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On the low-inclination bias of the Precambrian geomagnetic field

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ABSTRACT

A long tradition has emerged in applying the inclination frequency analysis to estimate the functionality of the Geocentric Axial Dipole (GAD) hypothesis in paleomagnetism. In the present study, the theory has been tested to the database with 3246 records of the Precambrian geomagnetic field. To find the best-fitting inclination distribution, different combinations of geocentric axial dipolar (GAD), quadrupolar (G2) and octupolar (G3) spherical harmonics have been analyzed. The influence of various factors on the inclination distribution has been studied, including the geologic age, rock type, magnetic polarity, quality of data and their spatiotemporal distribution. By two-dimensional chi-square analysis on crystalline rocks only, which avoid problems associated with remanence shallowing among sedimentary rocks, the most plausible estimates for the zonal non-dipolar contributions of the field have been determined as 2% for G2 and 5% for G3, values much lower than in previous estimates using the same method. However, the inherent non-uniqueness of the inclination frequency analysis and the uneven spatiotemporal sampling of the field around the globe during the Precambrian necessitate other independent methods of testing the GAD hypothesis.

1. Introduction

The introduction of the GAD hypothesis has been mainstream in paleomagnetism since its very beginning. Its validity in various geological timescales has been tested e.g. using sedimentary paleoclimatic indicators of latitude (Evans, 2006), virtual axial dipole moment (Donadini et al., 2007), scatter of virtual geomagnetic poles (VGPs) as a function of paleolatitude (Biggin et al., 2008; Smirnov et al., 2011) or reversal asymmetries (Nevanlinna and Pesonen, 1983). One of the most commonly employed tests is the global inclination frequency analysis (e.g. Evans, 1976), which is based on the fact that the average geomagnetic field can be described as a combination of zonal harmonic terms and each set of them generates a distinct inclination frequency distribution, where the absolute value of inclination ($|I|$) is shown as a function of its proportion. This method is advantageous since it uses a simple measurable property (inclination) of the geomagnetic field and can be extended to the Precambrian eon. To create a discrete distribution of $|I|$, the real or synthetic dataset must be classified into intervals. The choice is arbitrary, but 10-degree intervals have been generally used (e.g. Kent and Smethurst, 1998). Distributions for pure axial dipole (g_1^0), quadrupole dipole (g_2^0) and octupole (g_3^0) are based on Eq. (1) and shown in Fig. 1. In the equation, P_n stands for the Legendre polynomial of the n:th spherical harmonic degree and θ for paleocolatitude of the sampling site (Merrill et al., 1998).

$$\tan I = \frac{P_n(1+n)}{\partial P_n/\partial\theta} \quad (1)$$

In this analysis, the sign of inclination is not taken into account, since the sign of paleolatitudes (90°-θ) cannot be properly determined for Precambrian data due to insufficient knowledge of continental or cratonic motions. Theoretical curves of $|I|$ have a peak at mid- to high inclinations ($60^\circ \le |I| \le 70^\circ$) because the field equations for g_1^0, g_2^0 and g_3^0 are nonlinear, as are the areas between various latitude circles. For example, in the case of a pure GAD field, if a statistically significant amount of inclination data have been gathered from random locations, ca. 8.8% of those should fall into the interval $0^\circ \le |I| < 10^\circ$, but only 5.7% into the interval $80^\circ \le |I| \le 90^\circ$. A more detailed view of the geomagnetic field requires that superpositions, i.e. combinations of axial dipolar, quadrupolar and octupolar fields of different strengths, are considered. Distributions caused by higher multipoles, such as g_4^0, however, cannot be applied to studies of the Precambrian in a meaningful way, as the spatiotemporal limitations of the data available do not allow a detailed spherical harmonic analysis to be done.

