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Reorienting the West African craton in Paleoproterozoic–Mesoproterozoic supercontinent Nuna

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ABSTRACT

The location of the West African craton (WAC) has been poorly constrained in the Paleoproterozoic–Mesoproterozoic supercontinent Nuna (also known as Columbia). Previous Nuna reconstruction models suggested that the WAC was connected to Amazonia in a way similar to their relative position in Gondwana. By an integrated paleomagnetic and geochronological study of the Proterozoic mafic dikes in the Anti-Atlas Belt, Morocco, we provide two reliable paleomagnetic poles to test this connection. Incorporating our new poles with quality-filtered poles from the neighboring cratons of the WAC, we propose an inverted WAC-Amazonia connection, with the northern WAC attached to northeastern Amazonia, as well as a refined configuration of Nuna. Global large igneous province records also conform to our new reconstruction. The inverted WAC-Amazonia connection suggests a substantial change in their relative orientation from Nuna to Gondwana, providing an additional example of large-magnitude cumulative azimuthal rotations between adjacent continental blocks over supercontinental cycles.

INTRODUCTION

The assembly and dispersal of the Paleoproterozoic–Mesoproterozoic supercontinent Nuna (also known as Columbia) are possibly the earliest manifestations of Earth's supercontinent cycle, which has profoundly influenced Earth's geosphere, biosphere, and atmosphere (Nance et al., 2014). In the past two decades, numerous attempts have been made to reconstruct Nuna, mainly tectono-stratigraphically and paleomagnetically (Evans, 2013). Though still debated, the broad configuration of Nuna is gradually becoming clearer: composed of a central kernel of Laurentia and Baltica (Gower et al., 1990; Evans and Pisarevsky, 2008), Siberia either closely or more distally adjacent to northern Laurentia (Evans and Mitchell, 2011; Pisarevsky et al., 2014; Ernst et al., 2016), and proto-Australia near western Laurentia (Payne et al., 2009; Kirscher et al., 2021). However, the positions of the remaining building blocks have great uncertainties, which make the configuration of Nuna and its transition to the successor supercontinent Rodinia unclear.

The West African craton (WAC, including the São Luís block in Brazil) is one of the least-constrained cratonic pieces of Nuna. Previous Nuna models usually considered an "upright" connection between the WAC and Amazonia, with the southern WAC attached to northeastern Amazonia, similar to their relationship in Gondwana (Onstott and Hargraves, 1981; Nomade et al., 2003; D'Agrella-Filho et al., 2016). This upright connection was presumed to be long-lived, with little change from the Paleoproterozoic to Jurassic (Onstott and Hargraves, 1981). With this upright connection model being accepted, as well as the lack of reliable pre-Ediacaran paleomagnetic data, the WAC is essentially a "puppet" of Amazonia, where its paleogeography in Nuna is entirely determined by data from Amazonia. For example, Johansson (2009) and Zhang et al. (2012) placed Baltica, Amazonia, and the WAC in juxtaposition to each other along the northeastern margin of Laurentia, known as the "SAMBA" model. Pisarevsky et al. (2014) placed the WAC and Amazonia off the Grenville margin of Laurentia, where the two cratons are separated from Nuna by oceans and subduction zones, yet the upright WAC-Amazonia relationship is maintained. Due to the large gap in pre-Ediacaran paleomagnetic data from the WAC, both the upright connection between the WAC and Amazonia and the position of the WAC in Nuna await further tests.

We present an integrated paleomagnetic and geochronological study of two Proterozoic mafic dike swarms in the Anti-Atlas Belt, Morocco (Fig. 1), which provides direct constraints on the paleogeography of the WAC. Combined with time-correlative, quality-filtered paleomagnetic poles, and the global large igneous province (LIP) records from other major bounding cratons, we propose a new connection between the WAC and Amazonia, and a refined configuration of Nuna.

