GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G50941.1

Manuscript received 16 November 2022
Revised manuscript received 8 March 2023
Manuscript accepted 23 March 2023

Published online 13 April 2023

Mid-Proterozoic geomagnetic field was more consistent with a dipole than a quadrupole

Zheng Gong[1,2,*], David A.D. Evans[1], Zhongtian Zhang[1], and Chi Yan[3]
[1]Department of Earth and Planetary Sciences, Yale University, New Haven, Connecticut 06511, USA
[2]Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
[3]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland 21218, USA

ABSTRACT

The current morphology of Earth's time-averaged magnetic field can be approximated to a geocentric axial dipole (GAD), but whether such an approximation remains valid in deep time needs to be investigated. Studies have used paleomagnetic data to reconstruct the ancient field and generally support a GAD morphology since 2 Ga. Recently, the GAD model for mid-Proterozoic time has been challenged, and an alternative model was proposed wherein the mid-Proterozoic field was dominated by a normal-tesseral quadrupole (NTQ) with spherical harmonics of degree $l = 2$ and order $m = 1$. We performed forward modeling to quantitatively compare whether a GAD or an NTQ could provide a better fit to mid-Proterozoic paleomagnetic directions. To deal with the ambiguity in plate reconstruction, we first considered data only from Laurentia, and then we expanded the analysis to Baltica by reconstructing its position relative to Laurentia using the geologically based Northern Europe–North America (NENA) configuration. Finally, we included data from Siberia using two reconstruction models. Results showed that in three mid-Proterozoic intervals (1790–1740 Ma, 1485–1425 Ma, 1095–1080 Ma), a GAD morphology gives better, or equally good, fits compared to the NTQ morphology. In addition, a stable NTQ that persisted for hundreds of millions of years is disfavored from a geodynamic perspective. Overall, mid-Proterozoic paleomagnetic directions are more consistent with a dipolar field. We suggest that the GAD remains the most parsimonious model to describe the morphology of the mid-Proterozoic magnetic field.

INTRODUCTION

The geomagnetic field, as well as its morphology, plays a vital role in maintaining Earth as a habitable planet. It has been considered that the time-averaged field (TAF) could be approximated as a magnetic dipole at the center of Earth and aligned with the spin axis, known as the geocentric-axial-dipole (GAD) model. By studying volcanic rocks, the GAD model has been rigorously tested to be valid for the last 5 m.y. (Hatakeyama and Kono, 2002). Marine magnetic anomalies and the geomagnetic polarity time scale seem to support a dominant GAD field back to the early Mesozoic (Gee and Kent, 2007). However, the field morphology in deeper time still merits investigation.

Many studies have attempted to test from different perspectives whether the TAF in the Precambrian behaved like a GAD. The pioneering study of M.E. Evans (1976) tested a global paleomagnetic database against models of GAD versus pure axial-quadrupole or axial-octupole fields. Kent and Smethurst (1998) modified the test to consider predominantly GAD with variably subsidiary axial-quadrupolar and axial-octupolar components. This suite of tests, limited to pure axial field components due to symmetry, required an assumption of sufficient time for uniform global sampling by randomly moving continental blocks, which could be substantially more than 1 b.y. (Rolf and Pesonen, 2018). Using rocks that bear independent paleoclimatic indications such as evaporites, Evans (2006) proposed that the GAD model was likely valid to first order since ca. 2 Ga. Other studies leveraged paleomagnetic data to test the uniformitarianism of the ancient TAF. Smirnov and Tarduno (2004) investigated the latitudinal distribution of paleosecular variations, as did Smirnov et al. (2011). Driscoll and Evans (2016) studied the frequency of geomagnetic superchrons. Swanson-Hysell et al. (2009) and Salminen et al. (2017) explored whether geomagnetic reversals were symmetric or asymmetric. Veikkolainen et al. (2017) investigated the latitudinal distribution of paleointensity. Veikkolainen and Pesonen (2021) looked into the latitudinal distribution of paleomagnetic inclinations. The main conclusion from these studies is that the TAF was likely predominantly axial-dipolar since at least the early Proterozoic.

Given that the recent TAF is dominated by the dipolar component, previous analyses often treated high-order components (i.e., quadrupolar, octopolar, etc.) as subsidiary and spin-axial (i.e., spherical harmonics of order $m = 0$). Few studies have tested whether the ancient TAF was multipolar-dominated and/or non-axisymmetric. Recently, Sears (2022) proposed that the TAF during 1.75–1.0 Ga was a normal-tesseral quadrupole (NTQ) with spherical harmonics of degree $l = 2$ and order $m = 1$. By juxtaposing Siberia next to southwest Laurentia, the paleomagnetic directions compiled by Sears (2022) seemed to conform to that model (Fig. 1). However, the necessity of invoking such a nonuniformitarian field morphology for a 750-m.y.-long period in the Proterozoic needs to be rigorously tested.

