GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G48575.1

Manuscript received 1 November 2020
Revised manuscript received 9 January 2021
Manuscript accepted 13 January 2021

Archean geodynamics: Ephemeral supercontinents or long-lived supercratons

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ABSTRACT

Many Archean cratons exhibit Paleoproterozoic rifted margins, implying they were pieces of some ancestral landmass(es). The idea that such an ancient continental assembly represents an Archean supercontinent has been proposed but remains to be justified. Starkly contrasting geological records between different clans of cratons have inspired an alternative hypothesis where cratons were clustered in multiple, separate "supercratons." A new ca. 2.62 Ga paleomagnetic pole from the Yilgarn craton of Australia is compatible with either two successive but ephemeral supercontinents or two long-lived supercratons across the Archean-Proterozoic transition. Neither interpretation supports the existence of a single, long-lived supercontinent, suggesting that Archean geodynamics were fundamentally different from subsequent times (Proterozoic to present), which were influenced largely by supercontinent cycles.

INTRODUCTION

The Archean-Proterozoic transition was one of the most dynamic periods in Earth history, involving globally diachronous cratonization (Bleeker, 2003; Laurent et al., 2014; Cawood et al., 2018), low-latitude glaciation (Evans et al., 1997), and the Great Oxygenation Event (Gumsley et al., 2017). Secular cooling of the mantle also appears to have occurred faster at this time than during any other time in Earth history (Keller and Schoene, 2012). Paleogeography during the Archean-Proterozoic transition is pertinent to the question of whether Archean geodynamics were similar to the post-Archean plate-tectonic regime, featuring the three largely accepted supercontinent cycles (Bleeker, 2003; Li et al., 2019), or markedly different in some form of small-scale mantle convection and/or prototectonic regime. The first-order question to answer is whether the Mesoproterozoic supercontinent Nuna (Zhao et al., 2002; Kirscher et al., 2021) was Earth's first Pangea-sized supercontinent, or whether it had an Archean predecessor. It has long been recognized that many Archean cratons are bounded by Paleoproterozoic rift margins, which indicate that some of the presently separated cratons once belonged to larger Archean continental blocks prior to breakup (Williams et al., 1991; Aspler and Chiarenzelli, 1998; Bleeker, 2003). A single, large supercontinent, putatively named "Kenorland" (Williams et al., 1991), represents one end-member model for this ancestral landmass (Salminen et al., 2019). As an alternative hypothesis, based mainly on diachronous cratonization timings, several independent "supercratons" are proposed to have characterized the late Archean tectonic regime (Bleeker, 2003).

Among the reconstruction methods used for Precambrian paleogeography, two are commonly employed: magmatic barcode matching (Bleeker, 2004; Bleeker and Ernst, 2006) and paleomagnetism. Dike swarms are particularly useful geological piercing points because they provide geometric constraints (radiating patterns) that can be dated precisely, with the possibility of multiple intrusion events on several different cratons over time confirming a hypothetical configuration (Bleeker and Ernst, 2006). The Superior craton is the largest Archean craton and has one of the best-sampled and dated magmatic barcodes, thus providing, via magmatic barcode matching, the "keystone" of the first hypothesized supercraton Superia (Bleeker and Ernst, 2006; Ernst and Bleeker, 2010; Davey et al., 2020). Paleomagnetism can independently test whether two cratons were (1) geographically near or distant and (2) moved together or separately. So far, both methods have been used to prove the existence of the "Superia" configuration for several cratons originally contiguous with the Superior craton (Bleeker et al., 2016; Gumsley et al., 2017; Salminen et al., 2019). However, determining whether Superia included all or most of the Archean cratons (i.e., approaching an Archean supercontinent in size) remains elusive (Mitchell et al., 2014).