MAFIC DIKE SWARMS IN THE ANTI-ATLAS BELT

The Anti-Atlas Belt is an 800-km-long, northeast-southwest–trending anticlinorium that marks the northernmost boundary of the WAC (Fig. 1). Paleoproterozoic basement is exposed in ~10 inliers that have been enveloped by sedimentary cover since the latest Ediacaran (Maloof et al., 2005). Numerous mafic dikes crosscut the basement, retaining near verticality in all directions. These dikes, if precisely dated, are ideal targets for paleomagnetic studies to test various reconstruction models. Recent geochronological work has proposed at least five swarms in the Anti-Atlas Belt, specifically: the east-west–striking 2.04 Ga swarm, the north-

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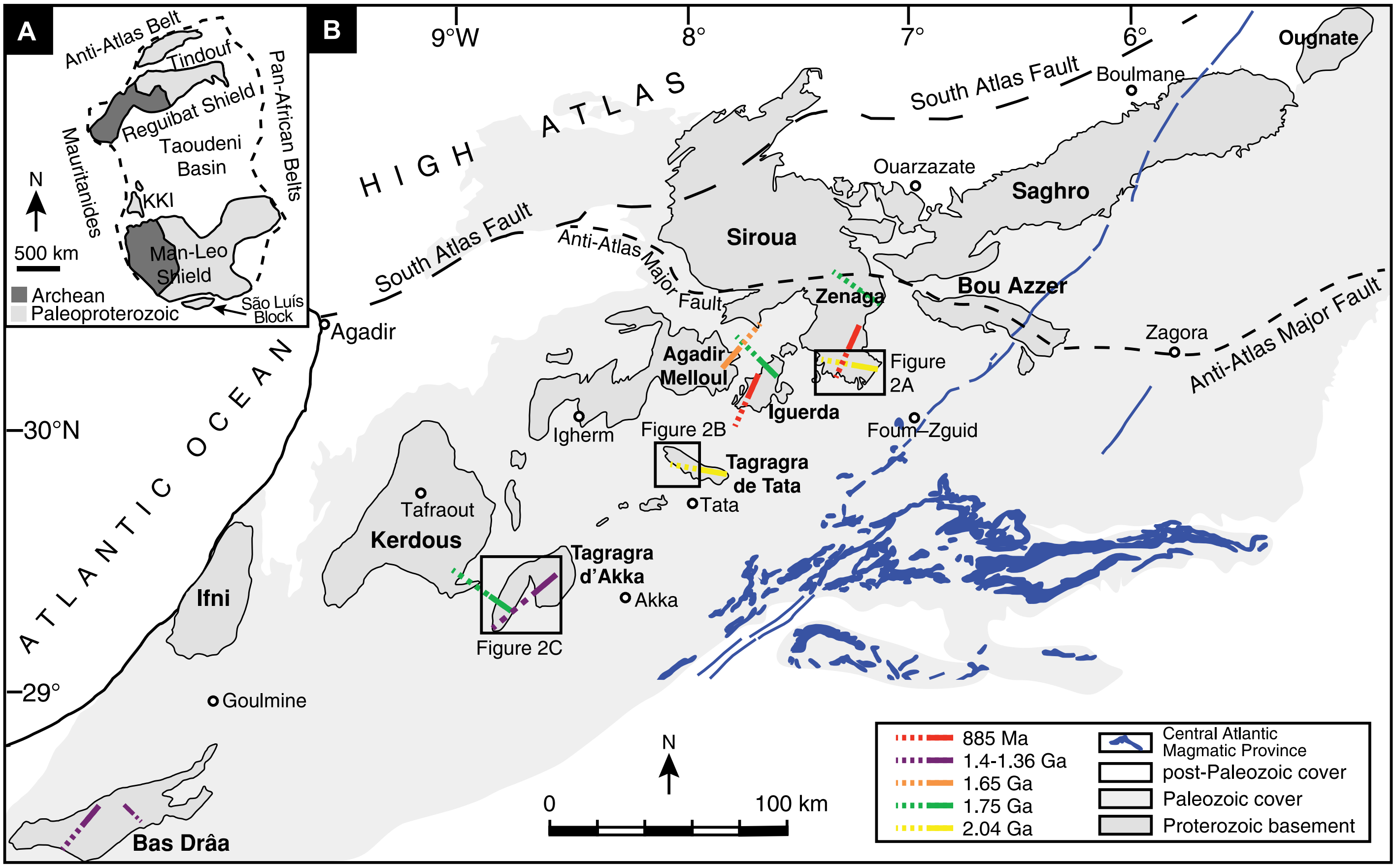