DEALING WITH MID-PROTEROZOIC PLATE RECONSTRUCTIONS

The fundamental basis of Sears's (2022) NTQ proposal is his plate reconstruction model in the mid-Proterozoic, which connects northern Siberia to southwestern Laurentia (Sears and Price, 2003). This connection is based on geological piercing points across the two cratons, including Archean crustal provinces, Orosirian and Statherian orogenic belts, and Calymmian and Stenian intracratonic basins (Sears, 2022). However, other geology-based models yield different reconstructions. For example, Condie and

Zheng Gong https://orcid.org/0000-0001-9482-5545
*zheng_gong@fas.harvard.edu

CITATION: Gong, Z., et al., 2023, Mid-Proterozoic geomagnetic field was more consistent with a dipole than a quadrupole: Geology, v. 51, p. 571–575, https://doi.org/10.1130/G50941.1

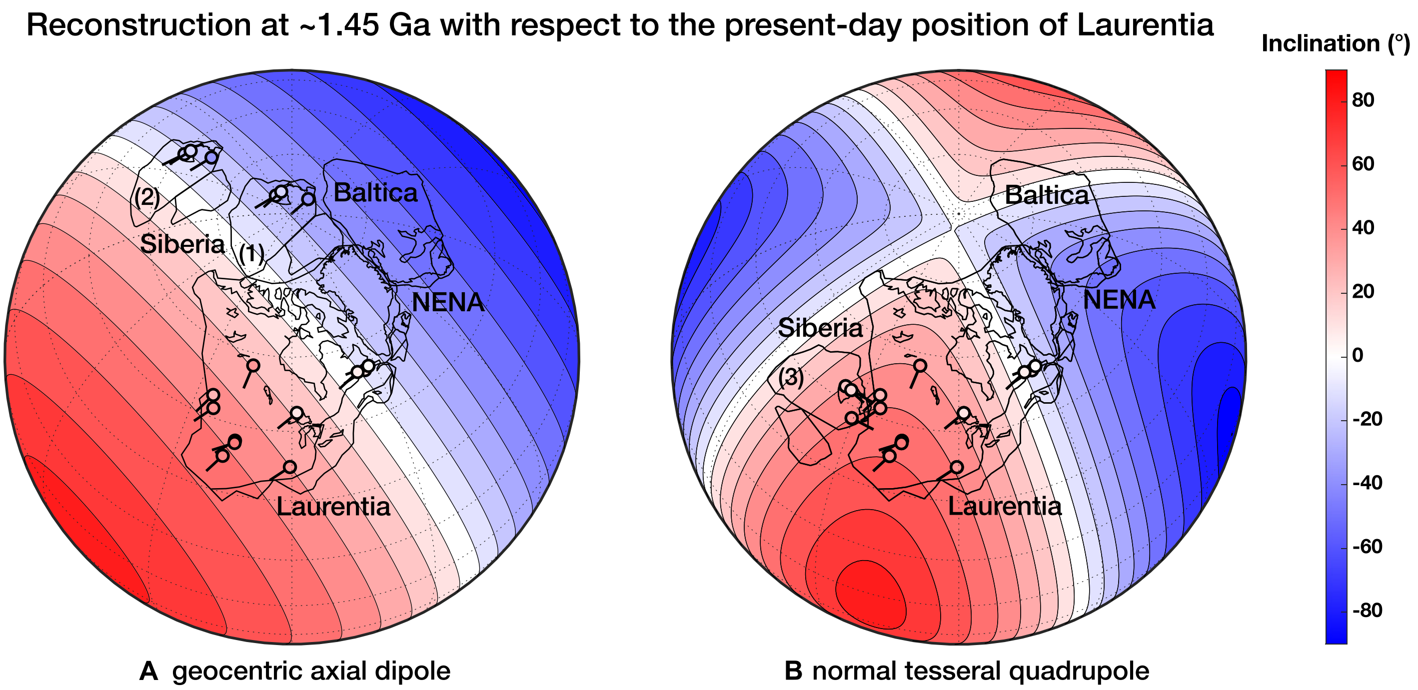

Figure 1. Different geomagnetic field and plate reconstruction models at ca. 1.45 Ga, with paleomagnetic data from Siberia and Laurentia as considered by Sears (2022): (A) reconstruction under geocentric-axial-dipole (GAD) assumption; (B) reconstruction under normal-tesseral quadrupole (NTQ) assumption (Sears, 2022). Note that relative positions between Laurentia and Siberia are different: 1—tight-fit model of Ernst et al. (2016); 2—loose-fit model of Pisarevsky et al. (2014); 3—Siberia–southwest Laurentia model of Sears and Price (2003) and Sears (2022). Baltica was rotated to Laurentia using the Northern Europe–North American (NENA) model (Gower et al., 1990). As can be seen, adding paleomagnetic data from Baltica can provide powerful test between GAD and NTQ hypotheses. Euler rotation parameters are listed in Table S2 (see text footnote 1). Black lines show paleomagnetic declinations, and colors of dots and contoured areas show paleomagnetic inclinations and predicted inclinations based on field morphologies, respectively.

