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Testing the geocentric axial dipole hypothesis using regional paleomagnetic intensity records from 0 to 300 ka

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ABSTRACT

Absolute and relative geomagnetic paleointensity records reveal variations in geomagnetic dipole strength, either via averaging time series of virtual axial dipole moments, or through formal inversion strategies like the penalized maximum likelihood (PML) method used for the PADM2M (Paleomagnetic Axial Dipole Moment for 0–2 Ma) model. However, departures from the most basic geocentric axial dipole (GAD) structure are obvious on centennial to millennial time scales, and paleomagnetic records from igneous rocks suggest small deviations persist on million year time scales. Spatial variations in heat flow at the core–mantle boundary (inferred from large low shear velocity provinces, LLSVPs) are widely suspected to influence both the average geomagnetic field and its regional secular variation. Long term departures from a GAD configuration should be visible from regional differences in paleointensity reconstructions. We use a PML method to construct time-varying models of regional axial dipole moment (RADMs) from a combined set of absolute and relative paleointensity data, and compare results from the last 300 kyr. RADMs are created from sediment records selected from specific latitude and longitude bands. We also test whether grouping records lying above each of the 2 major LLSVPs (centered on Africa and the Pacific) produce RADMs that are distinct from those above regions lacking anomalous seismic structure. Systematic differences appear in the various regional results. In the most recent part of the record regional differences are broadly similar to the Holocene, CALS10k.1b, time-varying geomagnetic field model spanning 0–10 ka. However, lack of Southern hemisphere records prevents direct confirmation of the hemispheric asymmetry present in CALS10k.1b in both average virtual axial dipole moment and its variability. As expected, the 300 kyr RADMs exhibit greater overall temporal field variability than is seen over 0–10 ka. Average RADM is higher in the Pacific and in Equatorial regions than in the Atlantic and in mid–high latitude northern hemisphere regions. Higher average RADMs are associated with lower overall field variability and less pronounced excursional signatures. Notably, the lower variability in the Pacific sector seen here (defined by either longitude band or LLSVP location) suggests that the modern low paleosecular variation there extends over at least the past few hundred thousand years. RADMs identified with LLSVPs show systematic deviations from the non-LLSVP group of records, with distinct characteristics for the African and Pacific provinces. The African LLSVP generates more pronounced RADM minima associated with geomagnetic excursions, and in general paleointensity decreases associated with excursions occur first in the Atlantic longitude sector and over the African LLSVP.

1. Introduction

Earth's magnetic field is on average dominated by an axial dipole field structure, with field magnitude and direction varying systematically with latitude. Field lines trace a path outward from one pole and inward at the other, with intensity at the poles double that at the equator. This fundamental pattern, along with observations of secular variation and occasional global polarity reversals, provides a basic description of the average field produced in Earth's iron core, and is a property expected of every Earth-like dynamo simulation (e.g., Kono and Roberts, 2002).

In the modern field, the geocentric axial dipole (GAD) component (g_1^0) at Earth's surface is almost six times the size of the next largest component (Finlay et al., 2010). Departures from the simple, global picture of an axial dipole field can be described

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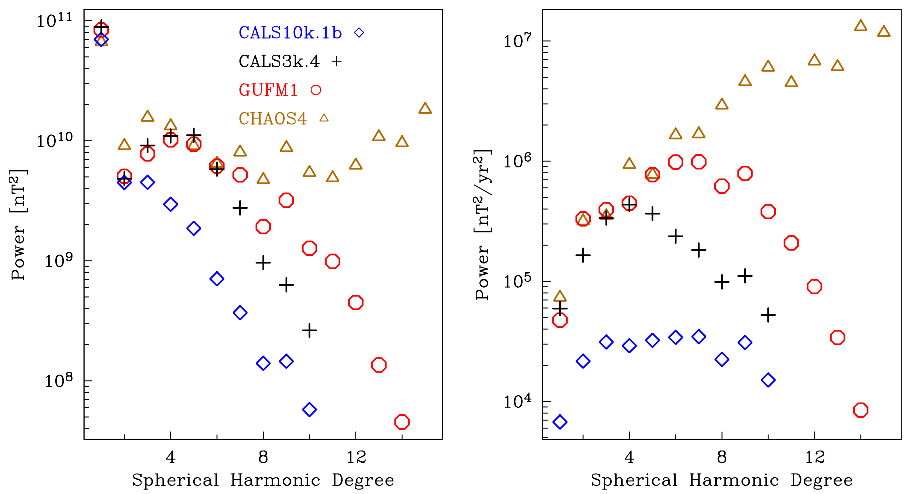

Fig. 1. Spatial power spectra for the geomagnetic main field (left) and secular variation (right) models CHAOS4 (Olsen et al., 2014), GUFM1 (Jackson et al., 2000), CALS3k.4 (Korte and Constable, 2011), and CALS10k.1b (Korte et al., 2011).