RESULTS

We report a high-quality paleomagnetic pole for the recently identified 2615 ± 6 Ma Yandinilling dike swarm (Stark et al., 2018) of the Yilgarn craton, Western Australia (Fig. 1). We collected 123 standard cores from 15 individual dikes for rock magnetic and paleomagnetic analysis (Fig. 1). Each site represents a distinct dike. Nearly all samples revealed well-defined demagnetization trajectories (Fig. 2A; Fig. S5 in the Supplemental Material[1]). The least stable

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[1] Supplemental Material. Supplemental text, six supplemental figures, and three supplemental tables providing further details for regional geology, methods, demagnetization data, rock magnetic results, poles used for paleogeography reconstructions and Euler poles for reproducing the models. Please visit https://doi.org/10.1130/GEOL.S.14150075 to access the supplemental material, and contact editing@geosociety.org with any questions.

CITATION: Liu, Y., et al., 2021, Archean geodynamics: Ephemeral supercontinents or long-lived supercratons: Geology, v. 49, p. 794–798, https://doi.org/10.1130/G48575.1

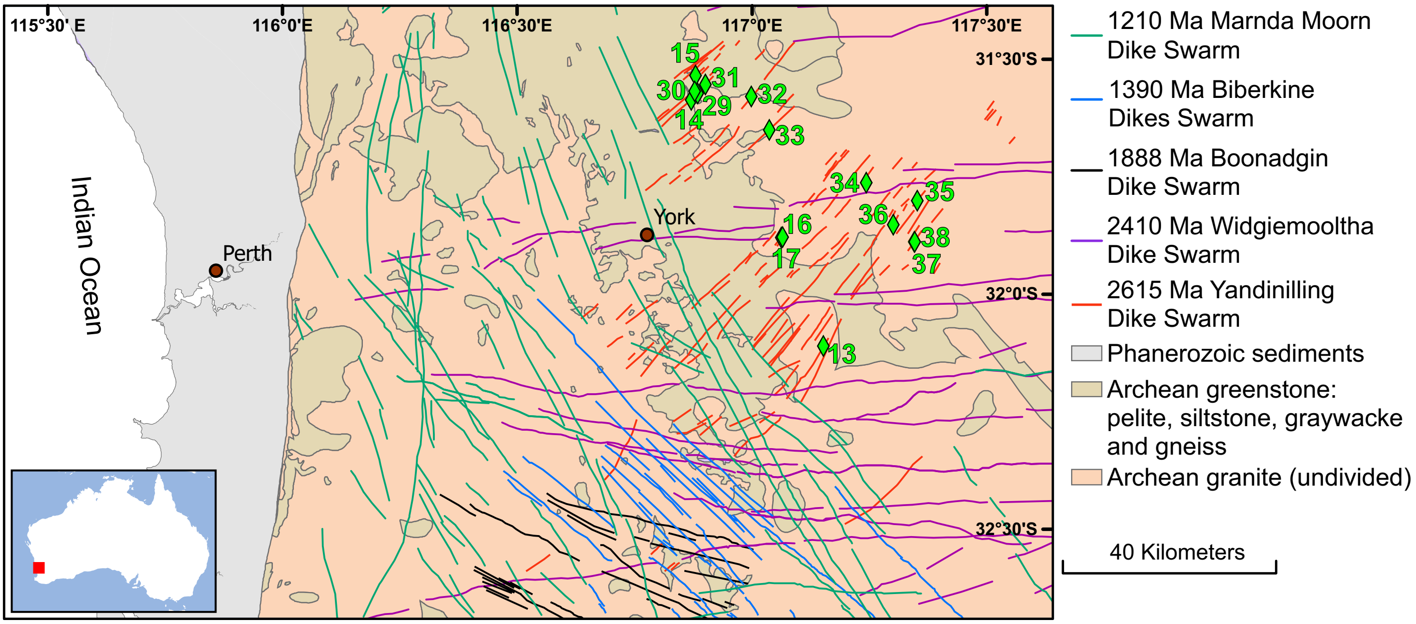

Figure 1. Simplified geological map of the sampling area in Western Australia with known dike swarms. "16WDS" prefixes of site names are omitted for simplicity. Inset shows location of sampling area.

