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# Paleomagnetic constraints on the duration of the Australia-Laurentia connection in the core of the Nuna supercontinent

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## ABSTRACT

**The Australia-Laurentia connection in the Paleoproterozoic to Mesoproterozoic supercontinent Nuna is thought to have initiated by ca. 1.6 Ga when both continents were locked in a proto-SWEAT (southwestern U.S.–East Antarctic) configuration. However, the longevity of that configuration is poorly constrained. Here, we present a new high-quality paleomagnetic pole from the ca. 1.3 Ga Derim Derim sills of northern Australia that suggests Australia and Laurentia were in the same configuration at that time. This new paleopole also supports a connection between Australia and North China and, in conjunction with previously reported data from all continents, indicates that the breakup of Nuna largely occurred between ca. 1.3 and 1.2 Ga.**

## INTRODUCTION

The hypothesized connection between western Laurentia (North America) and eastern proto-Australia (Australia-Antarctica shield, hereafter referred to as Australia), initially proposed for the latest Paleoproterozoic to Neoproterozoic, is one of the most intensively studied connections in the Proterozoic supercontinents Rodinia and Nuna (Dalziel, 1991; Moores, 1991; Idnurm and Giddings, 1995). In supercontinent Nuna (also known as Columbia), it is thought that Australia and Laurentia were connected throughout much of the Mesoproterozoic (Zhang et al., 2012; Pisarevsky et al., 2014a). However, critical uncertainties exist regarding the configuration and longevity due to a lack of high-quality paleomagnetic data and uncertain geological correlations (e.g., Morrissey et al., 2019).

Zhao et al. (2002) proposed that Nuna assembled between ca. 2.1 and 1.8 Ga during a period of global-scale orogenesis and broke up between ca. 1.6 and 1.2 Ga, placing Australia in a SWEAT (southwestern U.S.–East Antarctic) configuration (Moores, 1991) with respect to Laurentia. Based on paleomagnetic data, the original SWEAT fit was refined to a "proto-SWEAT" configuration for the 1.74–1.59 Ga interval, with Australia located further north in a Laurentian reference frame (Payne et al., 2009). Reinvestigation of the available paleomagnetic data for roughly the same time interval, including new data for ca. 1.8 Ga (Kirscher et al., 2019), suggests that the original proto-SWEAT connection is valid at ca. 1.8 Ga, but a reorganization between ca. 1.7 and 1.6 Ga would have led to a slightly modified (proto-SWEAT) configuration. Given the inherent paleomagnetic uncertainties, the reorganization between Australia and Laurentia in Nuna could reflect either (1) a connection between the continents at ca. 1.8 Ga, followed by dextral shearing or a divergence-convergence motion that led to separation and reassembly at ca. 1.6 Ga (Betts et al., 2016); or (2) that a small ocean existed between the continents at 1.8 Ga that closed by ca. 1.6 Ga (Betts et al., 2008; Pisarevsky et al., 2014a; Nordsvan et al., 2018; Kirscher et al., 2019). Nevertheless, this reorganization indicates that assembly of Nuna was a protracted process and took place until at least 1.6 Ga, which is supported by concurrent orogenesis in eastern Australian and western Laurentia (Pourteau et al., 2018).

Although the refined proto-SWEAT configuration between Australia and Laurentia is supported by ca. 1.58 Ga paleomagnetic data, the breakup age is poorly constrained (Evans and Mitchell, 2011; Meert and Santosh, 2017). The formation of ca. 1.5–1.2 Ga basins along the western margin of Laurentia has been used to argue that Australia rifted from Laurentia