The effect of a small quadrupole on the inclination frequency distribution is considered minor (Fig. 2). However, the contribution of g_2^0 to the inclination observed at a given paleolatitude is

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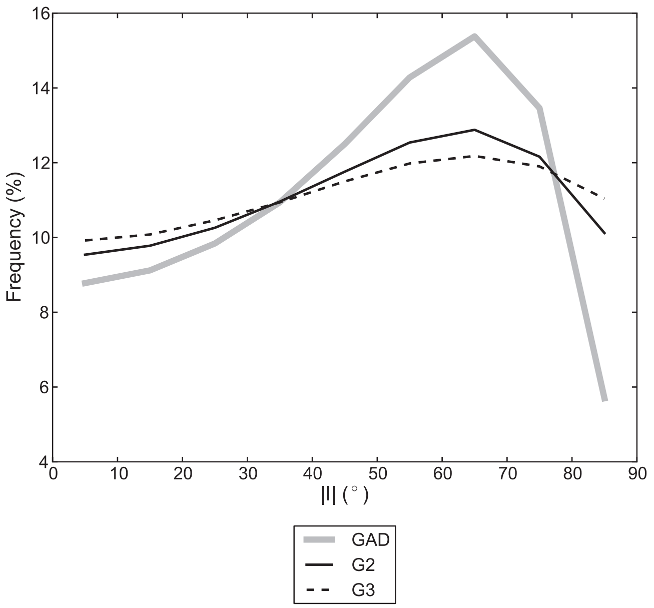

Fig. 1. Inclination distributions for pure dipolar, quadrupolar and octupolar fields. Frequencies within the 10-degree bins according to Evans (1976).

much more significant and similar on both hemispheres due to the symmetry of g_2^0 about the equator, leading to negative inclination anomalies if g_1^0 and g_2^0 are parallel, or to positive anomalies if they are antiparallel. Small octupolar fields, on the other hand, do not strongly alter local paleolatitudes, but do have a noticeable effect on the inclination frequency distribution. Practically the presence of a slight axial geocentric octupole of the same sign as the dipole (and presumed to reverse polarity coincident with the dipole) means that inclinations obtained from mid-latitude observations are systematically too shallow. On the contrary, the presence of a small octupole with a sign opposite to that of GAD (reversing along with the dipole always to maintain its opposite sign) steepens

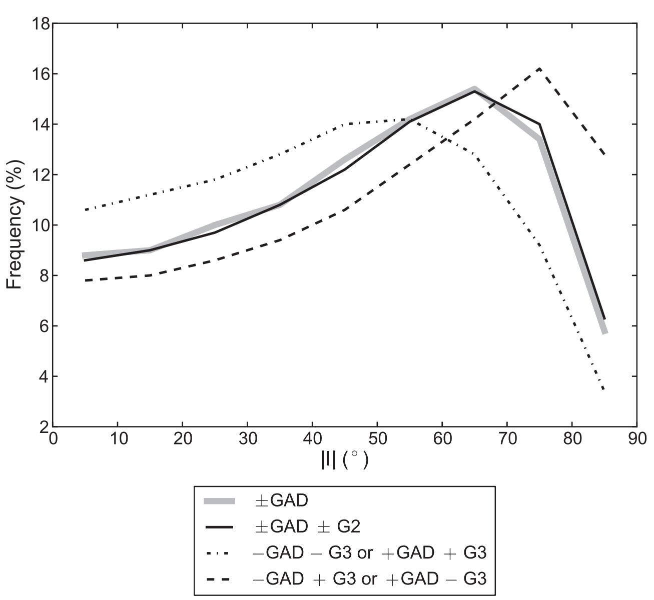

Fig. 2. Inclination distributions for pure GAD (±30,000 nT), and multipole models, where G2 and |G3 are 10% of the strength of GAD. Solid black line: negative or positive GAD with a negative or positive quadrupole. Dot-dashed black line: negative GAD with a negative octupole, or positive GAD with a positive octupole (g_3^0 parallel with g_1^0). Dashed black line: Negative GAD with a positive octupole, or positive GAD with a negative octupole (g_3^0 antiparallel with g_1^0).