Figure 1. (A) Geological map of basement rocks in the West African craton. KKI—Kédougou-Kéniéba and Kayes inliers. Dashed line delineates cratonic boundary. (B) Geological overview of mafic dike swarms in the Anti-Atlas Belt, Morocco. Boxes indicate the studied inliers.

west-southeast–striking 1.75 Ga swarm, the northeast-southwest–striking 1.65 Ga swarm, the northeast-southwest–striking 1.4–1.36 Ga swarm, and the NNE-SSW–striking 885 Ma swarm (Fig. 1; Walsh et al., 2002; El Bahat et al., 2013; Kouyaté et al., 2013; Söderlund et al., 2013; Youbi et al., 2013). The dikes show consistent ages and strikes across the Anti-Atlas inliers (Fig. 1). Contemporaneous dikes have also been recognized in the Man-Leo Shield in the southern WAC, such as the northeast-southwest–striking 1.76 Ga Kédougou swarm and the north-south–striking 867 Ma Manso swarm (Baratoux et al., 2019), which demonstrate the structural integrity of the WAC on a cratonic scale (Gong and Evans, 2021).

NEW PROTEROZOIC PALEOMAGNETIC POLES

We collected samples from nine dikes of the east-west–striking 2.04 Ga swarm from two regions: the Zenaga and Tagragra de Tata inliers (Figs. 2A and 2B). Field and laboratory methods are provided in the Supplemental Material[1].

[1]Supplemental Material. Detailed geochronological, paleomagnetic, and rock magnetic results. Please visit https://doi.org/10.1130/GEOL.S.14699598 to access the supplemental material, and contact editing@geosociety.org with any questions.

Two dikes have been precisely dated: one in the Zenaga inlier (dike G18M48) at 2040 ± 2 Ma (isotope dilution–thermal ionization mass spectrometry [ID-TIMS] baddeleyite age; Kouyaté et al., 2013), and one in the Tagragra de Tata inlier (dike G19M33) at 2040 ± 6 Ma (sensitive high-resolution ion microprobe [SHRIMP] zircon age; Walsh et al., 2002). Stable characteristic remanent magnetizations (ChRMs) are isolated typically from 535 °C to 580 °C, consistently showing northwest-up and southeast-down directions (Fig. 2D). Although lacking explicit field tests on the age of magnetization, the reliability of these ChRMs is supported by demagnetization results, antipodal directions, and rock magnetic experiments (see the Supplemental Material). Combining the virtual geomagnetic poles (VGPs) calculated from the nine site-mean directions yielded a 2.04 Ga pole at −22.3°N, 49.6°E ($A_{95} = 7.1°$, $K = 53.3$) for the WAC.

In the Tagragra d'Akka inlier, nine subparallel northeast-southwest–striking dikes were sampled (Fig. 2C). Results of the ID-TIMS baddeleyite geochronology on one dike (G18M01) showed that its age should be 1.4–1.36 Ga (see the Supplemental Material). Dikes with predominantly northeast-southwest strikes have also been observed in the Bas Drâa inlier, ~180 km southwest of the Tagragra d'Akka inlier (Fig. 1), and these have been dated to 1.4–1.38 Ga (Söderlund et al., 2013). We suggest that these northeast-southwest–striking dikes across the Anti-Atlas Belt belong to the same swarm, and the dikes in the Tagragra d'Akka inlier could represent the late-stage pulse of this magmatic episode. Thermal demagnetization revealed stable ChRMs from 350 °C to 580 °C, which are characterized by antipodal, north-down and south-up directions (Fig. 2D). One dike (G18M90) is crosscut by a younger north-south–striking dike (G18M89), which, although undated, is very likely Precambrian because it does not penetrate the Ediacaran–Cambrian sedimentary cover of the Anti-Atlas Belt. In the immediate baked-contact zone, remanences of the older dike with consistent magnetic mineralogy (Fig. S5) are deflected into near-parallelism with those of the younger dike (Fig. 2D), suggestive of a positive inverse baked-contact test and hence a Precambrian age of remanence for the Tagragra d'Akka northeast-southwest swarm. From the VGPs of the nine dikes, we obtained a 1.4–1.36 Ga pole at 87.4°N, 44.7°E ($A_{95} = 7.8°$, $K = 44.1$) for the WAC.

