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ARTICLE

The Ironian Ocean and the 2.2–1.8 Ga Introversion Process in the Formation of the Columbia (Nuna) Supercontinent

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ABSTRACT

Robust evidence on the existence of the Columbia (Nuna) supercontinent's internal ocean—the Ironian Ocean (name proposed here for the first time)—has been compiled from scientific literature. Remnants of Superior-type banded iron formations suggest the 2.5–2.2 Ga ocean spreading stage, as well as eclogites, blueschists, oceanic plateau, eclogite xenolith and ophiolites point to 2.2–1.8 Ga ocean closure stage along its suture zone. The 2.10–1.95 Ga collisional orogens of the Columbia (Nuna) supercontinent would have been formed throughout impact of continental lithospheric fragments during the consumption of the Ironian internal ocean by introversion process developed in the formation of the Columbia (Nuna) in the Paleoproterozoic Earth. These collisional orogens are located along the suture zone of the Ironian ocean, in a situation that indicates the process of introversion. Although tectonic stress associated with the 1.9-1.8 Ga accretionary and intracontinental orogenies contributed complementarily to the assembly of Columbia (Nuna) around 1.75 Ga, this supercontinent formed essentially by collisional orogenesis during Ironian Ocean closure and therefore by introversion process.

Keywords: Columbia (Nuna) Supercontinent; Internal Ocean; Introversion; Ironian

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1. Introduction

After Roberts and Nance [1,2], a key process in many models related to the formation and breakup of supercontinents involves mantle superdownwellings (often referred to as slab avalanches) and superupwellings (known as superplumes). Li et al. have proposed that when a supercontinent forms through extroversion, the consumption of the previous external superocean results in the destruction of the existing subduction girdle [3]. This leads to the creation of a large mantle superdownwelling beneath the newly forming supercontinent. This process triggers a mantle superupwelling, which is typically responsible for initiating the activity of large igneous provinces (LIPs) and eventually leads to the breakup of the supercontinent [4], perpetuating the coupled supercontinent-superplume cycle [5]. Extroversion occurs when the oceanic cell exterior to the subduction ring is closed. To achieve this closure, continents must drift across the exterior cell and collide with other continents on the opposing side [6].

On the other hand, a supercontinent formed through introversion would develop above a weaker mantle downwelling, which occurs as smaller and younger internal oceans are consumed during the process of continental assembly [3]. During introversion, the continents merge along the mantle downwelling girdle, but remain within the continental cell, isolated from the external ocean by the surrounding subduction ring [6]. According to Martin et al. [6], conflicting interpretations of introversion and extroversion often arise when trying to classify oceans as interior or exterior based on paleogeography or the age of oceanic lithosphere relative to the time of supercontinent breakup. These authors describe interior and exterior oceans in relation to the external subduction ring and the associated accretionary orogens that surround amalgamated supercontinents. All oceans within the continent-dominated cell, located inside the subduction ring, are considered interior oceans. Conversely, the exterior ocean is separated from the interior oceans by the subduction ring and bordered by external accretionary orogens [6].

This paper aims to present robust evidence on the existence of the Columbia (Nuna) supercontinent's internal ocean, in order to highlight the introversion process in Paleoproterozoic Earth.

2. Columbia (Nuna) Supercontinent

Rogers and Santosh proposed that the Columbia supercontinent existed sometime between 1.9 and 1.5 Ga and began to disassemble around 1.4 Ga [7]. Their original configuration of this supercontinent was based on correlations between sedimentary basins in India and the Columbia region of North America. Columbia included the ancient cores of Ur (comprising India and western Australia, Madagascar, South Africa and East Antarctic cratons), Atlantica (which consisted of the cratonic elements of western and central Africa and South America), and Arctica (comprising Greenland, cratonic North America and Siberia), along with Paleoproterozoic additions to those regions. The main evidence supporting this configuration includes the ages of rifting and the widespread collisional orogens that occurred between 1.9 and 1.8 Ga.