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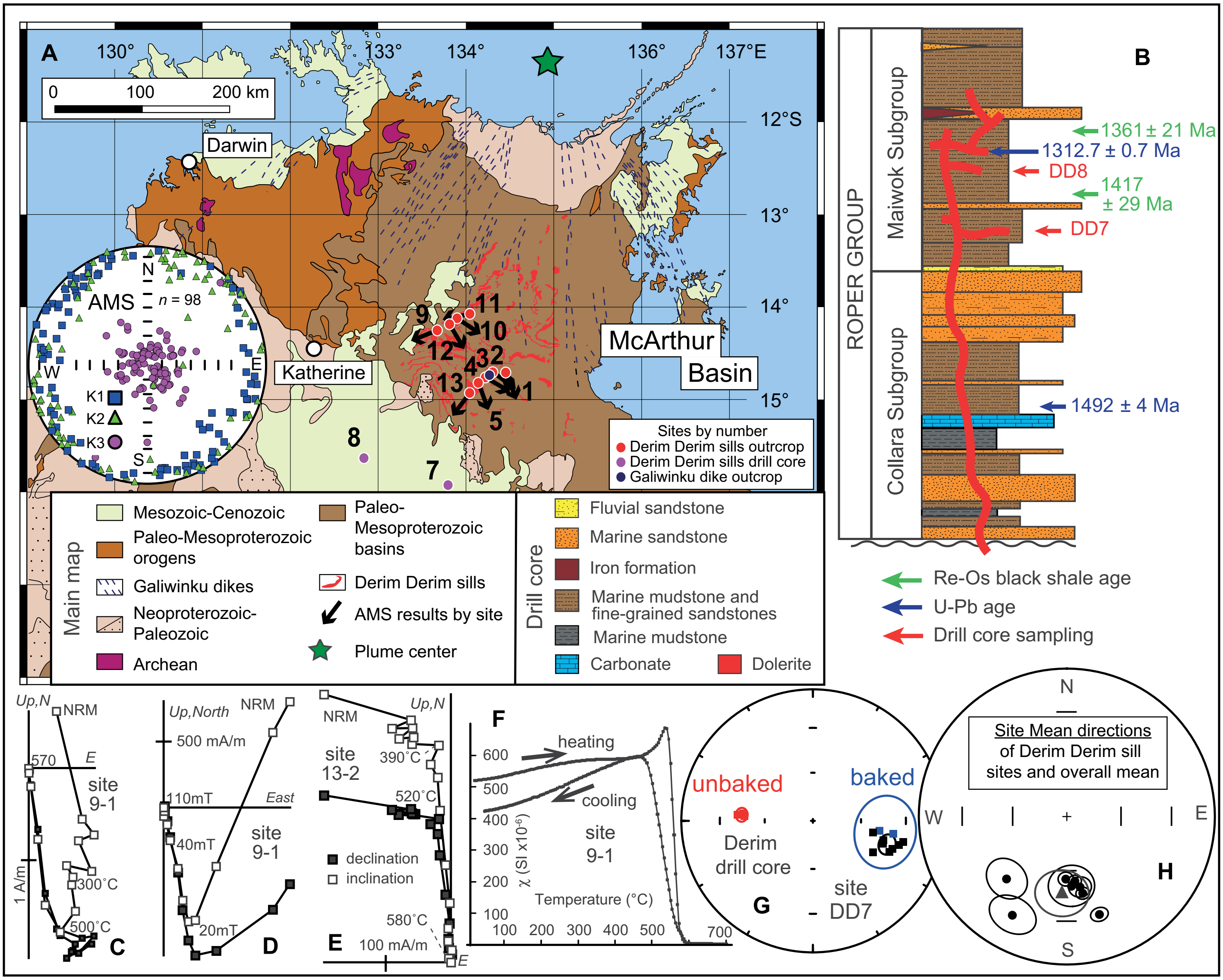

