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Frequency of Proterozoic geomagnetic superchrons

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ABSTRACT

Long-term geodynamo evolution is expected to respond to inner core growth and changing patterns of mantle convection. Three geomagnetic superchrons, during which Earth's magnetic field maintained a near-constant polarity state through tens of Myr, are known from the bio/magnetostratigraphic record of Phanerozoic time, perhaps timed according to supercontinental episodicity. Some geodynamo simulations incorporating a much smaller inner core, as would have characterized Proterozoic time, produce field reversals at a much lower rate. Here we compile polarity ratios of site means within a quality-filtered global Proterozoic paleomagnetic database, according to recent plate kinematic models. Various smoothing parameters, optimized to successfully identify the known Phanerozoic superchrons, indicate 3–10 possible Proterozoic superchrons during the 1300 Myr interval studied. Proterozoic geodynamo evolution thus appears to indicate a relatively narrow range of reversal behavior through the last two billion years, implying either remarkable stability of core dynamics over this time or insensitivity of reversal rate to core evolution.

1. Introduction

In the paleomagnetic record, absolute polarity of the geodynamo can be established unambiguously if there exists, for each tectonic plate, a succession of closely spaced poles defining a continuous apparent polar wander path (APWP). For major continental blocks, the most recent synthesis of such paths (Torsvik et al., 2012), plus magnetostratigraphic studies of well-exposed volcano-sedimentary successions, allow for precise temporal control on reversals (Gradstein et al., 2004). Within that time interval there are three known superchrons: Cretaceous (N), Kiaman (R), and Moyero (R), where (N) and (R) refer to Normal and Reversed states of the field relative to the present. Among these, the Moyero is least well resolved due to sparseness of sampling outside the type Siberian magnetostratigraphic sections. Nonetheless, Phanerozoic superchrons have occurred with a frequency of about one per 200 Myr (Biggin et al., 2012).

Here we present a new Proterozoic global paleomagnetic database (Fig. 1, Supplementary Data Table 1) and compare statistics of its polarity ratio series to an updated Phanerozoic data set. Proterozoic volcano-sedimentary successions with complete preservation of primary magnetic remanence are rare. Possible superchrons identified by magnetostratigraphy of such successions include: ca. 1000 Ma from Siberia ("Maya N", Pavlov and Gallet, 2010), ca. 1100–1085 Ma from central Laurentia ("Keweenawan N", Davis and Green, 1997), ca. 1460–1430 Ma from western Laurentia ("Middle Belt R", Elston et al., 2002), and ca. 1650–1590 Ma ("Upper McArthur", Idnurm et al., 1995). In addition, Irving et al. (2004) proposed a superchron at ca. 1760–1740 Ma ("Cleaver N") based on uniformity of polarity among magnetic overprints across the Canadian Shield. Gallet et al. (2012) propose that superchrons were more common during the Precambrian than the Phanerozoic based on the few continuous magnetostratigraphic data that indicate abrupt transitions from reversing to non-reversing states. Coe and Glatzmaier (2006) considered some of the proposed Proterozoic superchrons as evidence for more abundant superchron occurrence in early Earth history, but such an assertion lacks statistical rigor.

We aim to test these hypotheses with a global compilation of Proterozoic polarity ratios. We employ a polarity bias approach, assessing the entire global paleomagnetic database for abundances of one polarity over another, at the site-mean level. Our approach, broadly similar to that employed by previous analyses of Phanerozoic data (McElhinny, 1971; Irving and Pullaiah, 1976; Johnson et al., 1995; Algeo, 1996) and longer periods of Earth history (Irving et al., 1976; Roberts and Piper, 1989), is advantageous in allowing continuous future refinement because many high-quality paleomagnetic data derive from non-stratified rocks

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such as mafic dyke swarms (Buchan, 2013). The disadvantage of our approach is that it cannot distinguish a truly non-reversing superchron from a prolonged interval of a dominant polarity with ephemeral opposite-polarity states; but even the three Phanerozoic superchrons likely contained brief reversed states (Gradstein et al., 2004).

The second limitation of Proterozoic paleomagnetic poles is their lack of connectivity to Phanerozoic APWPs, commonly disjointed through the problematic Ediacaran Period (Raub et al., 2007; Abrajevitch and Van der Voo, 2010; Halls et al., 2015). Nonetheless, long isolated strands of APWPs are available for some Proterozoic cratons, notably Laurentia (1800–950 Ma), Baltica (1750–900 Ma), and Australia (1800–1550 Ma). Prior to initial amalgamation of those cratons, some of their component cratons are also linked by APWP extension to as old as 1800 Ma (Sarmatia), 1900 Ma (Fennoscandia, Slave), or even 2200 Ma (Superior). Initial polarity analysis of only Laurentian data indicated a strong N-polarity bias at ca. 1000 Ma (Irving et al., 1976), and global analysis under the assumption of a particular supercontinent model showed pronounced N-polarity biases at ca. 1000 and 1700 Ma (Roberts and Piper, 1989). More recently, several plate kinematic models incorporating geological and paleomagnetic data have begun to assemble the Neoproterozoic Rodinia supercontinent (Li et al., 2013) and its Mesoproterozoic predecessor Nuna (Pisarevsky et al., 2014; Pehrsson et al., 2015) to first order. The relative positions of Laurentia, Baltica, Siberia, proto-Australia, and North China are the most consistently placed through the 1800–900 Ma interval, with only minor variations that do not affect interpretation of relative geomagnetic polarity. Principal differences among the most recent models apply to the placement of India, Amazonia, and West Africa, but those differences do not substantially influence our conclusions because reliable data from those blocks are sparse (Fig. 1). In addition to the globally merged relative polarity records, absolute geomagnetic polarity may be assigned according to trade-wind orographic patterns across Slave craton at ca. 1900 Ma and Laurentia at ca. 1100 Ma (Hoffman and Grotzinger, 1993), and consequently, APWP connectivity expands this polarity choice throughout the reconstructed global dataset.

