Evolving core conditions ca. 2 billion years ago detected by paleosecular variation

Aleksey V. Smirnov, John A. Tarduno, David A.D. Evans

1. Introduction

There is currently much debate over the nature of Earth's early core. For example, estimates for the onset of solid inner core nucleation range from times younger than 1 Ga (Aubert et al., 2009) to 3.5 Ga (Gubbins et al., 2004). Paleointensity data indicate the presence of a geodynamo in Mesoarchean and Paleoarchean times (3.2–3.45 Ga) (Tarduno et al., 2007, 2010). But some models suggest that strong fields can be generated by an early dynamo without inner core growth (Sakuraba and Kono, 1999). We can gain insight into early core conditions by examining the morphology of the ancient geomagnetic field defined by paleomagnetic data. Specifically, we can track the importance of non-dipole fields in the past using the angular dispersion (S) of virtual geomagnetic poles (VGP) derived from paleomagnetic data:

\[ S = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} A_i^2} \]

where N is the number of VGPs and \( A_i \) is the angle between the ith VGP and the mean paleomagnetic pole. McFadden et al. (1991) modeled \( S \) as independent dipole (\( S_0 \), antisymmetric) and quadrupole (\( S_0 \), symmetric) families, with the latter dominating at the equator:

\[ S = \sqrt{S_0^2 + S_0^2} = \sqrt{(a\alpha)^2 + b^2} \]

where \( \alpha \) is paleolatitude, and a and b are constants. Complete independence of the two families is unlikely, but this interpretation (Model G) remains a useful framework to gauge past paleosecular variation (PSV).

Although lava flow sequences have yielded high resolution PSV values for the last 5 million years (e.g., Johnson et al., 2008), data on billion-year time scales are more difficult to obtain. A few extensive lava flow sequences are available, but these must be supplemented with data from dike swarms. Any given regional data set may fortuitously overestimate or underestimate PSV. But if data sets are available spanning many latitudinal belts from multiple ancient cratons, a synoptic view of PSV can be derived. Smirnov and Tarduno (2004) found that such data suggest that the field at the time of the Proterozoic/Archean boundary (~2.5 Ga) was more dipolar than the field of the last 5 million years. This result was...
confirmed by an analysis of the same time window by Biggin et al. (2008a). Here, we expand our initial analysis, to assess any PSV pattern that might reflect changes in the Precambrian core conditions.

2. Application and results

We have identified two Precambrian time windows where global igneous units allow a new assessment (Table 1; Fig. 1A). We used the Global Paleomagnetic Database GPMDB4-6 (Pisarevsky, 2005) (www.tsrc.uwa.edu.au/data_bases), supplemented with recent results for our new data set. We exclude data from sedimentary, metamorphic, plutonic and silicic extrusive rocks. In particular, the silicic lavas often do not form easily distinguishable lava flows and may be deposited on slopes, which makes it difficult to assess the number of independent cooling units and structural corrections. Therefore, our analysis was confined to mafic and intermediate extrusive rocks and shallow mafic intrusions that can record distinct field directions. We further apply the following criteria: (1) Directions must be from ≥10 sites each comprising ≥3 samples. (2) Data must be from modern demagnetization and processing techniques (e.g., principal component analysis). (3) A primary origin of the magnetization must be convincingly demonstrated. (4) Data must be consistent with a thermoremanent magnetization, without evidence of chemical remanence. (5) Magnetization age must be reliably constrained. No site selection criteria based on the precision parameter (k) or maximum 95% confidence area (z/2) were applied. However, for most (575 of 585) of the accepted sites, z/2 did not exceed 20°.

S values were corrected for within-site dispersion following Doell (1970). In three studies, published information is insufficient to correct S, but the large number of samples and site-level statistics lead us to believe that any additional uncertainty is less than a few degrees. S confidence intervals (1σ) were calculated using a N – 1 jackknife method (Efron, 1982).