AN INVERTED WAC-AMAZONIA CONNECTION

Incorporating our new 2.04 Ga and 1.4–1.36 Ga paleomagnetic poles with a 1.75 Ga

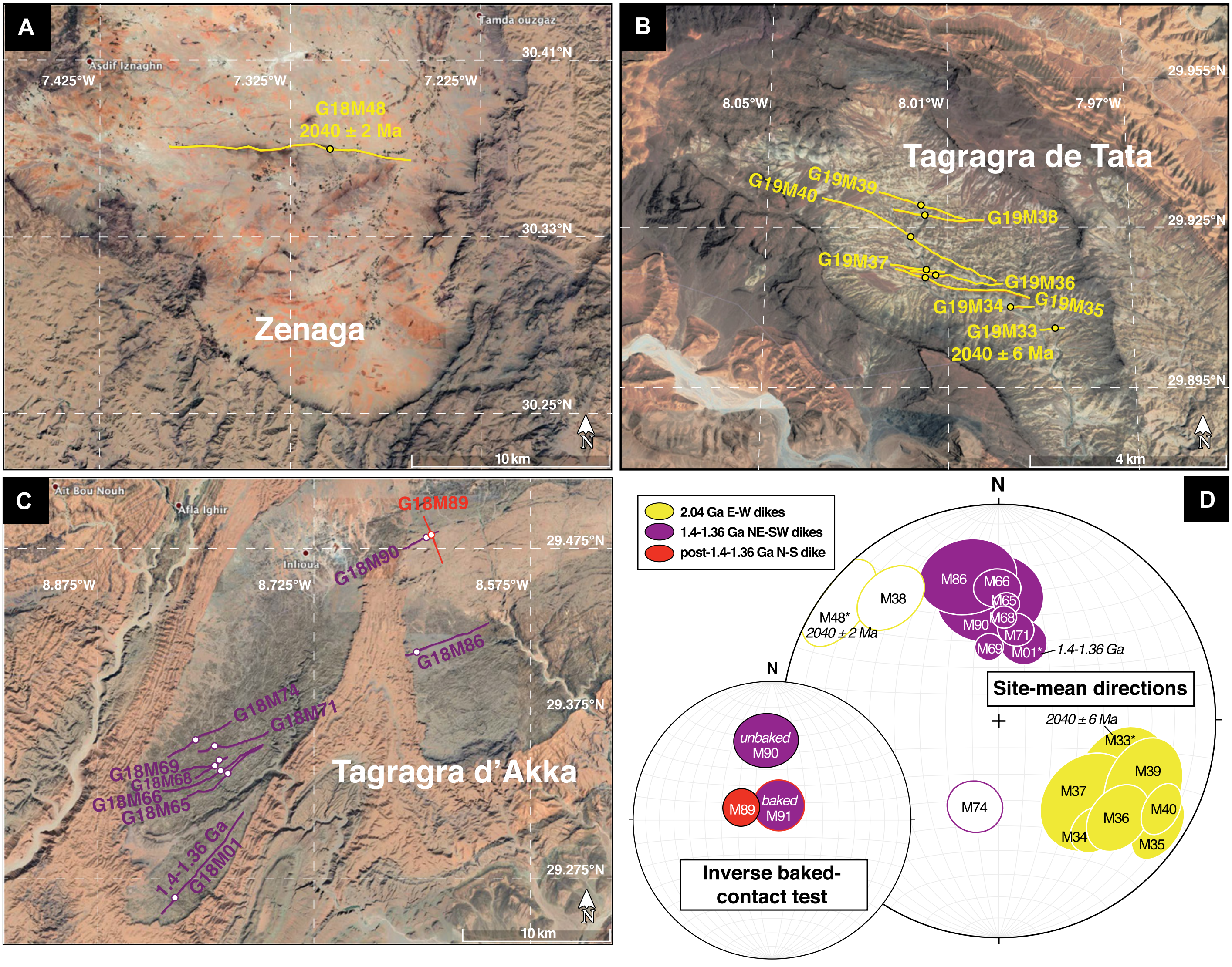

Figure 2. (A–C) Site locality maps of (A) Zenaga, (B) Tagragra de Tata, and (C) Tagragra d'Akka inliers (Anti-Atlas Belt, Morocco) with Google Earth™ satellite images as background. (D) Stereographic projection of site-mean directions of 2.04 Ga dikes (yellow) and 1.4–1.36 Ga dikes (purple), and results of inverse baked-contact test. Dated dikes are marked by asterisks.

VGP obtained from a 1747 ± 4 Ma mafic dike in the Iguerda inlier of the Anti-Atlas Belt (Neres et al., 2016), we can test the connection between the WAC and Amazonia. Previous upright models were generated by aligning the Sassandra shear zone in the Man-Leo Shield with the Guri shear zone in the Guiana Shield (Onstott and Hargraves, 1981), and these were supported by 2.1–2.0 Ga paleomagnetic data (Nomade et al., 2003; D'Agrella-Filho et al., 2016). More recently, Chardon et al. (2020) proposed that the Brobo and the Pisco-Jurua shear zones from the two cratons should be continuous, and to align these shear zones, they rotated Amazonia ~40° counterclockwise as compared to the reconstruction of Onstott and Hargraves (1981). In the model of Chardon et al. (2020), the WAC is still connected to Amazonia in an upright sense, and this connection could be accommodated by the ca. 2.0 Ga paleomagnetic data (Antonio et al., 2021).