Rosen (1994) placed northern Siberia next to northern Laurentia based on paired Proterozoic orogenic belts and magnetic anomaly patterns. By matching coeval Proterozoic large igneous provinces, Ernst et al. (2016) suggested that southern Siberia should have been in proximity to northern Laurentia. Therefore, the geology-based solution to the Laurentia-Siberia connection problem is nonunique (Fig. 1).

To deal with the uncertainties in the plate reconstructions in the mid-Proterozoic, we performed an analysis in three steps to expand the spatial extent of paleomagnetic observations of the ancient TAF. First, we focused on the data solely from Laurentia, which is the largest craton with the most high-quality and precisely dated paleomagnetic data of mid-Proterozoic age. Then, the analysis was extended to Baltica, because its relative position to Laurentia before the breakup of Nuna is fairly well constrained by geological correlations (Gower et al., 1990). Considering the nonunique solutions in the Laurentia-Siberia connection, we chose another reconstruction model in addition to that of Sears (2022), which is the tight-fit model between southern Siberia and northern Laurentia (Fig. 1; Ernst et al., 2016). The loose-fit Laurentia-Siberia connection, such as that delineated by Pisarevsky et al. (2014), was not considered because this model was largely based on paleomagnetic data.

SELECTION OF PALEOMAGNETIC DATA

Testing the TAF morphology requires the input paleomagnetic data to be high-quality and time-averaged. Sears (2022) compiled mid-Proterozoic data from Laurentia and Siberia and grouped them into three intervals: 1750–1700 Ma, 1503–1400 Ma, and 1100–1000 Ma, respectively. However, his selection included low-quality data, as well as time intervals that likely included non-negligible absolute plate motions. For example, data from the Molson dikes and Menihek Formation are post-Hudsonian overprints, and their ages are uncertain (Irving et al., 2004). The Sioux and Athabasca data are too young to be included in the 1750–1700 Ma interval. To improve the data selection, we chose the data that have recently been evaluated as the most reliable by the global paleomagnetic community (Evans et al., 2021). The selected data were grouped into three mid-Proterozoic intervals, namely 1790–1740 Ma, 1485–1425 Ma, and 1095–1080 Ma (Table S1[1]). The time intervals were narrower to ensure paleomagnetic directions within a given location had relative consistency and to preclude the significant variations of paleomagnetic directions that could be alternatively explained by plate motions.

FORWARD MODELING APPROACH

We developed a forward model to quantify the misfit between the paleomagnetic directions and the directions predicted by a GAD field and an NTQ field, respectively. First, the locations and directions of paleomagnetic data were rotated to Laurentia using the Euler rotation parameters listed in Table S2 (see footnote 1). The globe was divided into 3.6° by 3.6° grids. Under the GAD scenario, we placed the paleomagnetic pole in each grid and calculated the predicted direction for each data location. The predicted directions were compared with the paleomagnetic directions to get the normalized residual sum of squares (NRSS). The best-fit pole position in the grid gives the minimum NRSS. A similar approach was used for the NTQ scenario. The primary axis of the quadrupole was placed in each grid, and then all possible cardinal directions were explored to find the minimum NRSS between the predicted paleomagnetic directions. Detailed quantification of the forward modeling can be found in the Supplemental Material. It should be noted that our forward modeling only tested the end-member scenarios of GAD and NTQ. Monte Carlo simulation was used to account

[1]Supplemental Material. Descriptions of the forward model, compilations of paleomagnetic data, and figures showing additional modeling results. Please visit https://doi.org/10.1130/GEOL.S.22335568 to access the supplemental material, and contact editing@geosociety.org with any questions.

for the uncertainties associated with paleomagnetic directions. In each of 2000 iterations, we randomly sampled paleomagnetic directions within 95% confidence intervals of the site-mean declinations and inclinations.