component, which was removed by low-level demagnetization (heating to ∼200 °C or alternating field [AF] demagnetization to ∼7 mT), appeared sporadically in cores from several sites. After the removal of this magnetically unstable component, a mid-temperature component (MTC) was identified in several sites between 100–300 °C and 540 °C, but it was only prominent enough to be defined at site 16WDS15 (declination [Dec] = 225.2°, inclination [Inc] = −53.1°, cone of 95% confidence α_{95} = 12.0°). After removal of these soft components, a characteristic stable component decaying toward the origin of the projection plane was identified with a lower bound of

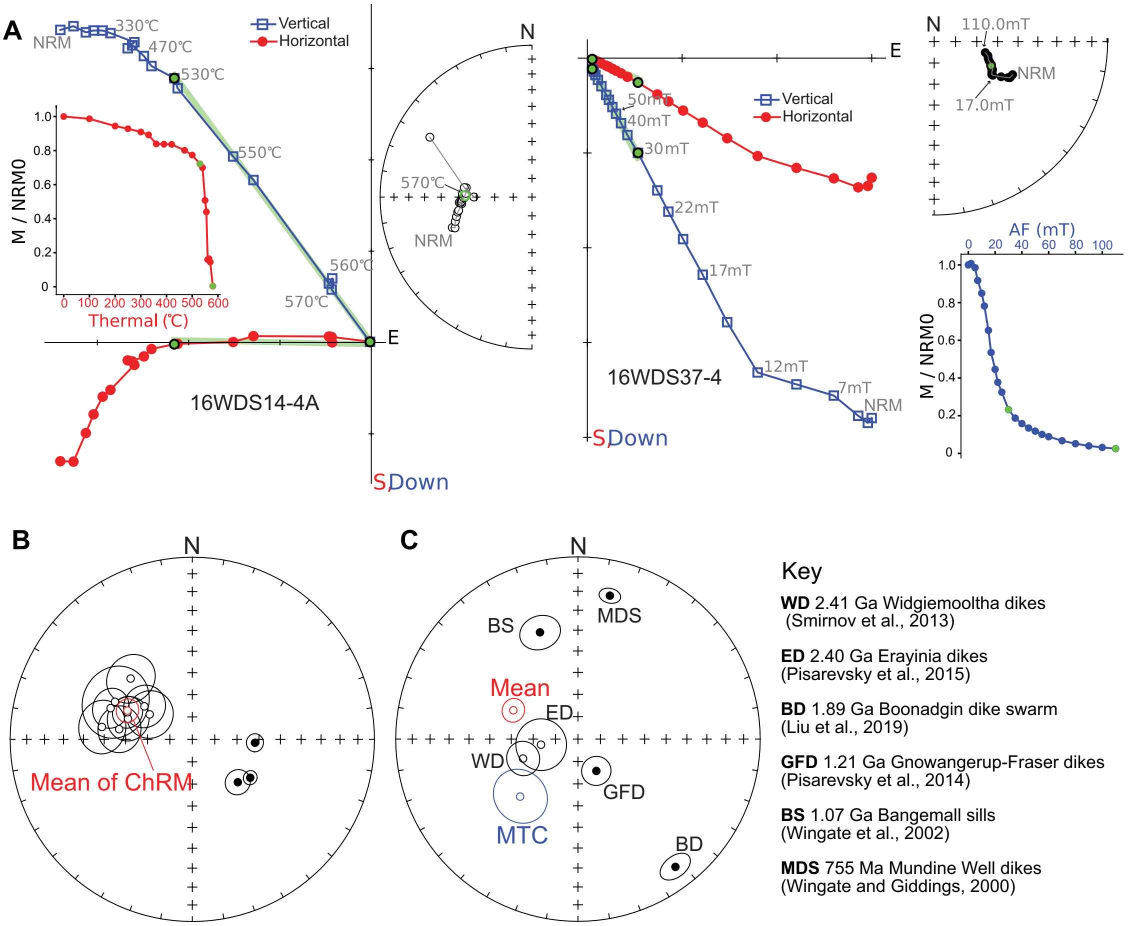

Figure 2. Paleomagnetic results. (A) Representative demagnetization data showing sample demagnetized thermally indicating up-directed geomagnetic polarity (left), and sample demagnetized with alternating-field (AF) methods indicating down-directed geomagnetic polarity (right). Additional demagnetization examples are provided in Figure S5 (see footnote 1). NRM—natural remanent magnetization. (B–C) Equal-area projections showing (B) site-mean directions of characteristic remanent magnetization (ChRM) with both magnetic polarities and (C) ChRM, mid-temperature component (MTC), and younger paleomagnetic directions in the region (recalculated for the present study area coordinates at 31.8°S, 117.1°E). Open/filled symbols in equal-area projections indicate upper/lower-hemisphere directions.

unblocking temperatures of 530–565 °C and an upper bound of 570–580 °C in the majority of samples (Fig. 2A).

The characteristic remanent magnetization (ChRM) directions are directed either moderately WNW-and-up or ESE-and-down (Fig. 2B). Excluding two sites with spurious data and one outlier site (16WDS33) possibly related to a magnetic reversal or excursion (Table S1), the remaining 12 dikes showed well-clustered and dual-polarity ChRMs (Fig. 2B) that passed a reversal test (McFadden, 1990) with a "C" classification ($\gamma = 5.4°$, $\gamma c = 14.2°$). It should be noted that the inclusion of site 16WDS33 did not change the positive result of the reversal test. The ChRM mean direction is Dec = 294.0°, Inc = −58.1°, and $\alpha_{95} = 5.0°$, with a corresponding paleomagnetic pole of 36.7°N, −0.5°E