shankar, R. Vijayagopal, B., and Kumar, A., 2014, Precise Pb–Pb baddeleyite ages of 1765 Ma for a Singhbhum 'newer dolerite' dyke swarm. *Current Science*, v. 106, pp. 1306–1310.
- Silveira, E.M., Söderlund, U., Oliveira, E.P., Ernst, R.E., and Menezes Leal, A.B., 2013, First precise U–Pb baddeleyite ages of 1500 Ma mafic dykes from the São Francisco Craton, Brazil, and tectonic implications. *Lithos*, v. 174, pp. 144–156.
- Stacey, J.S. and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters*, v. 26, pp. 207–221.
- Steinberger, B. and Torsvik, T.H., 2012, A geodynamic model of plumes from the margins of Large Low Shear Velocity Provinces. *Geochemistry Geophysics Geosystems* 13(1), Q01W09.
- Teixeira, W., D'Agrella-Filho, M.S., Hamilton, M.A., Ernst, R.E., Girardi, V.A.V., Mazzucchelli, M., and Bettencourt, J.S., 2013, U-Pb (ID-TIMS) baddeleyite ages and paleomagnetism of 1.79 and 1.59 Ga tholeiitic dyke swarms, and the position of the Rio de la Plata craton within the Columbia supercontinent. *Lithos*, v. 174, pp. 57–174.
- Thorne, M.S., Garnero, E.J., and Grand, S.P., 2004, Geographic correlation between hot spots and deep mantle lateral shear-wave velocity gradients. *Physics of Earth and Planetary Interiors*, v. 146, pp. 47–63.
- Tyler, I.M., Pirajno, F., Bagas, L., Myers, J.S. and Preston, W., 1998, The geology and mineral deposits of the Proterozoic in Western Australia. AGSO. *Journal of Geology and Geophysics*, v. 17, pp. 223–244.
- Xu, H., Yang, Z., Peng, P., Ge, K., Jin, Z., and Zhu, R., 2017, Magnetic fabrics and rock magnetism of the Xiong'er volcanic rocks and their implications for tectonic correlation of the North China Craton with other crustal blocks in the Nuna/Columbia supercontinent. *Tectonophysics*, v. 712–713, pp. 415–425.
- Youbi, N., Kouyate, D., Söderlund, U., Ernst, R., Soulaïmani, A., Hafid, A., Ikenne, M., El Bahat, A., Bertrand, H., R'kha Chaham, K., Ben Abbou, M., Mortaji, A., El Ghorfi, M., Zouhair, M. and El Janati, M., 2013, The 1750 Ma Magmatic Event of the West African Craton (Anti-Atlas, Morocco). *Precambrian Research*, v. 236, pp. 106–123.
- Zhang, S., Li, Z.-X., Evans, D.A.D., Wu, H., Li, H., and Dong, J., 2012, Pre-Rodinia supercontinent Nuna shaping up: A global synthesis with new paleomagnetic results from North China: *Earth and Planetary Science Letters*, v. 353–354, pp. 145–155.
- Zhao, D., 2001, Seismic structure and origin of hotspots and mantle plumes.

Earth and Planetary Science Letters, v. 192, pp. 251–265.

Zhao, G., Cawood, P.A., Wilde, S.A., and Sun, M., 2002, Review of global 2.1–1.8 Ga orogens: Implications for a pre-Rodinia supercontinent: Earth-Science Reviews, v. 59, pp. 125–162.

Zhao, G., Sun, M., Wilde, S.A., and Li, S., 2004, A Paleo-Mesoproterozoic supercontinent: Assembly, growth and breakup: Earth-Science Reviews, v. 67, pp. 91–123.

Zhao, G.C., He, Y.H., and Sun, M., 2009, The Xiong'er volcanic belt at the southern margin of the North China Craton: Petrographic and geochemical evidence for its outboard position in the Paleo-Mesoproterozoic Columbia Supercontinent. Gondwana Research, v. 16, pp. 170–181.



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