Post–2.0 Ga paleomagnetic data can test whether these upright-style models can permissibly persist in Nuna. We examined various Nuna reconstruction models that adopted an upright-style connection between the WAC and Amazonia (Zhang et al., 2012; D'Agrella-Filho et al., 2016, 2020; Chardon et al., 2020). None of these models simultaneously matched the 1.75 Ga VGP and our 1.4–1.36 Ga pole from the WAC with the coeval poles from other cratons (Fig. S8). In particular, in these upright-style models, a disagreement is shown between our 1.4–1.36 Ga pole and its time-equivalents from other cratons (Fig. S8). Only breaking the connection between the WAC and Amazonia can accommodate our 1.4–1.36 Ga pole in an upright-style model (Fig. S8), but then the compatible basement ages and LIP records of these two cratons become unsatisfyingly disjointed.

Alternatively, we considered the opposite polarity of all pre-Ediacaran paleomagnetic poles from the WAC, and we propose an inverted WAC-Amazonia connection, with the northern WAC attached to northeastern Amazonia. In this new model, the apparent polar wander paths (APWPs) of the two cratons still support a cratonic convergence at 2.1–2.0 Ga (Fig. 3A). More importantly, correlative poles from Amazonia and other cratons agree well with the 1.75 Ga VGP and our new 1.4–1.36 Ga pole from the WAC, considering the slight age differences and the uncertainties of the poles themselves (Figs. 3B and 3C). This inverted connection between the WAC and Amazonia would negate the shear zone alignments that were proposed as piercing points by Onstott and Hargraves (1981) and Chardon et al. (2020). However, shear zones of 2.1–1.8 Ga age are commonly observed features (Zhao et al., 2002), which make them less powerful as precise correlation tools. Our inverted model still permits the continuity of Eburnean orogens of the WAC with