As opposed to the small, select Matachewan dike data set used by Smirnov and Tarduno (2004), we use a new compilation (Evans and Halls, 2010); directions from the western subprovince of the Superior craton were rotated using an Euler pole at 51°N, 85°W and rotation angle of 14°CW. We exclude results from the Derdepoort basalts (Wingate, 1998) used by Biggin et al. (2008a) because

### Table 1

Summary of paleomagnetic studies used for estimating the paleosecular variation.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Age (Ma)</th>
<th>B</th>
<th>Plat</th>
<th>S ± dS</th>
<th>C/UC</th>
<th>Sexp</th>
<th>Sobs – Sexp</th>
<th>Sign</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangemall Basin Sillsa</td>
<td>1070</td>
<td>11</td>
<td>27.8</td>
<td>13.9 ± 2.6</td>
<td>C</td>
<td>11.6</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Lake Shore trapsb</td>
<td>1087</td>
<td>30</td>
<td>14.6</td>
<td>13.6 ± 0.8</td>
<td>C</td>
<td>10.6</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Portage Lake Volcanicsc</td>
<td>1095</td>
<td>28</td>
<td>16.9</td>
<td>14.5 ± 1.2</td>
<td>UC</td>
<td>10.7</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>North Shore Traps</td>
<td>1098</td>
<td>34</td>
<td>27.3</td>
<td>11.4 ± 2.1</td>
<td>C</td>
<td>11.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Mamanisse Point Upper N⁴</td>
<td>~1100</td>
<td>21</td>
<td>22.4</td>
<td>4.8 ± 3.0</td>
<td>C</td>
<td>11.1</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Unkomo doleritesd</td>
<td>1110</td>
<td>15</td>
<td>6.8</td>
<td>14.2 ± 3.1</td>
<td>C</td>
<td>10.3</td>
<td>3.9</td>
<td>*</td>
</tr>
<tr>
<td>Cleaver dikesh⁴</td>
<td>1740</td>
<td>17</td>
<td>39.1</td>
<td>14.4 ± 4.0</td>
<td>C</td>
<td>12.8</td>
<td>1.6</td>
<td>*</td>
</tr>
<tr>
<td>Taihang dikesh⁴</td>
<td>1769</td>
<td>19</td>
<td>2.6</td>
<td>8.5 ± 2.6</td>
<td>C</td>
<td>10.2</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Flaherty volcanicsi</td>
<td>1870</td>
<td>11</td>
<td>26.2</td>
<td>11.6 ± 1.7</td>
<td>UC</td>
<td>11.4</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Mashonaland doleritesj</td>
<td>1880</td>
<td>16</td>
<td>28.8</td>
<td>14.8 ± 4.0</td>
<td>C</td>
<td>11.7</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Fort Frances dikes</td>
<td>2067–2077</td>
<td>12</td>
<td>35.1</td>
<td>11.2 ± 3.3</td>
<td>C</td>
<td>12.3</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Marathon dikes (R)⁵</td>
<td>2101–2106</td>
<td>13</td>
<td>37.0</td>
<td>14.0 ± 2.5</td>
<td>C</td>
<td>12.6</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Marathon dikes (N)⁵</td>
<td>2121–2126</td>
<td>16</td>
<td>39.9</td>
<td>16.0 ± 2.6</td>
<td>C</td>
<td>12.9</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Biscotasing dikes⁵</td>
<td>2169</td>
<td>12</td>
<td>38.4</td>
<td>12.6 ± 2.3</td>
<td>C</td>
<td>12.7</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Ongeluk lavas⁶</td>
<td>2200</td>
<td>32</td>
<td>14.1</td>
<td>7.1 ± 7.5</td>
<td>C</td>
<td>10.5</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Dharwar dikesf</td>
<td>2367</td>
<td>25</td>
<td>69.1</td>
<td>15.5 ± 1.1</td>
<td>C</td>
<td>17.1</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Matachewan dikes (N)⁷</td>
<td>2473–2446</td>
<td>28</td>
<td>14.8</td>
<td>6.4 ± 2.9</td>
<td>C</td>
<td>10.6</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Matachewan dikes (R)⁷</td>
<td>2473–2446</td>
<td>101</td>
<td>7.7</td>
<td>8.8 ± 5.1</td>
<td>C</td>
<td>10.3</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Kareria dikesh⁷</td>
<td>2440</td>
<td>11</td>
<td>20.0</td>
<td>10.7 ± 1.3</td>
<td>UC</td>
<td>11.8</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Allandrie lavas</td>
<td>2664–2709</td>
<td>17</td>
<td>43.2</td>
<td>12.1 ± 5.7</td>
<td>C</td>
<td>13.3</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Upper Fortescue lavas</td>
<td>2715</td>
<td>16</td>
<td>35.0</td>
<td>12.9 ± 3.2</td>
<td>C</td>
<td>12.3</td>
<td>0.6</td>
<td>*</td>
</tr>
<tr>
<td>Fortescue Lower lavas</td>
<td>2746</td>
<td>75</td>
<td>49.5</td>
<td>12.8 ± 2.0</td>
<td>C</td>
<td>14.2</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Fortescue Package 0</td>
<td>&gt;2772</td>
<td>24</td>
<td>58.3</td>
<td>16.1 ± 2.8</td>
<td>C</td>
<td>15.4</td>
<td>0.7</td>
<td>*</td>
</tr>
</tbody>
</table>