**Figure 1. (A) Lithologic map of the North Australian craton with aeromagnetic expression of the Galiwinku dikes. Sampling sites (see Table S1 [see footnote 1]) indicate directions of magmatic flow inferred from anisotropy of magnetic susceptibility (AMS) results, where K1, K2, and K3, respectively, refer to the maximum, intermediate, and minimum axes of the triaxial ellipsoid of magnetic susceptibility magnitude (Table S2; Fig. S1). (B) Stratigraphy of the Roper Group with sills sampled from drill core and age constraints. (C–E) Thermal and alternating-field demagnetization of the Derim Derim sill samples (see also Fig. S2). NRM—natural remanent magnetization. (F) Thermal susceptibility results of a Derim Derim sill (Fig. S3). $\chi$—magnetic susceptibility (in SI units). (G) Directions of baked-contact test conducted on drill core samples. (H) Site-mean directions of high-temperature component of the Derim Derim sills (Table S3; Fig. S4). See the Supplemental Material for details. Triangle—overall-mean direction.**

during this interval (Zhao et al., 2004). However, detrital zircon populations in many of the Laurentian sequences are thought to have been sourced from Australia (Link et al., 2007; Medig et al., 2014), suggesting that the basins were likely intracontinental (Davidson, 2008). Paleomagnetic data indicate that Australia and Laurentia were together at ca. 1.58 Ga (Betts et al., 2016) and that the breakup was achieved by ca. 1.2 Ga (Pisarevsky et al., 2014b). Here, we report a new high-quality paleomagnetic pole from the ca. 1.32 Ga Derim Derim sills of Australia and discuss the configuration and breakup of the Australia-Laurentia connection and the implications for the Nuna supercontinent.

## DERIM DERIM SILLS

The Derim Derim sills intrude the ca. 1.5–1.35 Ga Roper Group of the McArthur Basin in northern Australia (Fig. 1) and are gently folded with tilts of <5° (Abbott et al., 2001). Thermal modeling of Mesoproterozoic natural-gas occurrences reveals that the Roper Group probably never reached temperatures >~300 °C (Hoffman, 2016). U-Pb geochronology for the Derim Derim sills yields ages of 1327.5 ± 0.6 Ma (isotope dilution–thermal ionization mass spectrometry [ID-TIMS] on baddeleyite; Bodorkos et al., 2020) and 1312.9 ± 0.7 Ma (ID-TIMS on baddeleyite; Yang et al., 2020), both coeval (within uncertainty) with the 1325 ± 36 Ma ($2\sigma$) Galiwinku dikes in northern Australia (Bodorkos et al., 2020). Aeromagnetic expression of the poorly exposed Galiwinku dikes reveals a radial pattern that projects to where the Derim Derim sills intrude the McArthur Basin, further indicating that both sets of intrusions are part of the same large igneous province (LIP) (Zhang et al., 2017).

## PALEOMAGNETIC RESULTS

We collected 170 oriented block samples from nine sites of the Derim Derim sills, where each site corresponds to one sill, in two outcrop areas (Fig. 1; Table S1 in the Supplemental

Material[1]). One site of the Derim Derim sills was obtained from a subvertical drill core (Altree-2, drilled by Pacific Oil and Gas Pty Ltd.; 15°55′28.698″S, 133°47′7.980″E), where samples of the sedimentary rocks from the overlying Corcoran Formation were also collected for a baked-contact test (Table S4). One site of the Galiwinku dike was also obtained from outcrop. For all samples, measurements proceeded with anisotropy of magnetic susceptibility (AMS), followed by natural remanent magnetization, then demagnetization using thermal (80% of all specimens) or alternating-field (AF; 20% of all specimens) treatments. Standard paleomagnetic laboratory and analytical procedures were used (see the Supplemental Material). AMS lineations range between northwest and northeast and define an average flow direction consistent with the orientation of the coeval Galiwinku dikes, supporting the hypothesis of a plume center located north-northeast of Australia (Fig. 1).