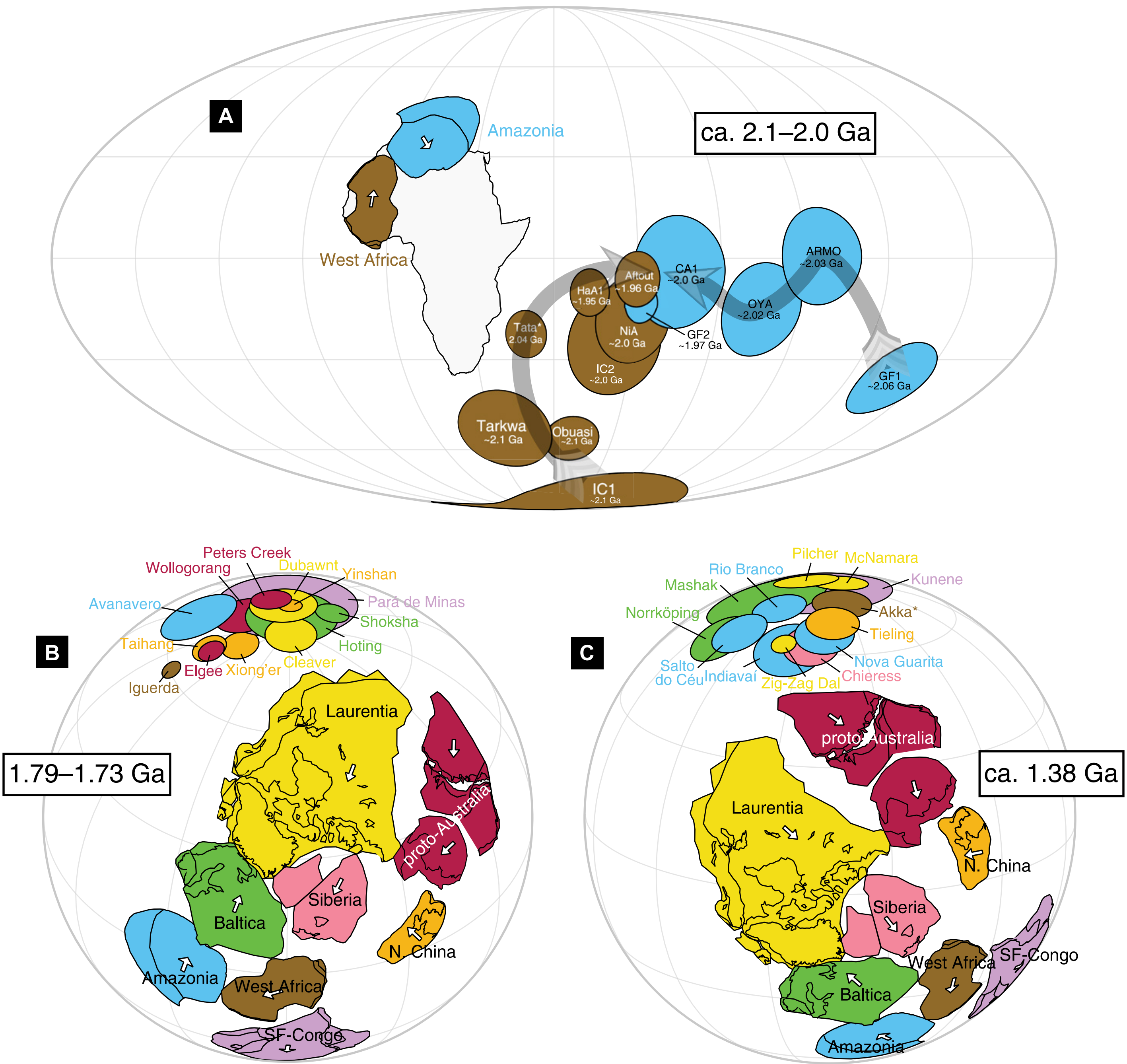

Figure 3. (A) Paleogeographic evolution between the West African craton and Amazonia at 2.1–2.0 Ga. Reconstruction is in the present West Africa reference frame, with an outline of Africa shown as background. Shaded arrows show younging direction of apparent polar wander paths. (B,C) Paleogeographic reconstruction of Nuna at 1.79–1.73 Ga (B) and ca. 1.38 Ga (C). White arrows indicate present-day north direction for cratons. Selected paleomagnetic poles of each craton (with their abbreviations) are listed in Table S3 (see footnote 1), where colors match those of cratons. Poles marked by asterisks are from this study. Table S4 lists Euler rotation parameters. SF—São Francisco.