B: number of units; Plat: paleolatitude; S, dS: angular dispersion of VGPs and confidence interval; C/UC: data corrected (uncorrected) for within-site dispersion; Sobs – Sexp, difference between observed S and that predicted (Sexp) from Model G fit to all data (α = 0.20 ± 0.04, b = 10.17 ± 0.90); Sign: result of Sign Test (see text). Paleomagnetic and age data sources: Global Paleomagnetic Database (GPD) (Pisarevsky, 2005) data identifier is listed.

See references cited for more recent works:

a Wingate et al. (2002) (GPD 3455).
b Diehl and Haig (1994) (GPD 2776).
c Hnat et al. (2006).
d Tauxe and Kodama (2009).
e Swanson-Hysell et al. (2009).
f Gose et al. (2006).
g Irving et al. (2004) (GPD 3609).
h Halls et al. (2000) (GPD 3394).
k Buchan et al. (1996) (GPD 3061).
l Halls et al. (2008).
m Halls and Davis (2004) (GPD 3644).
ν Evans et al. (1997) (GPD 3175).
ν Evans et al. (2007).
p Evans and Halls (2010).
q Mertanen et al. (1999) (GPD 3296).
r de Kock et al. (2009).
s Strik et al. (2007).
t Biggin et al. (2008a).
the large apparent S value (24.3°) probably reflects uncertainties in bedding corrections for the lavas which are found in faulted basins (Wingate, pers. comm., 2009). This tectonic uncertainty can masquerade as PSV. We exclude magnetizations carried by hematite as these may record chemical remanences acquired after cooling.

In all selected studies, the maximum deviation of VGPs from the mean paleopole did not exceed 35°. Therefore the application of a constant cutoff angle of 45° commonly used to exclude transitional VGPs (e.g., Johnson et al., 2008) did not modify any of the datasets. Because of the relatively small scatter of VGPs in our Precambrian datasets (Supplementary Table 1), we feel that the application of a variable cutoff (Vandamme, 1994) may remove some scatter related to the normal secular variation rather than to the transitional field. Therefore, we chose not to apply the variable cutoff in this study. However, when used, the variable cutoff affected only three datasets (Supplementary Table 1) and did not change the overall conclusions of this study (Supplementary Fig. 1).