Numerous attempts have been made to model the supercontinent Columbia [8–12], starting with Zhao et al. [13], who created a reconstruction based on the geometry and age relationships of orogenic belts within Columbia. Meert reviewed the history of the Columbia supercontinent and the debate over whether the name “Columbia” or “Nuna” should take precedence [14]. He argued that although the term Nuna was used before Columbia, it referred only to the landmasses of Siberia, Laurentia, and Baltica [14]. Therefore, Nuna should be viewed as the core of “Nena - Northern Europe and North America” [15,16]. Furthermore, the assessment of the manifestation of modern-style plate tectonics throughout Paleoproterozoic goes together with the development of the Columbia/Nuna supercontinent models. It has become consensus that modern-style plate tectonics was operative in Paleoproterozoic, evidenced by ophiolites, low T/P metamorphism including eclogites, passive margin formation, paleomagnetic constraints, ore deposits, abundant S-type granites, and seismic images of paleo-subduction zones [17–19].

Paleomagnetic data offer the only quantitative method for reconstructing supercontinents, as noted by Meert and Santosh [20]. Although a comprehensive worldwide paleomagnetic database is not yet fully available—particularly lacking data from the West Africa and Tanzania blocks—Chaves has proposed a new reconstruction of the Columbia (Nuna) supercontinent (**Figure 1**) [11]. This model positions Mawson/East Antarctica and proto-Australia together, following the work of Betts et al. [21,22], and places the Kalahari and Tanzania blocks in the Southern Hemisphere (**Figure 1A**). This reconstruction is supported by relevant paleomagnetic data provided by Xu et al. (**Figure 1B**) and Pesonen et al. (**Figure 1C**) [23,24]. It is based on the correlation of large igneous province (LIP) mafic unit fragments, particularly by linking their mafic dykes into radiating systems, as recommended by Ernst [25]. **Figure 1A** represents Columbia (Nuna) supercontinent assembled around 1.8 Ga and its disintegration would be around 1.4 Ga. This life span for Columbia is the same as proposed by Zhao et al. [8].