Transamazonian orogens in Amazonia. Specifically, the 2.2–2.0 Ga Anti-Atlas Belt and the Yetti-Eglab massifs in the Reguibat Shield of the WAC continue into the 2.2–1.95 Ga Maroni-Itacaiunas Province in Amazonia. In addition, the 2.2–2.05 Ga volcano-sedimentary sequences in the Baoulé-Mossi domain and São Luís block of the WAC and the Guiana Shield of Amazonia can still be correlated along an accretionary belt, as suggested by Klein et al. (2020), but in a more general sense (Fig. 3A). The subsequent cratonization following the WAC-Amazonia assembly is compatibly reflected by the broadly overlapping 2.0–1.95 Ga poles from the two cratons, with only insignificant APWP distances through late Paleoproterozoic time (Fig. 3A; Gong and Evans, 2021).

REFINED NUNA CONFIGURATION

Combining our inverted WAC-Amazonia connection with newly published paleomagnetic results from other cratons, we propose a refined configuration of Nuna (Fig. 3). In our reconstruction, Laurentia and Baltica are located in the core of Nuna, with northern Europe connected to eastern Greenland (Gower et al., 1990; Evans and Pisarevsky, 2008). Pisarevsky et al. (2014) suggested that Siberia should be distal to northern Laurentia, which is paleomagnetically permissive. However, we prefer a tight fit between Siberia and Laurentia, as suggested by the paleomagnetic study of Evans and Mitchell (2011), which is also supported by their