Rock magnetic studies of the Derim Derim sill samples indicate magnetite and/or Ti-poor titanomagnetite as the main magnetic phase (Fig. 1; Fig. S3 in the Supplemental Material). Prominent single-domain and/or pseudo-single-domain signals in most of the samples indicate that the sills carry stable remanence. Baked and unbaked sediments in drill core show slightly different magnetic mineralogy (Fig. S5). The degree of AMS is generally low (<1.06; Table S2; Fig. S1), typical of mafic intrusions (Ferré, 2002), and indicates the absence of any significant deformation after the emplacement of the sills. The Galiwinku dike is characterized by a different magnetic mineralogy, showing a prominent low-temperature phase potentially related to maghemite (Fig. S3i) and much weaker magnetic signals (Figs. S2e and S2f).

Thermal and AF demagnetization of the Derim Derim sill samples yield well-defined and comparable directional behavior leading to high-stability characteristic remanent magnetization (ChRM) directions that are generally well clustered (Fig. 1; Figs. S2 and S4). The ChRM directions are of one polarity except one site yielding an antipodal direction. Due to the lack of chilled margin contacts in outcrop, a baked-contact test was carried out in a drill core where chilled margins are exceptionally preserved. The azimuth of the drill core is unknown, so the drill-core sites cannot be used in the mean direction calculation. Nonetheless, the drill core has an azimuthally consistent reference line, so all drill core samples can be oriented relative to each other, which is sufficient for conducting the test. Two sedimentary host-rock samples near the contact with the Derim Derim sill (3 and 8 cm above) yield similar directions to the sill (Fig. 1G) and also have similar inclinations to those obtained from Derim Derim outcrops, indicating that the sill sites within the drill core likely retain a primary magnetization direction. Another three samples from the sedimentary host rock of the same core but ~30 m stratigraphically above the contact show a well-defined ChRM with a completely different direction from that of both the sill and the baked samples (Fig. 1G), constituting a positive baked contact test, i.e., the sill ChRM was acquired at the time of cooling.

Combining eight site-mean directions of Derim Derim sill outcrops yields a mean ChRM direction of declination 183.6°, inclination 46.2°, and $\alpha_{95}$ (95% confidence for spherical distribution) = 13.7° for the 1.32 Ga Derim Derim sills, with a corresponding pole position at 76.5°S, 120.2°E, and $A_{95}$ = 15.0° (Table S3). The Galiwinku dike site-mean direction was not included due to its large confidence interval (Table S3) and rock magnetic and directional differences. The Derim Derim sills pole demonstrably represents a primary thermoremanent magnetization, and can thus be used for paleogeographic reconstructions. This interpretation is based on: (1) the paleomagnetic results from the drill core, which constitute a positive baked contact test; (2) rock magnetic studies of the drill core, which reveal the presence versus absence of pyrrhotite in the baked versus unbaked zones of the sedimentary host rock, which indicates metamorphic changes in the mineral composition of the host rock due to baking (Fig. S5); (3) starkly contrasting paleomagnetic directions of the Derim Derim sills compared to the next-younger unit with paleomagnetism, the ca. 500 Ma Antrim Plateau Volcanics (McElbinny and Luck, 1970); (4) geomagnetic secular variation, which can be assumed to be sufficiently averaged given the number of sampled cooling units and a reasonable estimate of paleosecular variation (*S* [angular dispersion of poles] value of 21.51; see the Supplemental Material) for the paleolatitude; and (5) the presence of antipodal site-mean directions that overlap within uncertainties after reversing the polarity of one site (see the Supplemental Material for details; Fig. S4).