We split the Precambrian dataset into two age groups at ~2.2 Ga (specifically, 1.0–2.2 Ga and 2.2–3.0 Ga) and fit the data in each group using Model G (Eq. (2)). The fitting was done using the Levenberg–Marquardt least-square iterative algorithm (e.g., Björck, 1996). We find Model G parameters $a = 0.21 \pm 0.09$ (1σ), $b = 11.10 \pm 1.46$ and $a = 0.22 \pm 0.02$, $b = 7.56 \pm 0.84$ for the <2.2 Ga and >2.2 Ga groups, respectively. While the statistically indistinguishable values of the parameter $a$ indicate similar shapes of the fitting curves, their equatorial intercepts (defined by the parameter $b$) are different at the 95% confidence level.

Any individual Proterozoic or Neoarchean S value may overestimate or underestimate PSV because of under-sampling, and/or there may be trends on ten to 100 million year timescales related to the core–mantle boundary processes (McFadden et al., 1991; Tarduno et al., 2002); this may account for variability such as apparently low S observed from the ~1.8 Ga Taihang and ~1.1 Ga Mamainse Point lavas (Fig. 1A). We interpret here only the long-term signal. To test for differences between the pre- and post-2.2 Ga data, we use a non-parametric Sign Test. The combined data were fit with Model G to produce an expected S curve (Table 1). When the difference between the observed and fit data is negative (positive), a minus (plus) is assigned. This comparison versus the Model G fit to all data suggests that the pre- and post-2.2 Ga data are different at the 78% confidence level.

Directions from extrusives are usually obtained from spatially limited stratigraphic sections and these may be particularly prone to undersampling of the field due to rapid lava emplacement. In contrast, studies of dikes often represent greater spatial sampling and are less likely to sample extremely short magmatic pulses. To further test our conclusions, we fit Model G to the intrusive data sets only (Fig. 1B), yielding $a = 0.21 \pm 0.07$, $b = 11.56 \pm 1.43$ and $a = 0.20 \pm 0.03$, $b = 7.66 \pm 1.13$ for the <2.2 Ga and >2.2 Ga groups, respectively. These values are indistinguishable from those
obtained from fitting the total data set, supporting the difference in PSV.

3. Discussion and conclusion

According to the Model G (Eq. (2)), the equatorial intercept (the parameter \( b \)) of a PSV curve reflects the contribution only from the quadrupole (symmetric) family. Consequently, the lower values of \( b \) indicate a stronger contribution from the dipole (anti-symmetric) family that includes the axial dipole and octupole. As noted by the authors of Model G, and emphasized by others (e.g., Hulot and Gallet, 1996), the model by itself does not discern the relative strength of the dipole and higher order components such as the octupole. However, analyses of the time-averaged 0–5 Ma field (e.g., Johnson et al., 2008), Cretaceous field (Tarduno et al., 2002) and Proterozoic field (Evans, 2006) have failed to detect significant octupole components, and very large contributions relative to those of the dipole would be needed to influence our interpretations. Therefore we feel that the interpretation of lower \( b \) values as reflecting higher contribution from the axial dipole is justified, although we note that sensu stricto some higher octupole contribution cannot be excluded from the data analyses we present alone.

When compared with data for the last 5 million years (Johnson et al., 2008; Lawrence et al., 2009; Kent et al., 2010; Opdyke et al., 2010; a = 0.25 ± 0.03, b = 13.24 ± 0.81) we find that data from both time windows suggest a more dipolar field; the further observation that data from the pre-2.2 Ga window suggest a more dipolar field than that in the post-2.2 Ga interval implies that the process causing the change of PSV was operating by at least ~2.2 billion years ago. The trend is even more expressed when the comparison is made versus the data for 5–195 Ma (a = 0.25 ± 0.04, b = 14.10 ± 1.24; McFadden et al., 1991; Tarduno et al., 2002) (Fig. 1). We note that Biggin et al. (2008b) claimed that differences in their analysis of Mid-Cretaceous and Jurassic PSV differed from those of McFadden et al. (1991) because the latter authors used a constant value to correct site-level data, which can impart a bias that is especially apparent for low latitudes. Although it is as yet unclear whether this explanation is correct (e.g., it may more simply relate to the use of some more extensive data sets), some bias does exist with the use of a constant value. Because this affects low latitude preferentially, lowering the \( S \) value, if present this bias would lead us to conclude that the 5–195 Ma average has a lower-than-actual \( b \) value. In this sense, our handling of the data is conservative because it would lead us to believe there was less of a difference between the 5–195 Ma data and the Proterozoic/Neoproterozoic data sets than what actually existed.