Forward modeling showed that when only Laurentian data were used, the minimum residual in 1790–1740 Ma for GAD is 10.9° ± 3.3° (1σ), and that for NTQ is 10.6° ± 3.1°, the minimum residual in 1485–1425 Ma for GAD is 18.5° ± 2.5°, and that for NTQ is 21.4° ± 2.3°, and the minimum residual in 1095–1080 Ma for GAD is 12.0° ± 2.1°, and that for NTQ is 11.6° ± 2.1° (Figs. S1–S3). When we added data from Baltica, in 1790–1740 Ma, the mini-

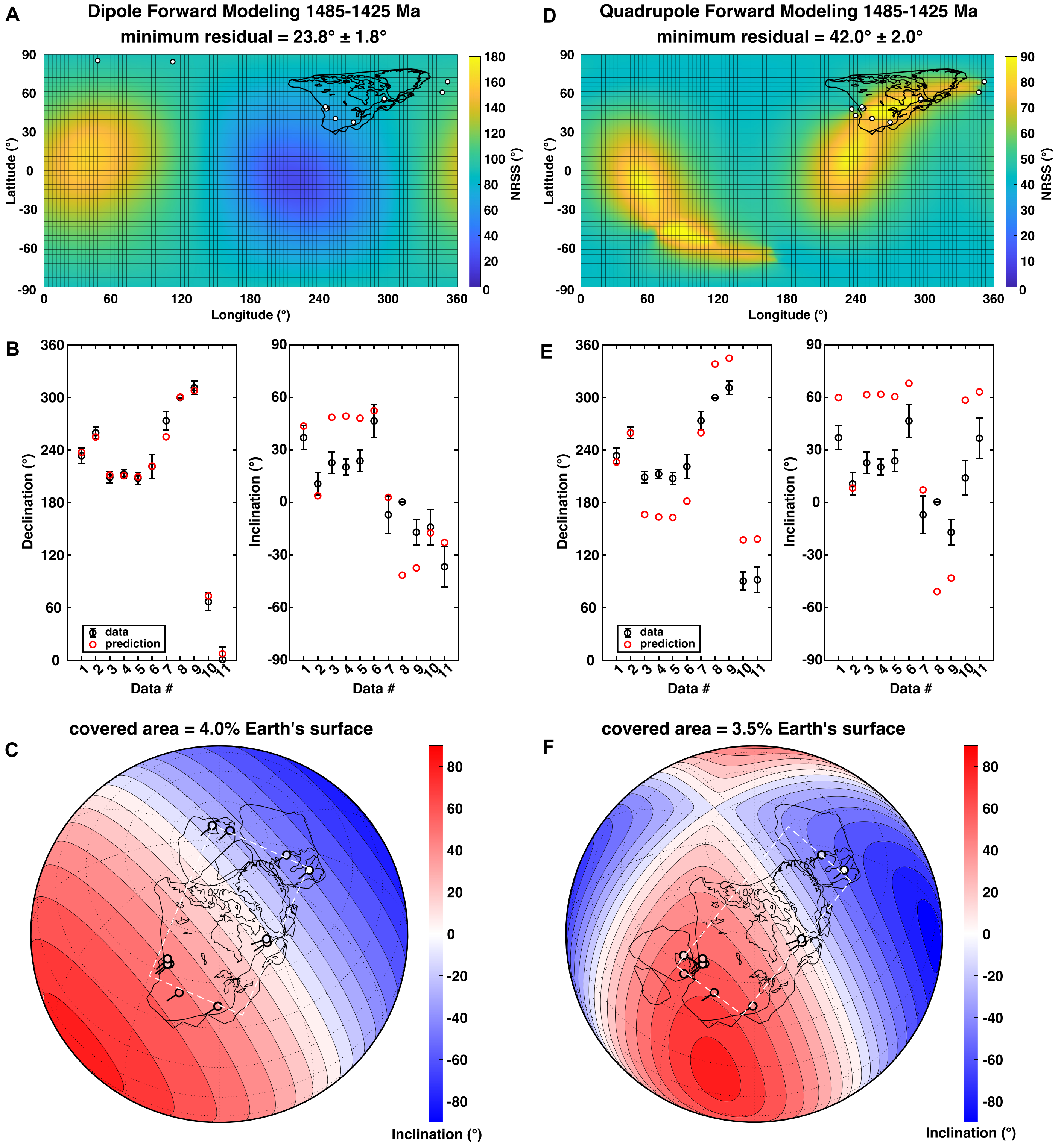

Figure 2. (A, D) Color maps showing normalized residual sum of squares (NRSS) between paleomagnetic directions and predicted directions of (A) geocentric-axial-dipole (GAD) and (D) normal-tesseral quadrupole (NTQ) morphologies in 1485–1425 Ma interval. White dots are site locations. Dots outside Laurentia are data from Baltica and Siberia that were rotated with respect to Laurentia. (B, E) Comparisons between paleomagnetic directions and directions predicted by (B) GAD and (E) NTQ using minimum NRSS. (C, F) Paleomagnetic and predicted directions shown with plate reconstructions under (C) GAD and (F) NTQ models. White dashed boxes are minimum bounding rectangles.