and $A_{95} = 7.4°$. At site 16WDS14, the host granite was sampled for a baked contact test. Although the ChRM direction of the baked host rock is similar to that of the dike, the unbaked granites carried unstable magnetizations, rendering the baked contact test suggestive but inconclusive. Most outcrops in this area did not allow for the measurement of dike dips. However, for those dikes where we could measure dips, vertical/subvertical dike planes were consistently observed. Therefore, no tilt correction was applied to the paleomagnetic data.

The high level and narrow range of unblocking temperatures (Fig. 2A), together with rock magnetic analyses (Figs. S2 and S3), indicate that the ChRM is carried by single-domain/single-vortex magnetite, which is a common carrier of thermal remanence in mafic dikes and is resistant to viscous and/or thermal remagnetization. Both younger dike swarms, the ca. 2.41 Ga Widgiemooltha dikes (Smirnov et al., 2013) and the ca. 1.89 Ga Boonadgin dikes (Liu et al., 2019), have been shown to preserve primary magnetizations in our study area, ruling out pervasive remagnetization. Some samples of the Yandinilling dikes carry an MTC with a direction close to that of the younger Widgiemooltha dikes, which could have imparted a partial thermal overprint on the studied Yandinilling dikes in our study area. Although this direction is not particularly well resolved in our samples, the preservation of the partial thermal overprint imparted by the Widgiemooltha event implies that the more stable ChRM of the Yandinilling dikes was acquired before ca. 2.4 Ga, consistent with our interpretation of the ChRM of the Yandinilling dikes being primary. Additional support for the absence of wholesale remagnetization is the dissimilarity between the ChRM direction and published younger paleomagnetic directions from the region, including the Gnowangerup-Fraser dikes, the Bangemall sills, and the Mundine Well dikes (Fig. 3C; Wingate and Giddings, 2000; Wingate et al., 2002; Pisarevsky et al., 2014). The positive reversal test is also consistent with a primary origin. In summary, we interpret the ChRM of the Yandinilling dikes to be thermoremanent magnetization acquired at the time of dike cooling and therefore useful for providing paleogeographic constraints.