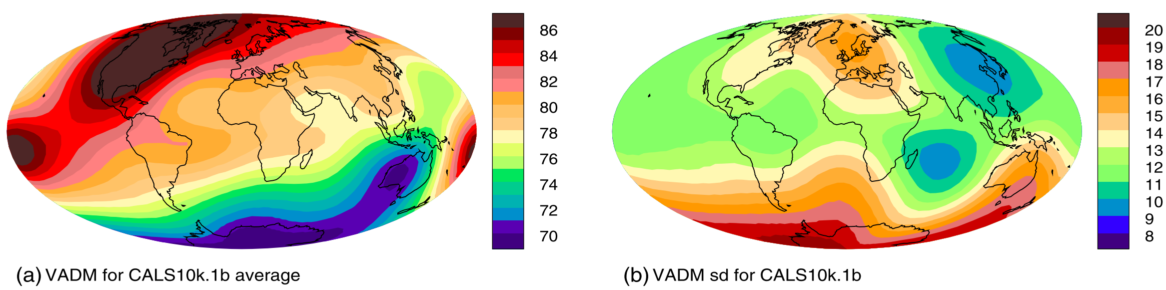

Fig. 2. a) Geographic variability in VADMs (units of $Z\,\mathrm{A\,m}^2$) calculated from the average of the time-varying CALS10k.1b field model (Korte et al., 2011). (b) Standard deviation, σ_T, about the mean (in $Z\,\mathrm{A\,m}^2$) over the 0–10 ka time interval. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mathematically using the usual g_l^m and h_l^m Gauss coefficients of degree l and order m from a spherical harmonic expansion Ψ for the magnetic scalar potential with $\mathbf{B} = -\nabla\Psi$ (e.g., Hulot et al., 2010). The components other than g_1^0 are collectively referred to as the non-axial-dipole (NAD) field, and represent regional departures from an axial dipole field.

NAD field features in general vary more rapidly than the GAD field. In time-varying models of the modern and historical field, NAD field structures are readily observed and mathematically described even at short length scales (e.g., the CHAOS-4 models based on satellite and observatory data include core and terms up to $l = 20$ and secular variation terms up to $l = 16$, and static terms from the lithosphere are considered robust to $l = 85$, Olsen et al., 2014). Data quality and availability from the ancient field limit our ability to describe short wavelength departures from a GAD structure beyond a few hundred years. However, in areas with good data coverage millennial scale models, which now extend to 10 ka (Korte et al., 2011; Nilsson et al., 2014; Panovska et al., 2015), recover NAD field structures with varying reliability up to about degree 4 or 5 (length scales of about 8000 km). Spatial geomagnetic power spectra (Lowes, 1974) for modern and paleomagnetic models are shown in Fig. 1.

Much NAD structure on short time scales is highly variable, reflecting the dynamic non-linear processes that generate the field. However, persistence of, or trends in, NAD features over long time scales in the time-averaged field may reflect fundamental, long-term features of fluid flow in the core, such as effects of the solid inner core on flow (e.g., tangent cylinder effects or gravitational coupling of inner core to mantle Aubert et al., 2013), or geographically variable structure in thermal core–mantle boundary conditions (Gubbins et al., 2007; Aubert et al., 2010).

Departures from a GAD field configuration extend to million year time scales, with time-averaged field models mainly based on paleomagnetic directional data indicating that a GAD field does not fit the data as well as one with some NAD structure (Johnson and Constable, 1997; Gubbins and Kelly, 1993). Aubert et al. (2010) in particular noted longitudinal structure in their model of the Brunhes Chron (0-780 ka) time averaged field, and recent paleomagnetic data collected at high latitudes in both northern (Cromwell et al., 2013) and southern (Lawrence et al., 2009) hemispheres hint at long-term north/south asymmetry in both the average field and its variability. These effects are particularly visible in recent global directional PSV compilations (Cromwell et al., 2012). Archeointensity data spanning the 0–3 ka interval indicate clear regional differences in time variations of the virtual axial dipole moment (Genevey et al., 2008).

In Fig. 2, we show global variations in both average VADM and its standard deviation about the mean for the time-varying field model *CALS10k.1b*, which spans the interval 0–10 ka (Korte et al., 2011). It is notable that the average VADM has significant geographic structure, with high values extending across the Pacific, North America, and towards Eurasia, and lowest values at high southern latitudes extending north towards Australia. The standard deviation map reveals that VADMs are most variable at mid–high southern latitudes and in a swath through the Middle East, Europe and the North Atlantic region. The long-term robustness of such features is of interest. A question that has received considerable attention is whether the relatively high/low levels of secular variation found in the modern field (Jackson et al., 2000) in the Atlantic/Pacific sectors persist over longer time scales.

Persistent NAD structure of the type seen in time-averaged field models should be visible in time-varying field models over tens of