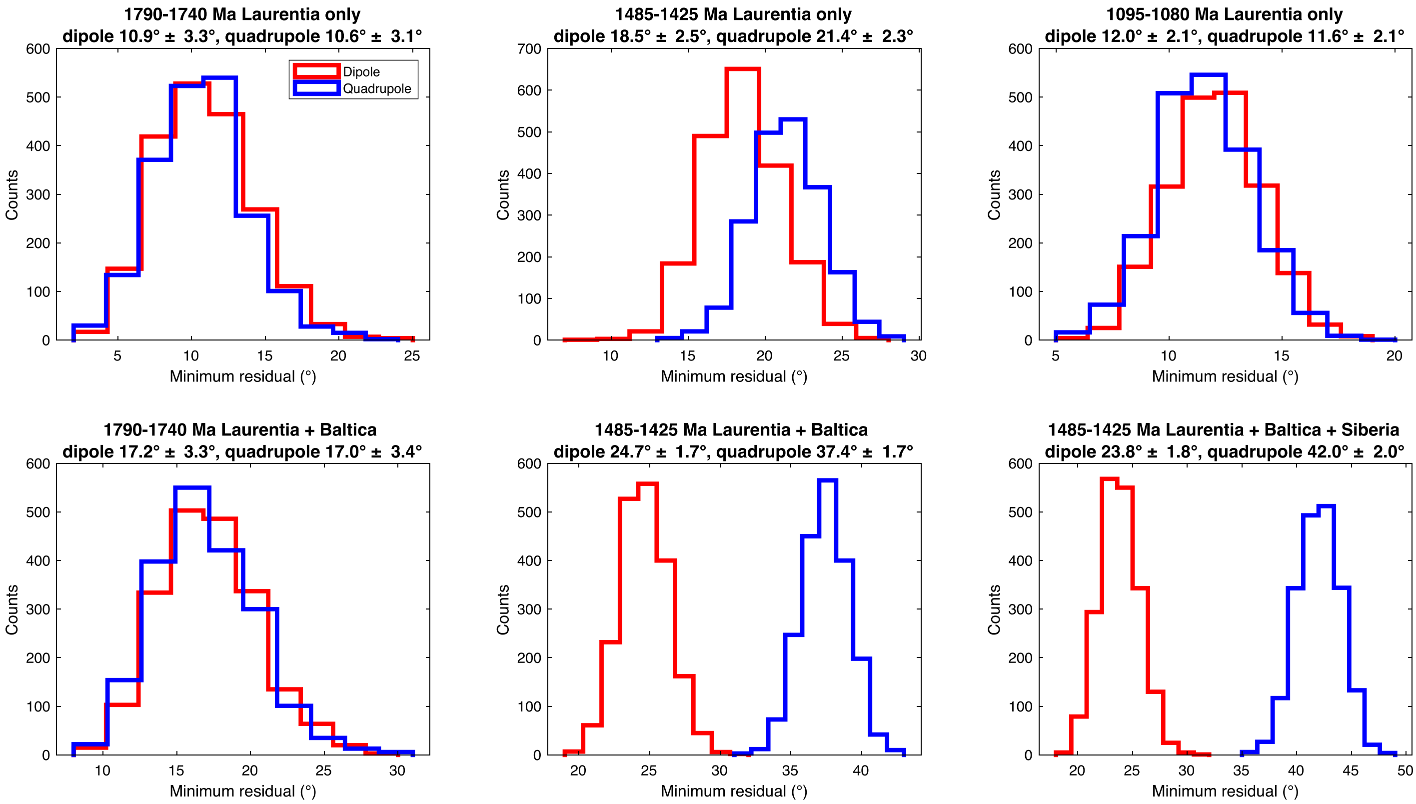

Figure 3. Distribution of minimum residuals between modeled geomagnetic fields and Monte Carlo simulation of paleomagnetic directions.

mum residual is 17.2° ± 3.3° for GAD and 17.0° ± 3.4° for NTQ, and in 1485–1425 Ma, the minimum residual is 24.7° ± 1.7° for GAD and 37.4° ± 1.7° for NTQ (Figs. S4–S5). When data from all three cratons were included at 1485–1425 Ma, the minimum residual is 23.8° ± 1.8° for GAD in the tight-fit Laurentia-Siberia connection and 42.0° ± 2.0° for NTQ in Sears's (2022) Siberia–northwest Laurentia connection (Fig. 2).

We then performed a two-sample, left-tailed *t*-test with nonequal variances. The *t*-test results showed that during 1485–1425 Ma, a GAD would yield significantly smaller minimum residuals than an NTQ, no matter whether data are included from only Laurentia, or Laurentia and Baltica, or all three cratons (Fig. 3). In the 1790–1740 Ma and 1095–1080 Ma intervals, both a GAD and an NTQ morphology give similar minimum residuals (Fig. 3). We suspect that these indistinguishable results could be due to the limited spatial coverage of the data. To quantify the spatial coverage, we calculated the minimum rectangle that bounds the data on the spherical surface. Calculations showed that the difference between the GAD and NTQ models generally becomes more significant when data have a wider spread. This is well demonstrated by the results in the 1485–1425 Ma interval (Fig. 2), where data have fairly large coverage and extend in two orthogonal directions. By contrast, the Laurentian data in the 1095–1080 Ma interval only cover 0.1% of Earth's surface and spread in one direction, making them nonideal for testing (Fig. S3).