There are several processes that could be recorded by the PSV signal. Forcing of the dynamo could have changed in the absence of inner core growth (e.g., Olson and Christensen, 2006; Hori et al., 2010). However, these models predict lower CMB heat flow during superchrons, something that appears to be inconsistent with geological observations during the best known superchron, the Cretaceous Normal Polarity Superchron. Specifically, this interval is marked by extraordinarily high mantle plume activity, during which the giant oceanic plateaus such as Ontong Java formed (Labrosse et al., 2007). A null or weak field at 3.8–3.9 Ga is suggested by a hypothesis seeking to explain lunar nitrogen values through transport from Earth’s atmosphere by the solar wind (Ozima et al., 2005). After breakdown of the dense liquid layer, a geodynamo may have been present. But sources of field generation in the shallow outer core, related to convection associated with heat transport across the core–mantle boundary (Fig. 2A) could have produced a less dipolar field than that of latter times. Plate tectonics may have started very early on Earth, but cooling relevant for generation of the geodynamo may require cooling of the lower mantle. We envision this cooling accumulating with the penetration of slabs into the lower mantle, favoring super-adiabatic conditions and possibly inner core growth (Fig. 2B). The geodynamo at this time was deeply seated, related to compositional convection associated with inner core growth. The resulting field was highly dipolar, and is recorded by the oldest time window examined here (Fig. 2B). Subsequent subduction resulted in core–mantle boundary compositional and heat flux heterogeneity, resulting in sources for shallow field generation in addition to deeper sources near the inner core/outer core boundary. While the overall field was still dipolar, it was less so than prior to ca. 2 Ga (Fig. 2C). These field generation regions are similar to those of more recent times (Hoffman and Singer, 2008), with the exception that the inner core was smaller. We note that the decrease in the field dipolarity may also be promoted by increase in the CMB heat flow as suggested by some models (e.g., Hori et al., 2010), but we caution that these models still need to be.
rigorously examined against the Mesozoic-Recent interval where geologic data may be used to infer changes in CMB conditions.

The relatively old inner core age implied by our PSV analysis favors radioactive heat sources in the core (Buffett, 2002). However, we note that the inner core nucleation age we call upon is older than that envisioned in many models (e.g., Aubert et al., 2009, 2010). Resolution of this important question should come as numerical models improve and are able to accommodate values representing the real Earth, and PSV data sets become larger. In particular, the possibility that a change in core cooling explicitly related to deep subduction as envisioned here led to inner core formation should be considered in future modeling. Finally, we

---

Fig. 2. One scenario for core evolution consistent with paleosecular variation and paleointensity data discussed here. Hypothetical equatorial Earth cross sections, highlighting regions of convective flow within the core most important for the dynamo. (A) Before approximately 3.5 Ga, an entirely liquid core may not have hosted a geodynamo (e.g., Labrosse et al., 2007; Ozima et al., 2005). However, given sufficient heat transport across the core-mantle boundary, a geodynamo could have been generated. If so, sources in the shallow outer core may have been more important for generating the dynamo relative to deeper convection, resulting in a field that was less dipolar than that generated in later times (B–C). (B) Onset of inner core nucleation sometime before approximately 2 Ga is driven by secular cooling of the lower mantle, possibly related to deep subduction. This results in a geodynamo that is more deeply seated in the core producing a highly dipolar field. (C) With the development of core-mantle boundary heterogeneity by continued deep subduction, shallow core contributions to the geomagnetic field grow in importance, resulting in a less dipolar field than in (B).
note that the paleomagnetic data (Table 1) were generally collected for paleolatitude (tectonic) studies. The change we have identified is testable through renewed paleomagnetic studies of igneous units, with an eye toward dense sampling needed to reduce uncertainties in PSV analyses. Additional efforts should also be made to obtain robust PSV estimates for the time periods for which such estimates are currently rare or absent (for example, for the early/mid-Mesoproterozoic).