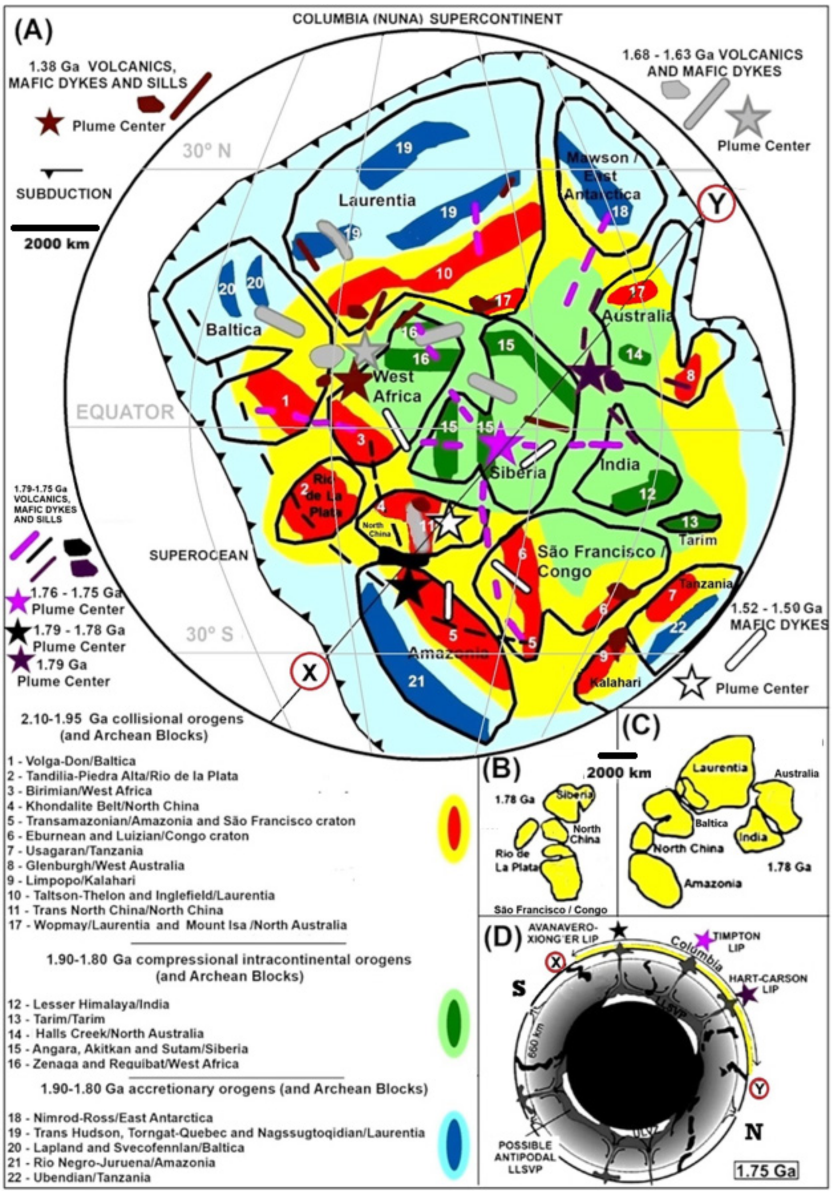

Figure 1. The Columbia (Nuna) Supercontinent and Mantle Dynamics around 1.75–1.78 Ga: **(A)** The Columbia (Nuna) Supercontinent (Modified by the Fusion of Figures from Chaves [11]). **(B)** Continental Reconstructions After Xu at 1.78 Ga. **(C)** Continental Reconstructions After Pesonen at 1.78 Ga. **(D)** X-Y Cross Section of the Earth at 1.75 Ga, Showing Ascent of Mantle Plumes from LLSVPs (Large Low Shear Velocity Provinces) and Subductions in Different Places Under Columbia (Nuna) [23,24]. ULVZ = Ultra-Low Velocity Zone. N = North. S = South. Reproduced/Modified with Permission from [11]. Copyright © [2021] [Elsevier].

Probably related to mantle plume activity, there are six Columbia (Nuna) supercontinent LIPs of different ages, represented by remnant mafic dykes, sills and volcanics (**Table 1**, **Figure 1A**) [26–49]. The Columbia (Nuna) reconstruction elaborated by Chaves is suitable due to the radiating mafic dykes of the LIPs Hart-Carson, Avanavero-Xiong'er, Timpton, Hame, Essakane, and Trans-Columbia [11].

Table 1. The Six Large Igneous Provinces of the Columbia (Nuna) Supercontinent (Compiled in This Work).

Large Igneous Province	Continental Block	Name of the LIP fragments	U-Pb Age (Ga)	LIP fragments
Hart-Carson	Australia/East Antarctica	Hart, Carson, Hamersley-Mt.Isa-Gawler	1.79	Sills and dykes/volcanics/ mafic-ultra-mafics [26]
	India	Pebbair	1.79	Dyke [27]
Avanavero-Xiong'er	Amazonia	Avanavero	1.79	Sills/dykes [28]
	Amazonia	Crepori	1.78	Sill [28]
	North China	Taihang	1.78	Dykes [29]
	North China	Xiong'er	1.78	Volcanics [29]
	São Francisco/Congo	Pará de Minas (first generation)	1.79	Dykes [30]
	Rio de la Plata	Uruguayan (Florida)	1.79	Dykes [31]
	Baltica	Tomashgorod-Belokorovichi	1.79	Dykes [32]
	Baltica	Oskarshamn	1.78	ENE dykes [33]
	West Africa	Libiri	1.79	Dykes [34]
Timpton	Siberia	Timpton	1.75	Radiating dykes [35]
	India	Newer dolerites	1.76	Dykes [36]
	East Antarctica	Vestfold Hills-3	1.75	Dykes [37]
	São Francisco/Congo	Januária	1.76	Dykes [38]
	West Africa	Kédougou	1.76	Dykes [34]
	West Africa	Tagragra of Akka	1.75	Dykes [39]
	Laurentia	Kivalliq (Cleaver-Hadley Bay-Nueltin)	1.75	Dykes and sills [37]
	Baltica	Subbottsy-Nosachev	1.76	Dykes/mafic intrusions [32]
	Baltica	Pugachevka-Fedorovka	1.76	Dykes/mafic intrusions [32]
Hame	Baltica	Hame-Suomenniemi	1.64	Dykes [40]
	Laurentia	Melville-Bugt	1.63	Dykes [41]
	West Africa	Zenaga	1.66	Dykes [42]
	Siberia	Nersa	1.64	Mafic intrusions [43]
	North China	Western Shandong	1.68–1.63	Dykes [44]
Essakane	West Africa	Essakane	1.52	Dykes [34]
	São Francisco/Congo	Curaça-Chapada Diamantina	1.50	Dykes [45]
	São Francisco/Congo	Humpata	1.50	Sills [46]
	Amazonia	Kayser	1.52	Dykes [34]
	Siberia	Kuonamka	1.50	Dykes [47]
	North China	Gaoyuzhuang	1.50	Volcanics [48]
Trans-Columbia	Laurentia	Midsommerso-Zig Zag Dal	1.38	Dykes [46]
	Baltica	Mashak	1.38	Volcanics [46]
	São Francisco/Congo	Kunene	1.38	Volcanics [46]
	Kalahari	Pilanesberg	1.38	Volcanics [46]
	Siberia	Chieress	1.38	Dykes [46]
	Laurentia	Hart -Salmon River Arch	1.38	Sills/Volcanics [46]
	North China	Yanliao	1.32	Dykes [48]
	West Africa	Bas Draa	1.38	Dykes [49]