DISCUSSION

Zimgarn

Based on the age match of the ca. 2.41 Ga Sebanga Poort dike of the Zimbabwe craton and the ca. 2.41 Ma Widgiemooltha dikes of the Yilgarn craton, a possible connection between the two cratons has been suggested (Söderlund et al., 2010). Subsequent paleomagnetic comparison confirmed that putting Zimbabwe in the vicinity of Yilgarn ca. 2.4 Ga was permissible in a "Zimgarn" configuration (Fig. S6), but the exact configuration of Zimgarn remains debatable (Smirnov et al., 2013; Pisarevsky et al., 2015). Available paleomagnetic poles from the two cratons, including now our new pole, fall along similar broad swaths in both putative Zimgarn configurations (Fig. S6), thus supporting the Zimgarn hypothesis with an extended duration back to ca. 2.62 Ga. However, other pairs of precisely coeval poles (e.g., the 2.62 Ga pole from Zimbabwe) are lacking, so the question of whether to put Zimbabwe along the eastern or western margin of Yilgarn cannot be resolved at present, and more data are required (Fig. S6).

Supercontinent or Supercratons

By incorporating regional paleogeographic models such as the Superia supercraton (Bleeker, 2003) into a global reconstruction for two distinct times, we tested if clusters of cratons (or supercratons) can be collocated to form a single large entity (i.e., a supercontinent) without violating available paleomagnetic data. Based mainly on barcode matching, as well as the correlations among the Huronian Supergroup of the Superior craton, the Sariolian Sequence of the Kola/Karelia cratons, the Snowy Pass Supergroup of the Wyoming craton, and the Hurwitz Group of the Hearne craton, the Superia supercraton is proposed to include these cratons positioned along the present-day southern margin of the Superior craton (Fig. 3; Bleeker, 2003; Bleeker and Ernst, 2006; Ernst and Bleeker, 2010). The position of Wyoming in Superia based on matching geology has been confirmed and refined with paleomagnetism (Kilian et al., 2016). Recent geochronologic studies defining the magmatic barcode and stratigraphy of the Kaapvaal craton of southern Africa (Gumsley, 2017; Gumsley et al., 2017) have led to the proposal of adding "Vaalbara," a supercraton consisting of the Kaapvaal and Pilbara cratons (de Kock et al., 2009; Gumsley et al., 2017), to the larger Superia supercraton (Bleeker et al., 2016), which we adopted with slight modifications (Fig. 3; Table S3).

The Slave (Canada) and Dharwar (India) cratons are proposed to be part of the "Sclavia" supercraton (Fig. 3; Bleeker, 2003; French and Heaman, 2010). Fundamental geological similarities shared by the Zimbabwe, Dharwar, and Slave cratons suggest that they should be grouped together (Bleeker, 2003). The ca. 2.62 Ga poles of Sclavia and Zimgarn put them at similar paleolatitudes (Fig. 3), tentatively allowing their proximity. We also followed previous suggestions by placing Yilgarn and São Francisco (Brazil) close to each other (Salminen et al., 2019), albeit in a modified configuration in accordance with our new pole. This supercraton, including the Zimgarn, Sclavia, and São Francisco cratons, is referred to, for simplicity, as Sclavia hereafter. Cratons sharing two collisional phases of magmatism and metamorphism between 2.5 and 2.3 Ga are proposed to have been part of a supercraton called Nunavutia (Pehrsson et al., 2013); however, no testable reconstruction of this putative supercraton has been provided to date. Since not enough hypothesized constituent cratons have reliable paleomagnetic data for the Archean-Proterozoic transition, we did not include Nunavutia in our reconstructions.