## AUSTRALIA-LAURENTIA CONNECTION

The paleomagnetic inclination of the Derim Derim sills indicates that Australia was located at a paleolatitude of ~30° at ca. 1.3 Ga. Comparing these new data with coeval poles from Laurentia (Murthy, 1978) using the modified Australia-Laurentia fit from 1.65 to 1.58 Ga (Euler rotation of Kirscher et al. [2019]; Fig. 2;

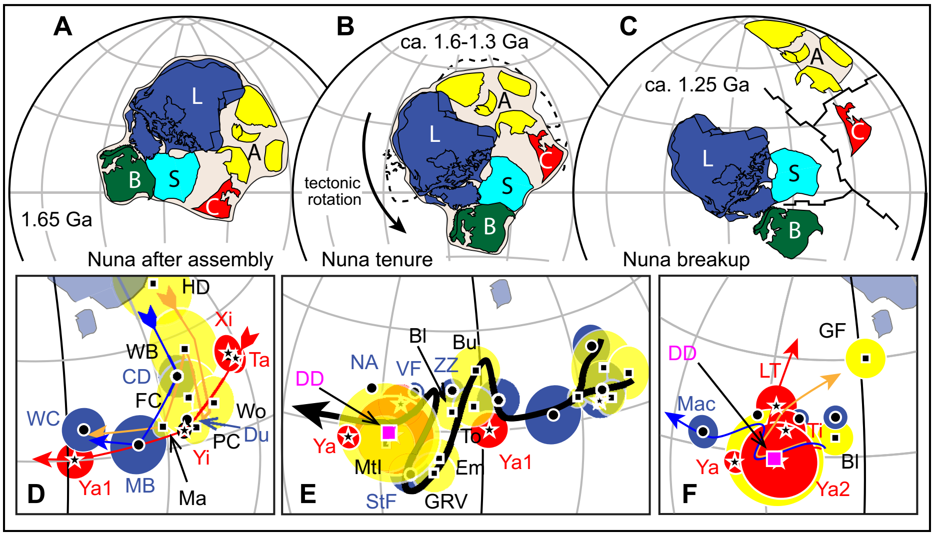

**Figure 2. Paleogeographic reconstruction of supercontinent Nuna including its core constituents (L—Laurentia; B—Baltica; S—Siberia; A—Australia, including Mawson; C—North China craton) at assembly (A), tenure (B), and breakup (C), and associated paleopoles of the five continents at roughly the respective interval (D–F, respectively). Poles plotted include: GF—Gnowangerup-Fraser dikes; Mtl—Mt. Isa Metamorphosed dikes; GRV—Gawler Rangev; Bu—Balbirini Dolomite, upper part; Bl—Balbirini Dolomite, lower part; Em—Emmerugga Dolomite; To—Tooganinie Formation; Ma—Mallapunyah Formation; WB—West Branch volcanics; FC—Fiery Creek Formation; Wo—Wollogorang Formation; PC—Peters Creek volcanics, upper part; HD—Hart Dolerite; LT—Liaoning and Taihang area; Ya—Yanliao mafic sills; Ti—Tieling Formation; Ya1—Yangzhuang Formation; Ya2—Yangzhuang Formation; Ta—Taihang dikes; Yi—Yinshan dikes; Xi—Xiong'er Group; Mac—Mackenzie dikes grand mean; NA—Nain Anorthosite; VF—Victoria Fjord dolerite dikes; ZZ—Zig-Zag Dal basalts; StF—St. Francois Mountains; WC—Western Channel Diabase; MB—Melville Bugt diabase dikes; CD—Cleaver dikes; Du—Dubawnt Group. Stars with red A95 intervals (NCC), circles/blue (Laurentia) and squares/yellow (Australia) indicate the studied continents. See the Supplemental Material (see footnote 1) for details.**

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[1] Supplemental Material. Materials and methods, five supplemental figures, seven supplemental tables, and references providing further detail on paleomagnetic and rock-magnetic results, sampling descriptions, performed analysis, and reconstruction data. Please visit https://doi.org/10.1130/GEOL.S.12935030 to access the supplemental material, and contact editing@geosociety.org with any questions.