The interpretation of the geological records of orogenic belts is an additional tool to determining global paleogeography of Columbia (Nuna) supercontinent. After Cawood et al. [50], reconstructing orogens is fraught with difficulty. However, they can be grouped within a spectrum of three endmember types: intracratonic (intracontinental), accretionary and collisional. Collisional orogens develop from the collision of continental lithospheric fragments, while accretionary orogens form at locations of ongoing oceanic plate subduction. In contrast, intracontinental orogens are found within a continent, away from an active plate margin, as a response to far-field stresses [50]. An example of intracontinental orogen would be an inverted rift, where there are no remnants of oceanic lithosphere.

The concentric orogenic pattern (configuration composed of orogenic belts surrounded by each other) of the Columbia (Nuna) paleogeography proposed by Chaves reveals 2.10–1.95 Ga collisional orogens (Tandilia-Piedra Alta/Rio de la Plata, Volga-Don/Baltica, Khondalite Belt/North China, Birimian/West Africa, Eburnean and Luizian/Congo craton, Transamazonian/ Amazonia and São Francisco craton, Glenburgh/ West Australia, Usagaran/Tanzania, Taltson-Thelon and Inglefield/Laurentia, Limpopo/Kalahari, Mount Isa/ North Australia, Trans-North China/ North China, and Wopmay/Laurentia) bordered by 1.90–1.80 Ga compressional intracontinental orogens located in the supercontinent core (Lesser Himalaya/India, Halls Creek/ North Australia, Angara, Akitkan, Sutam/Siberia, Zenaga and Reguibat/West Africa, and Tarim/Tarim) and by 1.90–1.80 Ga accretionary orogens located at the supercontinent margins (Trans-Hudson, Nimrod-Ross/East Antarctica, Lapland and Svecofennian/Baltica, Torngat-Quebec and Nagssugtoqidian/Laurentia, Ubendian/ Tanzania, and Rio Negro- Juruena/Amazonia) [11], with accretionary ones encircled by an external subduction girdle (**Figure 1A)** – all names of collisional, intracontinental and accretionary orogens are compiled from Condie at 1.75 Ga [51]. This concentric pattern exposes a perceptible synchronicity concerning intracontinental and accretionary orogens, both which would have been formed respectively as response to far- and near-field stress transmission from external subduction convergent girdle. Intracontinental orogens are characterized by the absence of oceanic lithosphere remnants (**Figure 1A**).