The third limitation of the Proterozoic paleomagnetic database is the relative sparseness of high-quality data ($n_{avg} = 0.12$ poles/Myr), a sampling rate about a factor of eight lower than that of the Phanerozoic dataset ($n_{avg} = 0.92$ poles/Myr). In order to assess the significance of Proterozoic geomagnetic superchrons our analysis is tested with the Phanerozoic dataset compiled from a recent quality-filtered global kinematic analysis (Torsvik et al., 2012), which encompasses two, or perhaps three, superchrons known from seafloor spreading records (e.g. CNS, Lowrie and Kent, 2004) or magnetostratigraphic compilations (e.g. KRS and MRS, Pavlov and Gallet, 2005). Both datasets are subjected to a range of statistical smoothing that seek the “correct” or at least reproducible identification of superchrons.

2. Methods

To provide a standard measure of geomagnetic polarity bias across Proterozoic–Phanerozoic time, we apply bootstrap subsampling to the Phanerozoic global database at a variety of sampling densities n_{samp} (including its full value, a value equivalent to the Proterozoic, and an intermediate value; Table 1). In our analysis, we define a superchron as a continuous period with a smoothed polarity ratio within 20% of normal or reverse polarity for at least 15 Myr. To test sensitivity of time-averaging, we vary the smoothing window interval (τ) from 1 to 25 Myr; with a small τ the method may exclude legitimate superchrons because of full weight applied to short-lived but densely sampled opposite-polarity intervals within extended single-polarity periods, or with a large τ the smoothed polarity ratio curve may exclude legitimate superchrons by averaging results from beyond their temporal limits.

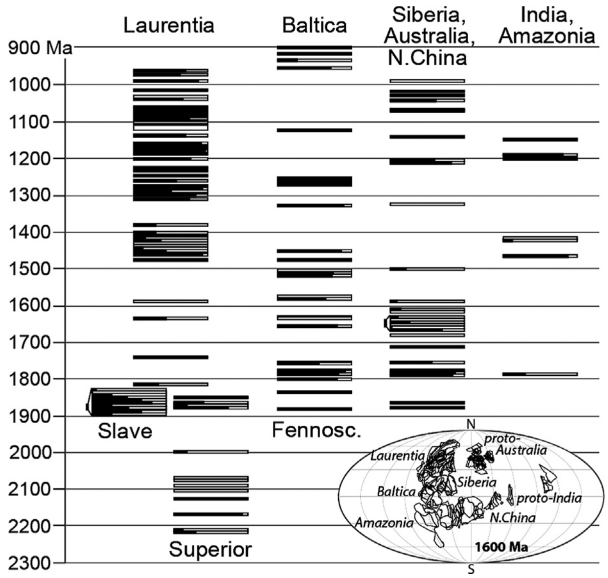

Fig. 1. Proterozoic geomagnetic polarity ratios from a global dataset merged according to the Nuna supercontinent reconstruction shown in the inset. Each bar represents a published paleomagnetic result (or compilation; Supplementary Data Table 1) with proportion of Normal (black) or Reversed (white) data.

Table 1
Summary of polarity ratio data sets where N is total number of polarity ratios in data set, Δt is the time span of the data set, and $n_{ave} = N/\Delta t$ is the sampling density.

Data set	N	Age range (Ma)	Δt (Myr)	n_{ave} (Myr^{-1})
Phanerozoic	505	0–550	550	0.918
Proterozoic	159	900–2219	1319	0.120

We compile paleopole data from the global paleomagnetic database with strict quality criteria so that all the polarity ratio data included have at least 4 site means and age precision within ±15 Myr (a nominal superchron duration). Phanerozoic global paleomagnetic data are taken from Torsvik et al. (2012), and Proterozoic data are largely from Veikkolainen et al. (2014) and updated by the authors. For each pole, assignment of polarity bias on a site-mean level is checked manually for consistency with tectonic reconstructions; numerous discrepancies exist between our globally merged polarity selection and those of individual studies due to arbitrary conventions applied at local scales (e.g., Northern Hemisphere data are generally described as N polarity if remanence directions are downward).

The Phanerozoic polarity ratio sequence contains 505 polarity ratios over 550 Myr, corresponding to a sampling frequency of $n_{ave} = 0.92$ Myr^{-1} (Table 1). Our smoothing analysis broadly replicates that of Algeo (1996) and we employ the same inverse-distance squared smoothing function (see Appendix A). The mean polarity ratio of a frequently reversing dipole should be close to 50%, while superchron periods correlate with extreme values (0–20% or 80–100%). To quantify the statistical significance of a superchron identified in a polarity ratio series we generate an ensemble of polarity ratio sequences from the Phanerozoic and Proterozoic data sets for a chosen sampling density n_{samp}, apply a given smoothing window size τ, and search the smoothed sequence for superchrons using the criteria above. These superchrons are recorded and their statistics tabulated (Tables 2 and 3).

In the Phanerozoic where the ages of superchrons are known this is a test of the method, and an opportunity to distinguish po-