Table S7) indicates the two continents were in a similar configuration at 1.3 Ga. We propose that the Derim Derim sills pole, showing that Australia and Laurentia were in the same proto-SWEAT fit at ca. 1.3 Ga as they were at ca. 1.6 Ga, strongly suggests that this configuration was maintained throughout that time interval. Although published 1.6–1.3 Ga paleomagnetic poles from Australia and Laurentia permit this proto-SWEAT configuration during this interval, comparative data are not always coeval, and some are of low quality and/or have significant age uncertainties (Table S5). This new pole, being coeval with poles in Laurentia and showing the same configuration at ca. 1.6–1.3 Ga, provides robust support for the proto-SWEAT interpretation at ca. 1.58 Ga and, by implication, the correlation of the ca. 1.6 Ga Racklan and Isan orogenies in northwestern Canada and northeastern Australia, respectively (Thorkelson et al., 2001; Nordsvan et al., 2018; Pourteau et al., 2018).

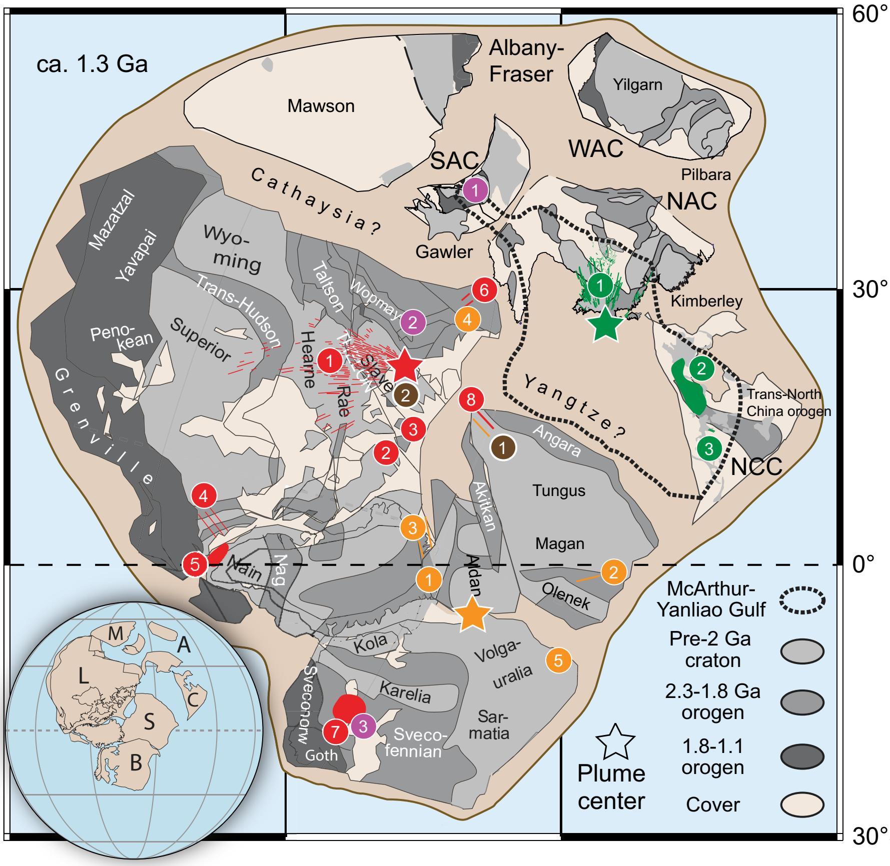

**Figure 3. Paleogeography of Nuna at ca. 1.3 Ga including its core constituents Laurentia (L), Baltica (B), Siberia (S), Australia (A, including Mawson, M), and North China Craton (C). Main orogens are indicated. Large igneous provinces (LIPs) emplaced during Nuna breakup are also shown with associated dike swarms (lines) and proposed plume centers color-coded by age (stars; Table S6 [see footnote 1]). See Table S7 for Euler rotations. McArthur-Yanliao Gulf is outlined (Collins et al., 2019), also known as the Gulf of Nuna (Mitchell et al., 2020). NAC—North Australia craton; NCC—North China craton; SAC, South Australia craton; WAC, West Australia craton.**