Acknowledgments

We thank R.D. Cottrell for discussions and for preparation of figures. We also thank U. Christensen and A.J. Biggin for their constructive reviews. This research was funded by the NSF and by the David and Lucile Packard Foundation.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.pepi.2011.05.003.

References


**Supplementary Table 1.** Summary of the data used for estimating the paleosecular variation after applying the variable cutoff filter (Vandamme, 1994). The three datasets affected by the procedure are highlighted by bold font.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Age (Ma)</th>
<th>B'</th>
<th>$\Delta_{max}$</th>
<th>$A_e$</th>
<th>Plat</th>
<th>$S \pm dS$</th>
<th>C/UC</th>
<th>$S_{exp}$</th>
<th>$S_{obs}$-$S_{exp}$</th>
<th>Sign</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangemall Basin Sills$^1$</td>
<td>1070</td>
<td>11</td>
<td>24.1</td>
<td>31.1</td>
<td>27.8</td>
<td>13.9 ± 2.6</td>
<td>C</td>
<td>11.3</td>
<td>2.6</td>
<td>+</td>
</tr>
<tr>
<td>Lake Shore traps$^2$</td>
<td>1087</td>
<td>30</td>
<td>18.3</td>
<td>29.7</td>
<td>14.6</td>
<td>13.6 ± 0.8</td>
<td>C</td>
<td>10.1</td>
<td>3.5</td>
<td>+</td>
</tr>
<tr>
<td>Portage Lake Volcanics$^3$</td>
<td>1095</td>
<td>28</td>
<td>26.2</td>
<td>31.1</td>
<td>16.9</td>
<td>14.5 ± 1.2</td>
<td>UC</td>
<td>10.3</td>
<td>4.2</td>
<td>+</td>
</tr>
<tr>
<td>North Shore Traps$^4$</td>
<td>1098</td>
<td>34</td>
<td>23.6</td>
<td>26.1</td>
<td>27.3</td>
<td>11.4 ± 2.1</td>
<td>C</td>
<td>11.2</td>
<td>0.2</td>
<td>+</td>
</tr>
<tr>
<td>Mamainse Point Upper N$^5$</td>
<td>~1100</td>
<td>21</td>
<td>10.1</td>
<td>14.8</td>
<td>22.4</td>
<td>4.8 ± 3.0</td>
<td>C</td>
<td>10.7</td>
<td>-5.9</td>
<td>−</td>
</tr>
<tr>
<td>Ümkondo dolerites$^6$</td>
<td>1110</td>
<td>15</td>
<td>28.0</td>
<td>31.3</td>
<td>6.8</td>
<td>14.2 ± 3.1</td>
<td>C</td>
<td>9.7</td>
<td>4.5</td>
<td>+</td>
</tr>
<tr>
<td>Cleaver dikes$^7$</td>
<td>1740</td>
<td>17</td>
<td>30.7</td>
<td>33.2</td>
<td>39.1</td>
<td>14.4 ± 4.0</td>
<td>C</td>
<td>12.6</td>
<td>1.8</td>
<td>+</td>
</tr>
<tr>
<td>Tailiang dikes$^8$</td>
<td>1769</td>
<td>18</td>
<td>11.6</td>
<td>16.2</td>
<td>2.3</td>
<td>5.9 ± 1.5</td>
<td>C</td>
<td>9.6</td>
<td>-3.7</td>
<td>−</td>
</tr>
<tr>
<td>Flaherty volcanics$^9$</td>
<td>1870</td>
<td>11</td>
<td>17.4</td>
<td>25.9</td>
<td>26.2</td>
<td>11.6 ± 1.7</td>
<td>UC</td>
<td>11.1</td>
<td>0.5</td>
<td>+</td>
</tr>
<tr>
<td>Mashonaland dolerites$^{10}$</td>
<td>1880</td>
<td>15</td>
<td>21.2</td>
<td>28.5</td>
