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Modelling the geomagnetic field from syntheses of paleomagnetic data

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ABSTRACT

This review examines results from time-varying geomagnetic field models that span several thousand years, and from variations in dipole moment strength up to million year time scales. For the past 400 years, twin magnetic flux lobes bordering the inner core tangent cylinder in both northern and southern hemispheres dominate the geomagnetic field and appear more or less fixed in location. In contrast, the millennial scale view shows that such features are quite mobile and subject to morphological changes on time scales of a few centuries to a thousand years, possibly reflecting large scale reorganization of core flow. The lobes rarely venture into the Pacific hemisphere, and average fields over various time scales generally reveal two or three sets of lobes, of diminished amplitude. Thus millennial scale models are suggestive of thermal core-mantle coupling generating a weak bias in the average field rather than a strong inhibition of large scale field changes. The recovery of variations in dipole moment on million year time scales allows frequency domain analyses to search for characteristic time scales for core dynamics that might be associated with excursion and reversal rate, time taken for reversals, or any signs of control by Earth's orbital parameters. The spectrum is characteristically red for the time interval 0–160 Ma, suggesting non-stationarity associated with average reversal rate changes, probably reflecting the impact of superchrons and a continually evolving core. Distinct regimes of power law decay with frequency may reflect different physical processes contributing to the secular variation. Evidence for non-stationarity at shorter time-scales is also present in dipole moment variations over 0–2 Ma with average growth rate faster than the decay process. Rates of change of dipole moment and rapid local field variations found in the paleomagnetic record are evaluated in the context of the 400 year historical record and the spectrum of geomagnetic variations for 0–160 Ma.

1. Introduction

Direct magnetic field observations have been made frequently and on a large scale, using a wide variety of instruments ranging from the first compasses used in ancient China (Kono, 2007) to modern scalar and vector magnetometers (Turner et al., 2007). The now classic *GUFM1* time-varying spherical harmonic model of geomagnetic field variations by Jackson et al. (2000) is based on 400 years of direct observations and has fueled numerous studies of short term core dynamics. Finlay et al. (2010) provide a recent review of both theoretical and observational analyses, but similar efforts for longer time scales have been hampered by the limited number and quality of paleomagnetic data. However, numerous paleomagnetic data have been gathered into compilations over the past decade and the resulting data sets allow the extension of global views of the geomagnetic field to earlier times. The most recent of these (Genevey et al., 2008; Donadini et al., 2009, 2010) have been used to produce greatly improved large scale spherical harmonic models reaching back several millennia in a series of time varying models under the generic names *CALSxk* with *xk* representing various time spans in thousands of years and ranging from 3 to 10 ky. Similar efforts for longer term data (Tauxe and Yamazaki, 2007; Biggin et al., 2009; Johnson et al., 2008) have enabled extended modeling efforts, including the reconstruction of time series of dipole moment variations for the past few million years (Ziegler et al., 2011; Valet et al., 2005; Channell et al., 2009). Naturally these models are less reliable than those based on numerous high quality direct observations and we should approach them with suitable caution, but they do allow us to identify some longer term characteristics of geomagnetic secular variations and start to investigate the underlying physical processes.

1.1. A few interesting questions

In what follows syntheses of paleomagnetic observations and the resulting models are used to review a number of interesting long-standing questions about the paleomagnetic field. Does the long-term structure of the geomagnetic field reflect persistent thermal heterogeneity in core-mantle-boundary conditions? Is the field locked to thermal anomalies or do such anomalies impart

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preferential structure to the long term average? Is there a long term hemispherical asymmetry in rates of change for the magnetic field? How rapidly does the field change? How high can the field go, and how long can high values be sustained? Does the field increase at the same rate as it decreases?

1.2. The road map

The structure of this review is as follows. Section 2 provides a summary of our current view of the geomagnetic field inferred from direct observations over the past 400 years. We then move on to millennial time scales, outlining some of the strengths and weaknesses of recently constructed time-varying geomagnetic field models, and comparing them to the historical record. Section 4 discusses the status of million year field models and our knowledge of dipole moment variations for the 0–2 Ma time interval. Sections 5 and 6 deal with the frequency spectrum of geomagnetic variations and rates of change of the field, respectively. The article closes with a brief summary and some consideration of the outlook for the future.

2. The historical period

Geomagnetic data can be observations of scalar field strength, declination, inclination, or full vector (see Fig. 1) along with a record of time and place. The combined set of historical observations since the early sixteenth century (Jonkers et al., 2003) and other more recent efforts (see Hulot et al. (2010) for a review) range from surveys which include modern satellites (since about 1960), maritime, airborne, and land expeditions, through numerous data recorded in ship logs during voyages for discovery and trade, to static observatory measurements and occasional observations. They sample a broad range of locations and times, with greatly improving spatial coverage for more recent times, and provide our most detailed view of the geomagnetic field. Over the past few hundred years these observations have shaped the geomagnetic community's evolving views of secular variation and the physical processes that generate it.