3. The Columbia (Nuna) Supercontinent's Internal Ocean and the Introversion Process Performance in the Paleoproterozoic Earth

The 2.10–1.95 Ga collisional orogens of the Columbia (Nuna) supercontinent would have been formed through impact of continental lithospheric fragments during the consumption of an internal ocean in subduction zones (associated superdownwellings are represented in **Figure 1D**, which represents a X-Y cross section drawn in the **Figure 1A**). This internal ocean, here named Ironian ("the iron-rich ocean", whose northern extension in central Canada was previously named as Manikewan ocean by Stauffer) [52], has its suture zone delineated in **Figure 2** according to the probable lateral prolongation of recognized oceanic remnants as 2.5–2.2 Ga Superior-type banded iron formations (evidence of the possible ocean spreading stage) [53–76]. Superior-type iron formations are developed in shallow marine environment in passive-margin sedimentary rock successions. The deposition of iron formations at 2.50 to 2.45 Ga preceded supercontinent assembly and the hydrothermal flux of iron was likely derived predominantly from mid-ocean ridges [77]. The suture zone of the Ironian Ocean is also delineated by 2.2–1.8 Ga eclogites, blueschists, oceanic plateau, eclogite xenolith and ophiolites (evidence of the ocean closure stage) [61–76]. In other words, when a paleoproterozoic rock association made of Superior type-BIF, eclogites, blueschists and ophiolites are found along a same suture zone (**Figure 2**), the suitable interpretation is that the geological scenario was composed of a subducted oceanic lithosphere, here named as Ironian Ocean. In addition, when comparing **Figure 1A** and **Figure 2**, we can see the collisional orogens along the proposed Ironian ocean suture zone in a situation that indicates an introversion process.