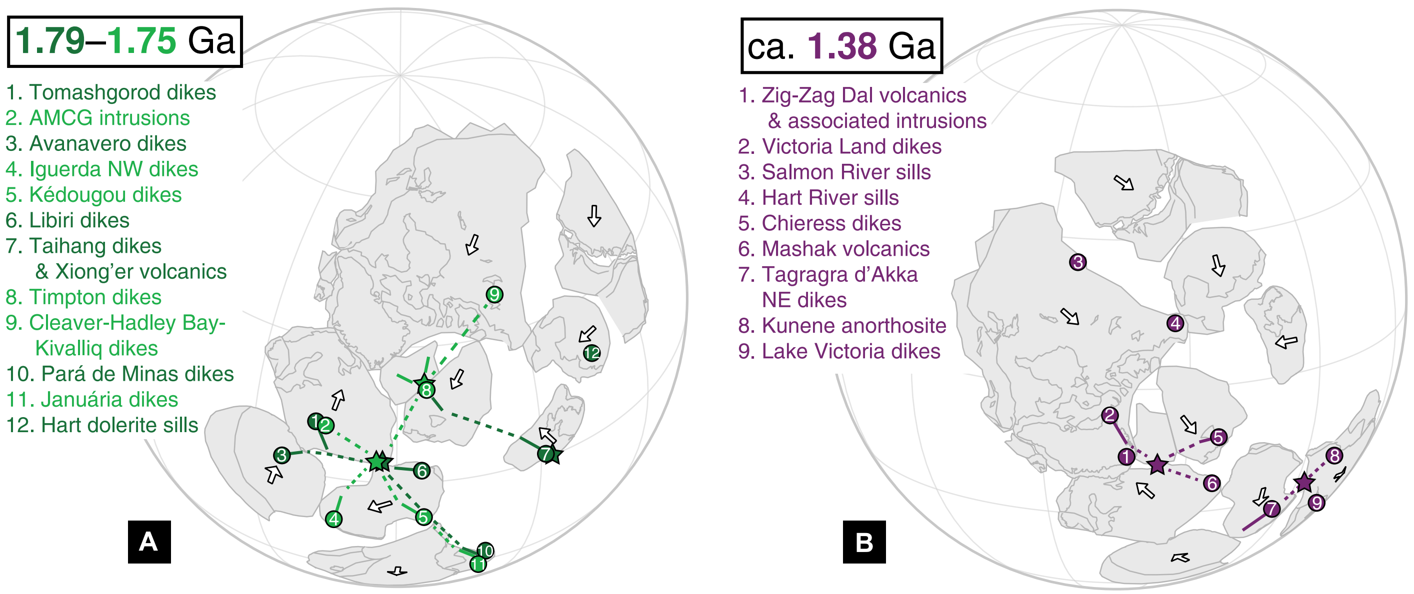

Figure 4. Global large igneous province (LIP) records at 1.79–1.75 Ga (A) and ca. 1.38 Ga (B) in Nuna. Solid line segments show trends of dike swarms. Dashed lines are potential linkages of LIPs. Stars indicate proposed plume centers. White arrows show present-day north direction for cratons. See Table S5 (see footnote 1) for bibliographic references for the LIPs. AMCG—anorthosite-mangerite-charnockite-granite.

closely matched Proterozoic magmatic records (Ernst et al., 2016). Proto-Australia is located near southwestern Laurentia at ca. 1.8 Ga, then becomes separated from Laurentia by a small ocean, and finally joins Nuna at ca. 1.65 Ga (Pisarevsky et al., 2014; Kirscher et al., 2019). The North China craton is attached to proto-Australia and off the western margin of Siberia (Kirscher et al., 2021). Unlike Pisarevsky et al. (2014)'s model, we place northwest Amazonia close to southwest Baltica, based on the shared histories of long-lived accretions (Johansson, 2009). Additionally, the São Francisco (SF)–Congo craton, constrained by the new 1.79 Ga Pará de Minas pole from SF (D'Agrella-Filho et al., 2020), juxtaposes with present-day western WAC (Fig. 3). The magmatic barcode of the WAC, when compared with the barcodes of its bounding cratons, shows time-correlative LIP records (Gong and Evans, 2021). With our new reconstruction, these LIPs and their geometries are placed in paleogeographic context. Collectively, the LIPs show broad radiating patterns that could indicate potential plume centers near the eastern margin of Baltica around 1.79–1.75 Ga (Fig. 4A), and the northern margin of Baltica and southern margin of SF-Congo at ca. 1.38 Ga (Fig. 4B). The former LIP events would have occurred during the assembly phase of Nuna, whereas the latter should have accompanied the early stages of the supercontinent's fragmentation (Kirscher et al., 2021).

RECONSTRUCTION IMPLICATIONS

Our inverted WAC-Amazonia connection in Nuna, compared to their configuration in Gondwana, indicates large (~180°) relative rotation between these two cratons. Large-scale azimuthal rotations of tectonic blocks are commonplace features of oroclines, where ribbon-like fragments of active continental margins can buckle isoclinally in map view (e.g., Şengör et al., 1993). In contrast, within larger tectonic plates, equidimensional continental blocks from the past few hundred million years have experienced more muted amounts of relative azimuthal rotation, with motions described by distally located Euler stage poles that give rise to long and quasi-linear seafloor spreading ridges (Vérard et al., 2012). There are exceptions to this general rule, however, leaving aside the more controversial pre-Jurassic ~180° rotational restoration of the Malvinas/Falkland microplate to Africa (Martin, 2007). For instance, the Siberian craton rotated nearly 180° relative to Baltica between Ediacaran and Permian time (Şengör et al., 1993) and a similar amount relative to Laurentia during the Rodinia-Pangea supercontinental transition (Merdith et al., 2021). As another example, Amazonia rotated ~180° relative to Laurentia prior to Rodinia assembly, regardless of which pre-Rodinia paleomagnetic polarity option one adopts (D'Agrella-Filho et al., 2016). The relative orientation of the North China craton and Australia also changed by ~180° between their likely Nuna configuration (Kirscher et al., 2021) and early Paleozoic time (Zhao et al., 2021). Although a global model of prescribed Meso-proterozoic–Neoproterozoic plate motions is not yet available, our proposal for the nearly 180° relative rotation between the WAC and Amazonia over supercontinental cycles provides an additional instance of this intriguing kinematic style. The dynamics of such large-scale changes in relative orientations are likely related to successive intervals of divergence, convergence, and transform motion accompanying the series of ancient global plate reorganizations (e.g., Müller et al., 2016).

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