Thorough analyses of direct field observations spanning the past 400 years are now encapsulated in the *GUFM1* time-varying spherical harmonic field model (Jackson et al., 2000), that covers the period 1590–1990 AD. Detailed discussion of the historical field evolution can be found in Jackson and Finlay (2007). At Earth's surface two important features of the secular variation are manifest in the form of westward drift, and decay of the axial dipole of around 5% per century since the first direct measurements of

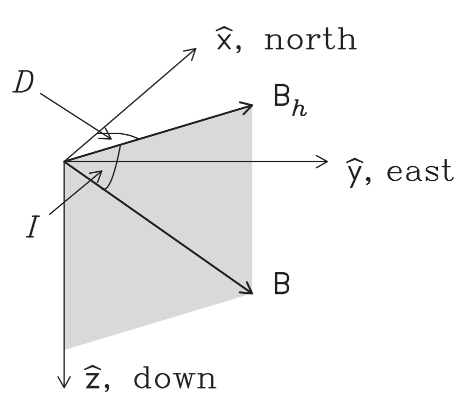

Fig. 1. Commonly measured geomagnetic elements are orthogonal components of local magnetic field vector B, its projection onto the local horizontal plane B_h, D angular deviation in horizontal plane from true north, and I dip of field vector, measured positive down from horizontal plane.

intensity in the mid-19th century. A third notable aspect is the hemispherical asymmetry between Pacific and Atlantic hemispheres, with most of the westward drift concentrated in the Atlantic hemisphere (90 °E–90 °W). The signature of these variations is seen in Fig. 2, a map of geomagnetic field strength and its rate of change at Earth's surface based on the Oersted secular variation model for the year 2000 (Olsen, 2002). The instantaneous picture provided by Fig. 2 is complemented by Fig. 3 which shows time averages for the field strength over three successively longer time intervals. The 400 year average for *GUFM1* is broadly similar to that for 2000 AD, albeit with less small scale structure as a result of temporal averaging and more limited data.

A closer view of the core field is provided by downward continuation of the surface field to the core-mantle boundary (CMB). B_r, the radial component of magnetic field, shows twin lobes of magnetic flux paired at high northern and southern latitudes bordering the cylinder tangent to Earth's inner core (Fig. 4). These have been associated by Gubbins and Bloxham (1987) with the geodynamo driving columnar convection in the core (Busse, 1975). Their persistence for several hundred years in essentially the same locations (beneath N. America and Siberia in the Northern Hemisphere) has been considered indicative of thermal coupling between the core and mantle, probably reflecting geographically variable heat flux at the CMB (Bloxham and Gubbins, 1987). Similar features have been replicated in a number of numerical geodynamo simulations with inhomogeneous boundary conditions (Bloxham, 2002; Olson and Christensen, 2002; Davies et al., 2008).

Westward drift at the CMB is pronounced at low latitudes where it appears to be associated with wave-like features (Bloxham et al., 1989) that are readily detectable in time-longitude plots after removing stationary parts of the field (Finlay and Jackson, 2003). At the CMB there are also a number of reverse flux features: particular interest is aroused by (1) a patch inside the tangent cylinder near the geographic north pole, away from the regime of columnar convection, and (2) the largest reverse flux feature, that has been associated with rapid decay of field strength in the Southern Atlantic Region. The westward drift and growth of this so-called S. Atlantic anomaly is the major contribution to the axial dipole decay since 1840 AD. Gubbins et al. (2006) have shown that the decay is disproportionately linked to changes in the southern hemisphere and suggested that the rate of decay and hemispheric asymmetry may be less pronounced or absent prior to 1840 AD. The South Atlantic is the subject of current regional studies and modelling particularly through repeat station surveys in South Africa (Geese et al., 2010).

3. Millennial time scales

Most of our knowledge of the geomagnetic field prior to 1600 AD comes from indirect observations supplied by archeomagnetic and paleomagnetic observations on man-made fired artifacts (pottery, bricks, hearths, metallurgic slag, etc.), rapidly cooled lava flows, and sedimentary material. The former acquire a thermoremanent magnetization on cooling and are (in principle) capable of providing a record of both direction and strength of the magnetizing field, while the latter rely on the deposition of already magnetized material recording direction and relative variations in magnetic field strength. Constable (2007) describes the use of a broad variety of such materials in building millennial-scale time-varying spherical harmonic models of the geomagnetic field.

The modelling strategy for thousand year time scales is similar to that used in constructing *GUFM1* (Korte and Constable, 2003). The magnetic field is represented by the spherical harmonic expansion of a scalar potential with temporal parametrization in cubic B-splines. A quadratic norm is used for regularization of the model in