<td>27.4</td>
<td>11.8 ± 5.1</td>
<td>C</td>
<td>11.2</td>
<td>0.6</td>
<td>+</td>
</tr>
<tr>
<td>Fort Frances dikes$^{11,12}$</td>
<td>2067-2077</td>
<td>12</td>
<td>26.0</td>
<td>26.0</td>
<td>35.1</td>
<td>11.2 ± 3.3</td>
<td>C</td>
<td>12.1</td>
<td>-0.9</td>
<td>−</td>
</tr>
<tr>
<td>Marathon dikes (R)$^{11,12}$</td>
<td>2101-2106</td>
<td>13</td>
<td>21.2</td>
<td>31.1</td>
<td>37.0</td>
<td>14.0 ± 2.5</td>
<td>C</td>
<td>12.4</td>
<td>1.6</td>
<td>+</td>
</tr>
<tr>
<td>Marathon dikes (N)$^{11,12}$</td>
<td>2121-2126</td>
<td>16</td>
<td>26.3</td>
<td>34.8</td>
<td>39.9</td>
<td>16.0 ± 2.6</td>
<td>C</td>
<td>12.8</td>
<td>3.2</td>
<td>+</td>
</tr>
<tr>
<td>Biscotasing dikes$^{13}$</td>
<td>2169</td>
<td>12</td>
<td>20.7</td>
<td>28.2</td>
<td>38.4</td>
<td>12.6 ± 2.3</td>
<td>C</td>
<td>12.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ongeluk lavas$^{14}$</td>
<td>2200</td>
<td>32</td>
<td>19.5</td>
<td>20.1</td>
<td>14.1</td>
<td>7.1 ± 7.5</td>
<td>C</td>
<td>10.1</td>
<td>-3.0</td>
<td>−</td>
</tr>
<tr>
<td>Dharwar dikes$^{15}$</td>
<td>2367</td>
<td>25</td>
<td>24.7</td>
<td>32.8</td>
<td>69.1</td>
<td>15.5 ± 1.1</td>
<td>C</td>
<td>17.4</td>
<td>-1.9</td>
<td>−</td>
</tr>
<tr>
<td>Matachewan dikes (N)$^{16}$</td>
<td>2473-2446</td>
<td>28</td>
<td>16.7</td>
<td>17.5</td>
<td>14.8</td>
<td>6.4 ± 2.9</td>
<td>C</td>
<td>10.1</td>
<td>-3.7</td>
<td>−</td>
</tr>
<tr>
<td>Matachewan dikes (R)$^{16}$</td>
<td>2473-2446</td>
<td>99</td>
<td>18.3</td>
<td>20.4</td>
<td>7.7</td>
<td>8.0 ± 5.5</td>
<td>C</td>
<td>9.8</td>
<td>-1.8</td>
<td>−</td>
</tr>
<tr>
<td>Karelia dikes$^{17}$</td>
<td>2440</td>
<td>11</td>
<td>16.6</td>
<td>24.2</td>
<td>30.0</td>
<td>10.7 ± 1.3</td>
<td>UC</td>
<td>11.5</td>
<td>-0.8</td>
<td>−</td>
</tr>
<tr>
<td>Allanridge lavas$^{18-19}$</td>
<td>2664-2709</td>
<td>17</td>
<td>25.5</td>
<td>29.0</td>
<td>43.2</td>
<td>12.1 ± 5.7</td>
<td>C</td>
<td>13.2</td>
<td>-1.1</td>
<td>−</td>
</tr>
<tr>
<td>Upper Fortescue lavas$^{20}$</td>
<td>2715</td>
<td>16</td>
<td>21.8</td>
<td>30.0</td>
<td>35.0</td>
<td>12.9 ± 3.2</td>
<td>C</td>
<td>12.1</td>
<td>0.8</td>
<td>+</td>
</tr>
<tr>
<td>Fortescue Lower lavas$^{20}$</td>
<td>2746</td>
<td>75</td>
<td>28.7</td>
<td>30.7</td>
<td>49.5</td>
<td>12.8 ± 2.0</td>
<td>C</td>
<td>14.2</td>
<td>-1.4</td>
<td>−</td>
</tr>
<tr>
<td>Fortescue Package U$^{20}$</td>
<td>&gt;2772</td>
<td>24</td>
<td>26.4</td>
<td>30.5</td>
<td>58.3</td>
<td>16.1 ± 2.8</td>
<td>C</td>
<td>15.6</td>
<td>0.5</td>
<td>+</td>
</tr>
</tbody>
</table>