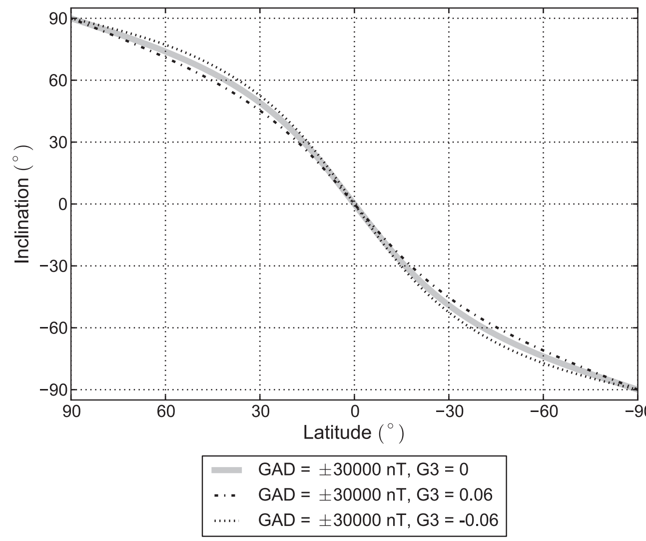

Fig. 3. Inclination vs paleolatitude for a permanent 6% octupole field model. Dot-dashed line describes the situation where g_1^0 and g_3^0 are of the same sign and dotted line describes the situation where they are of the opposite sign.

inclinations from those resulting from pure GAD, as demonstrated by Fig. 3. A combination of permanent (standing) quadrupolar and octupolar components (or alternatively modelled as an axial, eccentric, non-reversing subsidiary dipole) was used by Nevanlinna and Pesonen (1983) to explain the steepened R and shallowed N directions observed in the Late Mesoproterozoic Keweenawan rocks. The present study, however, follows earlier database-wide inclination frequency analyses in considering only axial and geocentric field harmonics, with "odd" terms such as the octupole reversing so as to maintain a consistent polarity relationship to the dominant dipole component.

In the inclination frequency method, geomagnetic declinations are neglected, since by definition, the model uses zonal harmonics only, and these are not influenced by the geographic longitude. Even if there were non-zonal harmonics too, declination is very poorly constrained in the vicinity of geomagnetic poles and values of *D* from different paleolatitudes should first be reduced to a single latitude to be useful in statistical calculations. The rejection of declination means that the method cannot distinguish between different types of dipolar fields. For example, inclination distributions resulting from a GAD field and a tilted, or equatorial geocentric dipole field are equal. This demonstrates the fact that as long as the field is sampled spatiotemporally adequately enough, the inclination distribution remains unchanged even if the field is being rotated. Therefore other methods, such as paleosecular variation studies (Tauxe and Kodama, 2009; Smirnov et al., 2011) and asymmetries in dual-polarity paleomagnetic results (Khramov and Iosifidi, 2012; Veikkolainen et al., 2013a) must be used to determine possible equatorial dipoles and other non-zonal features of the field.

For most purposes, it is useful not to express the absolute strengths of spherical harmonic terms, but to normalize them with the GAD component (g_1^0). In the case of zonal fields only, these are denoted using capital letters and numbers, such as G2 for g_2^0/g_1^0 and G3 for g_3^0/g_1^0. For example, Kent and Smethurst (1998) modelled the mean geomagnetic field of Paleozoic (250–542 Ma) and Precambrian (>542 Ma) together using terms G2 = 0.10 and G3 = 0.25. This cannot be considered to be just a minor adjustment to the GAD hypothesis. It would require a significant change in the magnetohydrodynamic conditions to have taken place, since an analysis of rocks from the past 210 Ma suggests G3 to be not more than 3 ± 8% (Courtillot and Besse, 2004). A study on the