With our new pole, there are now two time slices for which the building blocks of Superia and Sclavia have reliable poles with which to test whether they could have formed one coherent supercontinent: ca. 2.62 Ga and ca. 2.41 Ga. Previous interpretations suggest that Superia and parts of Sclavia were not far from each other and essentially contiguous at these times (Pisarevsky et al., 2015; Salminen et al., 2019). However, these hypothesized tight reconstructions employ single-pole comparisons of only one age, which offer poor resolution on the relative positions between cratons. If a supercontinent indeed existed during the Archean-Proterozoic transition, two critical criteria should be met simultaneously: (1) identical apparent polar wander (APW) paths of its building blocks, and (2) contiguous paleogeography when similar APW paths are superimposed. One or the other, but not both, of the supercontinent criteria appear to be satisfied by the data. If all cratons are placed in a contiguous configuration at either 2.6 Ga or 2.4 Ga, then poles of the other age are vastly discrepant (Fig. 3A). Thus, the supercontinent solution is only possible if there were two different, short-lived configurations that were reorganized between these two times, i.e., requiring an ~180° rotation of Superia relative to Sclavia (Fig. 3A). This solution of ephemeral supercontinents is only weakly supported by the poles of individual ages, but it is difficult to reject without more data.

Using poles for more than one age window, the relative longitude and azimuthal orientations of the Superia and Sclavia supercratons can be tested (Mitchell et al., 2014). Strikingly, the poles from Superia and Sclavia for these two time periods form APW paths of broadly similar arc distance (Fig. 3B). At face value, the