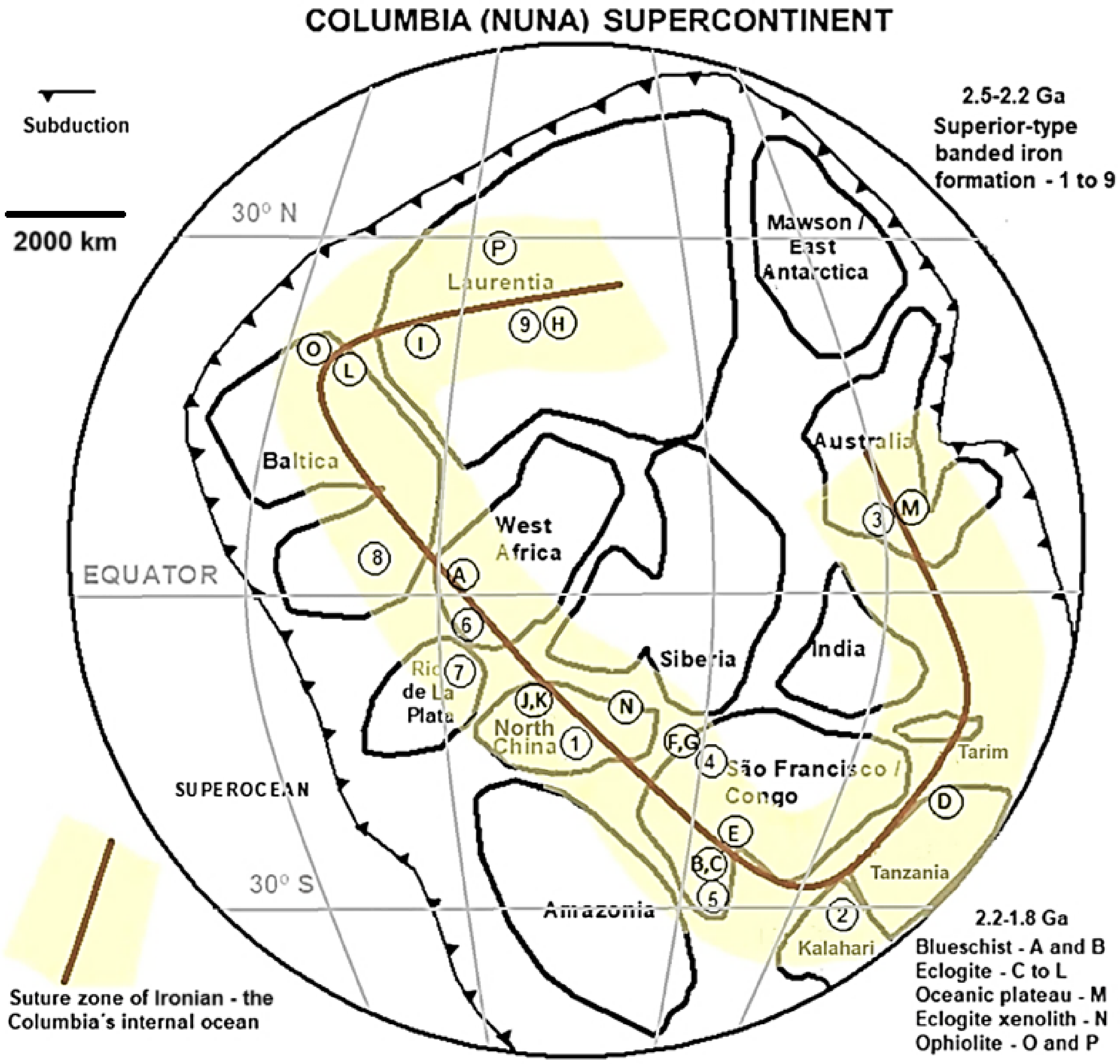

Figure 2. The Suture Zone Positioning of the Ironian—The Columbia's Internal Ocean—Around 1.75 Ga. 2.5–2.2 Ga Superior-Type Banded Iron Formations and 2.2–1.8 Ga Blueschists, Eclogites, Oceanic Plateau, Eclogite Xenolith and Ophiolites are Distributed Along the Ironian Ocean's Suture Zone.

Notes: Numbers: 1 – Reference [53], 2 and 3 – Reference [54], 4 – Reference [55], 5 – Reference [56], 6 – Reference [57], 7 – Reference [58], 8 – Reference [59], 9 – Reference [60]. Letters: A – Reference [61], B – Reference [62], C – Reference [63], D – Reference [64], E – Reference [65]; F – Reference [66], G – Reference [67], H – Reference [68], I – Reference [69], J – Reference [70], K – Reference [71], L – Reference [72], M – Reference [73], N – Reference [74], O – Reference [75], P – Reference [76].

Wan et al. present seismological evidence for subduction network at 2 Ga ago for North China, Laurentia, Siberia and Baltica continental blocks [78]. By considering the hypothesis of this evidence under Rio de La Plata, São Francisco/Congo, West Africa, Australia, Tanzania and Kalahari continental blocks as well, it is here suggested that possible spreading and subsequent subduction of the Ironian Ocean represent the activity of the modern-style plate tectonics during Paleoproterozoic. As mentioned, spreading along a central oceanic ridge occurred between 2.5–2.2 Ga, and its subduction, accompanied by 2.1–1.9 Ga collisional orogeny, was between 2.2–1.8 Ga. These geological processes have implications for economic geology, since the Ironian Ocean suture zone may contain more mineral deposits such as hematite, graphite and others than are currently known. It is important to mention that plate reconstruction is one of the fundamental geoscientific exercises that has geological implications and geometries and sizes of continental blocks of the Columbia (Nuna) supercontinent presented in **Figure 1** have been extracted from GPlates tool [79–81].

4. Conclusions

To understand individual stages of a supercontinent cycle, it is necessary to decipher the relationships between paleogeography, tectonics and mantle dynamics and thermal evolution [6,80]. During the 2.2–1.9 Ga introversion of the Columbia (Nuna) supercontinent, continental blocks collided and remained within the continental cell isolated from the exterior superocean by the external subduction ring (**Figure 2**). Although tectonic stress associated with the 1.9–1.8 Ga accretionary and intracontinental orogenies contributed complementarily to the assembly of Columbia (Nuna) around 1.75 Ga, this supercontinent formed essentially by collisional orogenesis during Ironian Ocean closure (ocean name proposed here for the first time) and therefore by introversion process in the Paleoproterozic Earth.

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Data Availability Statement

The data are available in the respective references cited in the manuscript, which was prepared based on the scientific literature.

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Conflicts of Interest

The author declares no conflict of interest.

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