B': number of units not rejected by the variable cutoff; $\Delta_{max}$: maximum angular distance of the non-excluded VGPs from the mean paleopole; $A_e$: the variable cutoff angle; Plat: paleolatitude; $S$, $dS$: angular dispersion of VGPs and confidence interval; C/UC: data corrected (uncorrected) for within-site dispersion; $S_{obs}$-$S_{exp}$: difference between observed $S$ and that predicted ($S_{exp}$) from Model G fit to all data ($a = 0.21 \pm 0.03$, $b = 9.62 \pm 0.94$); Sign: result of Sign Test (see text). Paleomagnetic and age data sources: Global Paleomagnetic Database (GPD) (Pisarevsky, 2005) data identifier is listed; see references cited for more recent works: $^1$Wingate et al. 2002 (GPD 3455); $^2$Diehl and Haig, 1994 (GPD 2776); $^3$Hnat et al. 2006; $^4$Tauxe and Kodama, 2009; $^5$Swanson-Hysell et al., 2009; $^6$Gose et al. 2006; $^7$Irving et al. 2004 (GPD 3609); $^8$Halls et al. 2000 (GPD 3394); $^9$Schmidt 1980 (GPD 1862); $^{10}$Bates and Jones, 1996 (GPD 3088); $^{11}$Buchan et al. 1996 (GPD 3061); $^{12}$Halls et al. 2008; $^{13}$Halls and Davis 2004 (GPD 3644); $^{14}$Evans et al., 1997 (GPD 3175); $^{15}$Halls et al. 2007; $^{16}$Evans and Halls 2010; $^{17}$Mertanen et al. 1999 (GPD 3296); $^{18}$de Kock et al. 2009; $^{19}$Strik et al. 2007; $^{20}$Biggin et al. 2008.
References for supplementary table 1


**Supplementary Figure 1.** (A) Latitudinal dependence of angular dispersion S of virtual geomagnetic poles for the Precambrian (solid symbols) intrusive and extrusive units and extrusives of the last five million years (open inverted triangles). The Precambrian datasets are filtered using the variable cutoff angle (Vandamme, 1994). See Supplementary Table 1 for the Precambrian data sources. Grey and black symbols: younger and older than 2.2 Ga, respectively. Solid black, grey, and thick black lines: Model G fits for the 0-5 Ma (Time-Averaged Field Initiative, TAFI; Johnson et al., 2008; Lawrence et al., 2009; Kent et al., 2010; Opdyke et al., 2010), 1.0-2.2 Ga and 2.2-3.0 Ga data, respectively. The dashed line shows the model G fit for the 5-195 Ma data (McFadden et al., 1991; Tarduno et al., 2002; note individual data points are not shown here) (see text). (B) Latitudinal dependence of S only for the Precambrian (solid symbols) intrusive units (see text).