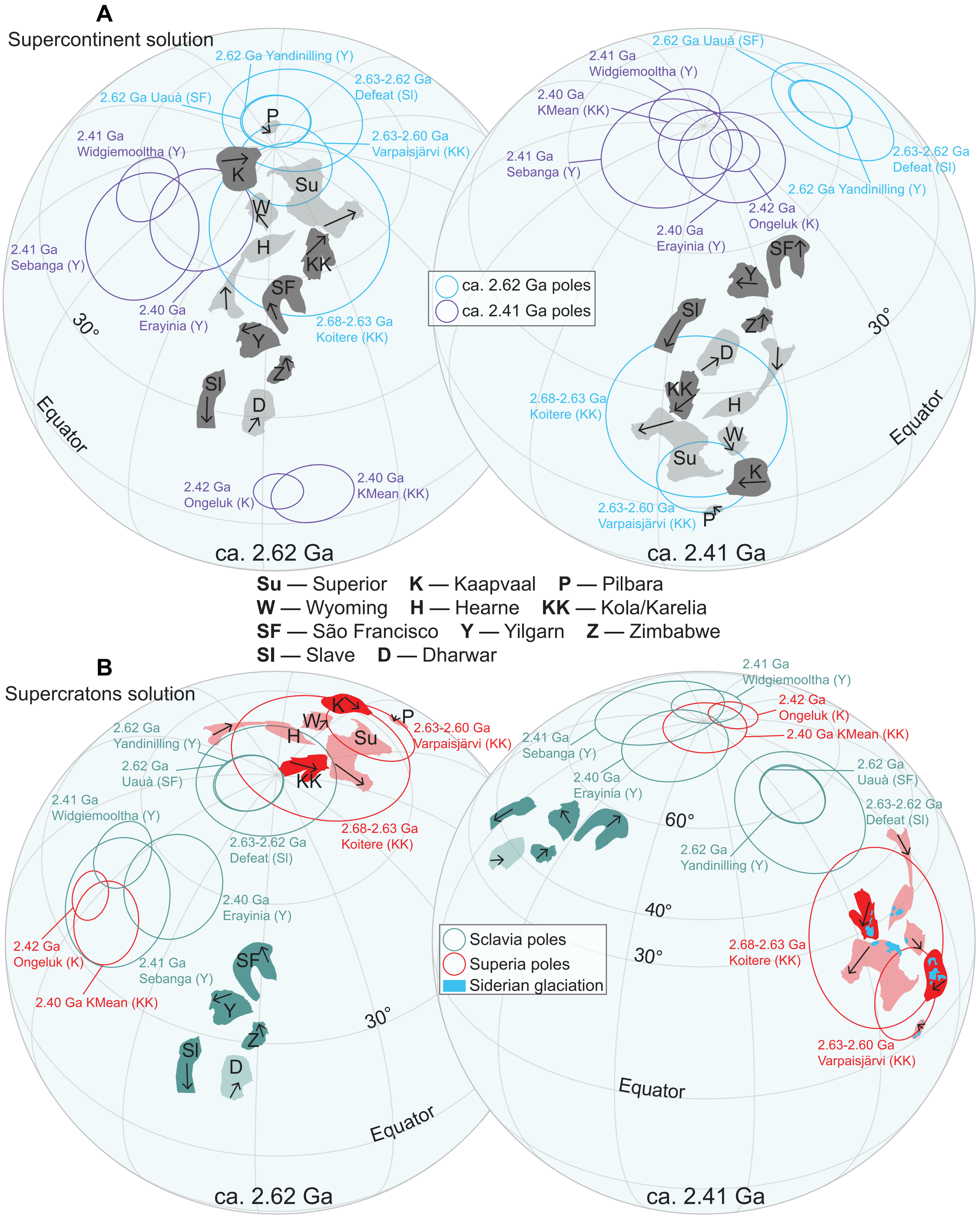

Figure 3. Paleogeographic solutions for the Archean-Proterozoic transition. (A) Supercontinent solutions for ca. 2.62 Ga and 2.41 Ga. Poles are color-coded by age. Note the differences in configuration of the two supercontinents. (B) Supercratons solution for ca. 2.62–2.41 Ga. Poles are color-coded by supercraton affinity. This solution is supported by poles of two ages and implies a large geographic separation between the two supercratons. Siderian glacial deposits preserved on all cratons of Superia are indicated (Gumsley et al., 2017). Note that configurations of Sclavia and Superior supercratons are the same in both solutions. Paleomagnetic poles used are listed in Table S3; Euler rotation parameters are provided in Table S4 (see footnote 1). Arrows indicate present-day north for each craton. Cratons without relevant paleomagnetic data have lighter shading. Reconstructions are in paleomagnetic reference frame and plotted on orthographic projections.

similarity in paths could signify coherent tectonic motion of a single supercontinental plate. However, overlapping the paleomagnetic poles results in a geographic separation of Superia and Sclavia of ~4000 km (Fig. 3B), which is suggestive of separate supercratons at this time, similar to the separation of the Slave and Superior cratons between 2.2 and 2.0 Ga (Mitchell et al., 2014). A single supercontinent solution would only be possible if essentially all remaining Archean cratons not considered here, due to a lack of constraints, happened to exactly fill the gap between Superia and Sclavia, leading to a dramatically elongated supercontinent not observed at any other time on Earth. Although conceivable, such a possibility seems ad hoc. Whereas the ephemeral supercontinents solution requires dramatic plate reorganization, the separate supercratons solution does not need to invoke any relative motion between Superia and Sclavia within paleomagnetic uncertainty, where the nearly identical APW paths of the separated supercratons could represent either true polar wander (Mitchell, 2014) or the mean motion of the continents with respect to external oceanic plates (Steinberger and Torsvik, 2008). Finally, the disparity between glacial deposits, which are preserved on all cratons of Superia (Fig. 3B) but on none of those of Sclavia, could provide independent support for the hypothesis of at least two distinct and spatially separated supercratonic landmasses across the Archean-Proterozoic transition. Paleoproterozoic glacial deposits are paradoxically found at low latitudes and have been interpreted as evidence of either snowball Earth (Evans et al., 1997) or high-obliquity (Williams et al., 1998) models. Face-value interpretation of Figure 3B would appear to imply that the high-obliquity scenario should be considered for Paleoproterozoic times. However, further study is needed to test this scenario.

ACKNOWLEDGMENTS

This work was supported by an Australian Research Council Laureate Fellowship grant to Z.X. Li (FL150100133), grants from the National Natural Science Foundation of China (41890833 and 41888101) and the Chinese Academy of Sciences (IGGCAS201905) to R.N. Mitchell, and the Ministry of Science and High Education of the Russian Federation grant (075–15–2019–1883) to S.A. Pisarevsky. This is an International Geoscience Programme (IGCP) 648 "Supercontinent Cycles & Global Geodynamics" contribution. Comments from Wouter Bleeker and two anonymous reviewers greatly improved the manuscript.

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