These forward modeling results suggest that a GAD could provide a better or equally good fit to mid-Proterozoic paleomagnetic data. It is not necessary to invoke a nonuniformitarian field such as an NTQ. It should be noted that, mathematically, our forward model cannot differentiate between a GAD and a geocentric equatorial dipole, which has been proposed to have occurred in the Ediacaran (Abrajevitch and Van der Voo, 2010). However, the paleomagnetic inclinations are consistent with the latitudinal distribution of evaporite bands throughout Proterozoic time, supporting the interpretation of the dipole as axial (Evans, 2006). Therefore, the GAD model remains the most parsimonious model for the mid-Proterozoic TAF.

GEODYNAMIC PERSPECTIVES

Different magnetic field morphologies have different geodynamic implications. For instance, the dipolar field intensity decays with radial distance as r^3, while the quadrupolar field intensity decays as r^4, where r is the distance from Earth's center (Knapp, 1980). This implies that if the mid-Proterozoic geomagnetic field was an NTQ, the field strength manifested on Earth's surface should be weaker than a dipolar field that is generated from a similar power source. Based on a recent compilation, mid-Proterozoic paleointensity data are similar to the mean Phanerozoic values (Bono et al., 2022). In fact, rocks from the ca. 1.1 Ga Midcontinent Rift show high paleointensity values (Kulakov et al., 2013; Zhang et al., 2022), which would require an extremely strongly powered source if the magnetic field was dominated by a quadrupole. Such a scenario is difficult to reconcile with the thermal budget of Earth's core (Nimmo, 2015; Landeau et al., 2022).

In addition, not only is Sears's (2022) model reliant on a controversial plate reconstruction model, but also on an NTQ that is strong and stable for ~750 m.y. Such morphology is not typically seen in planetary magnetic fields, except perhaps Uranus and Neptune (Stevenson, 2010). Specific interior structures (e.g., a thin dynamo region) are required in numerical dynamo simulations to produce non-dipolar, non-axisymmetric magnetic field features (Stanley and Bloxham, 2004), which lack any corroborating evidence from Earth's interior conditions in mid-Proterozoic time. Although geodynamo models predict that a transient multipolar field could exist during or just prior to the inner core nucleation (ICN) when the dynamo reaches a weak state (Driscoll, 2016; Landeau et al., 2017), that field is comparatively weak and highly timely variable on a scale of tens of thousands of years. The age of ICN is also debated. Recent paleointensity studies and core electrical resistivity estimates seem to favor a young ICN, which occurred in the latest Neoproterozoic (Ohta et al., 2016; Bono et al., 2019). If the young ICN model is true, then the transient multipolar field it produced would be at least a few hundred million years younger than the time interval considered here. Even if the ICN is much older, as implied by some thermal conductivity estimates (Konôpková et al., 2016), it is still unclear how to accommodate a long-lived and strong quadrupolar field in mid-Proterozoic time.

CONCLUSIONS

Reliable paleomagnetic directions from Laurentia, Baltica, and Siberia were used to test whether the morphology of the mid-Proterozoic TAF conforms to a GAD or an NTQ morphology, as proposed by Sears (2022). A forward model was developed to directly quantify the misfit between the paleomagnetic observations and predicted field directions that were calculated from different field morphologies. Results showed that for the three mid-Proterozoic time intervals (1790–1740 Ma, 1485–1425 Ma, and 1095–1080 Ma), a GAD fits statistically better than, or equally as good as, the NTQ morphology. Geodynamo models also suggest that a GAD field can maintain long-term stability, but multipolar fields are only transient and highly timely variable. Therefore, the GAD model remains the most parsimonious approximation for the mid-Proterozoic TAF.

ACKNOWLEDGMENTS

This study was funded by Yale University and Johns Hopkins University. We thank S. Pisarevsky, N. Swanson-Hysell, and an anonymous reviewer for constructive comments.

REFERENCES CITED

Abrajevitch, A., and Van der Voo, R., 2010, Incompatible Ediacaran paleomagnetic directions suggest an equatorial geomagnetic dipole hypothesis: Earth and Planetary Science Letters, v. 293, p. 164–170, https://doi.org/10.1016/j.epsl.2010.02.038.