Collectively, these data suggest that following their amalgamation at ca. 1.6 Ga, Australia and Laurentia were contiguous in the same proto-SWEAT configuration for at least ~300 m.y. This interpretation does not support the correlation of ca. 1.5–1.4 Ga A-type granites in northern South Australia and Mexico (Morrissey et al., 2019), but instead agrees with the interpretation of northern Australian (e.g., Mount Isa inlier)–derived detrital zircon in the ca. 1.5–1.4 Ga lower part of the Fifteenmile Group (PR1 unit; Yukon, Canada) of northwestern Laurentia (Medig et al., 2014). The divergence of ca. 1.2 Ga paleopoles from Australia and Laurentia indicate that the continents were separated by that time (Pisarevsky et al., 2014b), constraining the breakup age of the proto-SWEAT connection at ca. 1.3–1.2 Ga.

## AUSTRALIA–NORTH CHINA CONNECTION

These new data also support the connection between northern Australia and the North China craton, as proposed based on the correlation of paleomagnetic poles (Zhang et al., 2012; Pisarevsky et al., 2014a), ca. 1.4 Ga oceanic euxinic events (Mitchell et al., 2020) and ca. 1.3 Ga LIPs (Zhang et al., 2017). Our proposed configuration of Australia and the North China craton (Fig. 3) is similar to that of Zhang et al. (2017) with the modification that the North China craton is rotated slightly clockwise relative to Australia. This modified configuration is more compatible with the paleomagnetic data from both continents (Fig. 2; Table S5), while inferring a plume center related to the Galiwinku-Datong dike swarm to the present-day north of Australia (Zhang et al., 2017) (Fig. 1). The exact amalgamation age between Australia and the North China craton is still unclear due to a lack of paleomagnetic data (particularly from the North China craton; Wang et al., 2019). Lithostratigraphic similarities between the McArthur Basin of Australia and Yanshan Basin of north China (Zhang et al., 2018; Collins et al., 2019; Wang et al., 2019) suggest that the two continents were neighbors from at least ca. 1.8 to 1.3 Ga, and detrital zircon in <1.2 Ga North China craton sedimentary rocks indicates they might have been together longer (Yang et al., 2019). However, in contrast, new ca. 1.2 Ga paleomagnetic data from North China indicate that Australia and the North China craton had started to break apart at this time (Ding et al., 2020).

## IMPLICATIONS FOR SUPERCONTINENT NUNA

The core of Nuna, traditionally including Laurentia, Baltica, and Siberia, is thought to have been assembled by ca. 1.78 Ga (Wu et al., 2005). Paleomagnetic poles from these three core continents support the configuration in Figure 3 from ca. 1.7 Ga, although other arrangements have been proposed (Pisarevsky et al., 2014a). If the final collision between Australia and Laurentia occurred at 1.6 Ga, then the previously formed core of Nuna might represent a precursor large building block of the Nuna supercontinent, just like Gondwana was to Pangea (Nance and Murphy, 2019).

Our new paleomagnetic pole shows that the ca. 1.6 Ga Nuna configuration of Australia and Laurentia (Pisarevsky et al., 2014a ; Kirscher et al., 2019) likely remained until ca. 1.3 Ga, implying that Australia was a stable part of the Nuna core. While the connection between Laurentia and Siberia might have persisted longer, paleomagnetic data suggest that significant core components of Nuna were disassembled from 1.3 to 1.2 Ga (Fig. 2C) (e.g., Cawood et al., 2010; Pisarevsky et al., 2014b; Ding et al., 2020). Therefore, the ~300 m.y. duration of a stable Nuna core between 1.6 and 1.3 Ga, during which the supercontinent exhibited a slow counterclockwise tectonic rotation (Fig. 2), is strongly supported by paleomagnetic data from several continents and implies that Nuna was the longest lived among the three known supercontinents.

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