Bono, R.K., Tarduno, J.A., Nimmo, F., and Cottrell, R.D., 2019, Young inner core inferred from Ediacaran ultra-low geomagnetic field intensity: Nature Geoscience, v. 12, p. 143–147, https://doi.org/10.1038/s41561-018-0288-0.

Bono, R.K., et al., 2022, The PINT database: A definitive compilation of absolute palaeomagnetic intensity determinations since 4 billion years ago: Geophysical Journal International, v. 229, p. 522–545, https://doi.org/10.1093/gji/ggab490.

Condie, K.C., and Rosen, O.M., 1994, Laurentia-Siberia connection revisited: Geology, v. 22, p. 168–170, https://doi.org/10.1130/0091-7613(1994)022<0168:LSCR>2.3.CO;2.

Driscoll, P.E., 2016, Simulating 2 Ga of geodynamo history: Geophysical Research Letters, v. 43, p. 5680–5687, https://doi.org/10.1002/2016GL068858.

Driscoll, P.E., and Evans, D.A.D., 2016, Frequency of Proterozoic geomagnetic superchrons: Earth and Planetary Science Letters, v. 437, p. 9–14, https://doi.org/10.1016/j.epsl.2015.12.035.

Ernst, R.E., et al., 2016, Long-lived connection between southern Siberia and northern Laurentia in the Proterozoic: Nature Geoscience, v. 9, p. 464–469, https://doi.org/10.1038/ngeo2700.

Evans, D.A.D., 2006, Proterozoic low orbital obliquity and axial-dipolar geomagnetic field from evaporite palaeolatitudes: Nature, v. 444, p. 51–55, https://doi.org/10.1038/nature05203.

Evans, D.A.D., et al., 2021, An expanding list of reliable paleomagnetic poles for Precambrian tectonic reconstructions, *in* Pesonen, L.J., et al., eds., Ancient Supercontinents and the Paleogeography of Earth: Amsterdam, Netherlands, Elsevier, p. 605–639, https://doi.org/10.1016/B978-0-12-818533-9.00007-2.

Evans, M.E., 1976, Test of the dipolar nature of the geomagnetic field throughout Phanerozoic time: Nature, v. 262, p. 676–677, https://doi.org/10.1038/262676a0.

Gee, J.S., and Kent, D.V., 2007, Source of oceanic magnetic anomalies and the geomagnetic polarity time scale, *in* Schubert, G., ed., Treatise on Geophysics, Volume 5: Geomagnetism: Amsterdam, Netherlands, Elsevier, p. 455–507, https://doi.org/10.1016/B978-044452748-6.00097-3.

Gower, C.F., Ryan, A.B., and Rivers, T., 1990, Mid-Proterozoic Laurentia-Baltica: An overview of its geological evolution and a summary of the contributions made by this volume, *in* Gower, C.F., et al., eds., Mid-Proterozoic Laurentia-Baltica: Geological Association of Canada Special Paper 38, p. 1–20.

Hatakeyama, T., and Kono, M., 2002, Geomagnetic field model for the last 5 My: Time-averaged field and secular variation: Physics of the Earth and Planetary Interiors, v. 133, p. 181–215, https://doi.org/10.1016/S0031-9201(02)00084-5.

Irving, E., Baker, J., Hamilton, M., and Wynne, P.J., 2004, Early Proterozoic geomagnetic field in western Laurentia: Implications for paleolatitudes, local rotations, and stratigraphy: Precambrian Research, v. 129, p. 251–270, https://doi.org/10.1016/j.precamres.2003.10.002.

Kent, D.V., and Smethurst, M.A., 1998, Shallow bias of paleomagnetic inclinations in the Paleozoic and Precambrian: Earth and Planetary Science Letters, v. 160, p. 391–402, https://doi.org/10.1016/S0012-821X(98)00099-5.

Knapp, D.G., 1980, On Modeling Magnetic Fields on a Sphere with Dipoles and Quadrupoles: U.S. Geological Survey Professional Paper 1118, 37 p., https://doi.org/10.3133/pp1118.

Konôpková, Z., McWilliams, R.S., Gomez-Perez, N., and Goncharov, A.F., 2016, Direct measurement of thermal conductivity in solid iron at planetary core conditions: Nature, v. 534, p. 99–101, https://doi.org/10.1038/nature18009.

Kulakov, E.V., Smirnov, A.V., and Diehl, J.F., 2013, Absolute geomagnetic paleointensity as recorded by ~1.09 Ga Lake Shore Traps (Keweenaw Peninsula, Michigan): Studia Geophysica et Geodaetica, v. 57, p. 565–584, https://doi.org/10.1007/s11200-013-0606-3.

Landeau, M., Aubert, J., and Olson, P., 2017, The signature of inner-core nucleation on the geodynamo: Earth and Planetary Science Letters, v. 465, p. 193–204, https://doi.org/10.1016/j.epsl.2017.02.004.

Landeau, M., Fournier, A., Nataf, H.C., Cébron, D., and Schaeffer, N., 2022, Sustaining Earth's magnetic dynamo: Nature Reviews–Earth & Environment, v. 3, p. 255–269, https://doi.org/10.1038/s43017-022-00264-1.

Nimmo, F., 2015, Energetics of the core, *in* Schubert, G., ed., Treatise on Geophysics, Volume 8: Core Dynamics (2nd ed.): Amsterdam, Netherlands, Elsevier, p. 27–55, https://doi.org/10.1016/B978-0-444-53802-4.00139-1.

Ohta, K., Kuwayama, Y., Hirose, K., Shimizu, K., and Ohishi, Y., 2016, Experimental determination of the electrical resistivity of iron at Earth's core conditions: Nature, v. 534, p. 95–98, https://doi.org/10.1038/nature17957.

Pisarevsky, S.A., Elming, S.Å., Pesonen, L.J., and Li, Z.X., 2014, Mesoproterozoic paleogeography: Supercontinent and beyond: Precambrian Research, v. 244, p. 207–225, https://doi.org/10.1016/j.precamres.2013.05.014.

Rolf, T., and Pesonen, L.J., 2018, Geodynamically consistent inferences on the uniform sampling of Earth's paleomagnetic inclinations: Gondwana Research, v. 63, p. 1–14, https://doi.org/10.1016/j.gr.2018.05.008.

Salminen, J., Klein, R., Veikkolainen, T., Mertanen, S., and Mänttäri, I., 2017, Mesoproterozoic geomagnetic reversal asymmetry in light of new paleomagnetic and geochronological data for the Häme dyke swarm, Finland: Implications for the Nuna supercontinent: Precambrian Research, v. 288, p. 1–22, https://doi.org/10.1016/j.precamres.2016.11.003.

Sears, J.W., 2022, Challenging the dipolar paradigm for Proterozoic Earth, *in* Foulger, G.R., et al., eds., In the Footsteps of Warren B. Hamilton: New Ideas in Earth Science: Geological Society of America Special Paper 553, p. 201–211, https://doi.org/10.1130/2021.2553(17).

Sears, J.W., and Price, R.A., 2003, Tightening the Siberian connection to western Laurentia: Geological Society of America Bulletin, v. 115, p. 943–953, https://doi.org/10.1130/B25229.1.

Smirnov, A.V., and Tarduno, J.A., 2004, Secular variation of the late Archean–early Proterozoic geodynamo: Geophysical Research Letters, v. 31, L16607, https://doi.org/10.1029/2004GL020333.

Smirnov, A.V., Tarduno, J.A., and Evans, D.A.D., 2011, Evolving core conditions ca. 2 billion years ago detected by paleosecular variation: Physics of the Earth and Planetary Interiors, v. 187, p. 225–231, https://doi.org/10.1016/j.pepi.2011.05.003.

Stanley, S., and Bloxham, J., 2004, Convective-region geometry as the cause of Uranus' and Neptune's unusual magnetic fields: Nature, v. 428, p. 151–153, https://doi.org/10.1038/nature02376.

Stevenson, D.J., 2010, Planetary magnetic fields: Achievements and prospects: Space Science Reviews, v. 152, p. 651–664, https://doi.org/10.1007/s11214-009-9572-z.

Swanson-Hysell, N.L., Maloof, A.C., Weiss, B.P., and Evans, D.A.D., 2009, No asymmetry in geomagnetic reversals recorded by 1.1-billion-year-old Keweenawan basalts: Nature Geoscience, v. 2, p. 713–717, https://doi.org/10.1038/ngeo622; erratum available at https://doi.org/10.1038/ngeo850.

Veikkolainen, T., and Pesonen, L.J., 2021, Precambrian geomagnetic field—An overview, *in* Pesonen, L.J., et al., eds., Ancient Supercontinents and the Paleogeography of the Earth: Amsterdam, Netherlands, Elsevier, p. 81–108, https://doi.org/10.1016/B978-0-12-818533-9.00008-4.

Veikkolainen, T., Heimpel, M., Evans, M.E., Pesonen, L.J., and Korhonen, K., 2017, A paleointensity test of the geocentric axial dipole (GAD) hypothesis: Physics of the Earth and Planetary Interiors, v. 265, p. 54–61, https://doi.org/10.1016/j.pepi.2017.02.008.

Zhang, Y., Swanson-Hysell, N.L., Avery, M.S., and Fu, R.R., 2022, High geomagnetic field intensity recorded by anorthosite xenoliths requires a strongly powered late Mesoproterozoic geodynamo: Proceedings of the National Academy of Sciences of the United States of America, v. 119, https://doi.org/10.1073/pnas.2202875119.

Printed in USA