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Persistently Anomalous Pacific Geomagnetic Fields

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Abstract. A new average geomagnetic field model for the past 3kyr (ALS3K) helps bridge a large temporal sampling gap between historical models and more traditional paleomagnetic studies spanning the last 5 Myr. A quasi-static feature seen historically in the central Pacific has the opposite sign in ALS3K; its structure is similar to, but of larger amplitude than, that in the time-averaged geomagnetic field for the last 5 Myr. Anomalous geomagnetic fields exist beneath the Pacific over timescales ranging from 10^2–10^6 years. It is unlikely that bias over such long time scales arises from electromagnetic screening, but conceivable that the Lorentz force is influenced by long wavelength thermal variations and/or localized regions of increased electrical conductivity (associated with compositional anomalies and possibly partial melt). This is consistent with recent seismic observations of the lower mantle.

Introduction

Historical observations of the geomagnetic field have been used to produce time-varying smooth models of the radial geomagnetic field (B_r) at the core-mantle boundary (CMB) spanning the last few centuries [*Bloxham & Jackson*, 1992; hereafter *BJ92*]. For 1840–1980 AD the data coverage is good, with a full vector description of the field. In contrast, paleomagnetic investigations rely primarily on datasets of directions, which are more limited in temporal and spatial resolution. Although the 0–5 Myr time-averaged field has been studied extensively [see *Merrill et al.*, 1996], comparison of the historical record of geomagnetic field behavior with that from paleomagnetism has been hindered by the discrepancy in the timescales under consideration (10^2 versus 10^6 years). A recent compilation of paleomagnetic directions allows the investigation of global field behavior on intermediate timescales. We present a new average field model for 1800 AD–1000 BC, and discuss persistent anomalous field behavior and implications of long-lived lateral heterogeneities in physical properties of the CMB region for the geomagnetic field.

Three Time-Averaged Field Models

The historical field has been discussed extensively elsewhere [*Bloxham et al.*, 1989]—several features in model UFM1 (*BJ92*, Figure 1a) are pertinent here. Four high latitude static lobes of enhanced B_r exhibit minor changes in intensity and position with time, but no consistent drift. Preferential confinement of VGP reversal paths to longitude bands roughly coincident with the static flux lobes has been noted, though this result remains controversial [*Merrill et al.*, 1996]. Other quasi-permanent features of the historical field include regions of low flux near the poles, and a central Pacific flux concentration. There are large reverse flux patches in the Southern Atlantic / Indian Ocean. There is low secular variation and low average non-dipole radial field at the CMB [*Walker & Backus*, 1996] in the Pacific hemisphere, compared with the Atlantic hemisphere.

New time series of archeomagnetic and lake sediment paleomagnetic directions for approximately the last 3 kyr enable us to model the geomagnetic field globally at 100 year intervals ("snapshots") and to compute a time-average for 1800 AD–1000 BC. Details of the archeomagnetic dataset are discussed elsewhere [*Lund & Constable, in prep.*], as is the modeling procedure [*Johnson & Constable*, 1995; *Johnson & Constable*, 1997, hereafter *JC97*]. The spatial data distribution is sparser for the last 3 kyr than for 0–5 Myr, but the data are more internally consistent in terms of temporal sampling. At only 3 sites do the time series span less than 1.5 kyr. Our average field model for the past 3 kyr, designated ALS3K, is shown in Figure 1b.

In Figure 1b increased radial flux is seen at high northern latitude, with suggestions of longitudinal flux concentrations consistent with the locations of the historical field flux lobes. Removal of the axial dipole contribution to the field shows increased flux at the CMB below E. Asia, with a lower amplitude signal at the CMB below N. America. In models for 100 yr intervals these flux concentrations change position and intensity, but rarely venture into the Pacific hemisphere. The largest persistent deviation from an axial-dipole field geometry in the Pacific region is a northward deflection of the magnetic equator toward Hawaii, and a southward deflection toward Australia. The quasi-static anomaly beneath the Pacific seen in the historical model has undergone sign and intensity changes during the past 3 kyr, probably related to normal secular variation.

Figure 1c shows our smooth normal polarity time-averaged field (TAF) model for the time interval 0-5 Ma, designated LSN1, and constructed using the same methods as ALS3K [*JC97*]. Here we focus on structure observed in the normal polarity field model; differences between the normal and reverse polarity field models are smaller than the model uncertainties.

The largest non-zonal feature in LSN1 occurs in the central Pacific (Figure 1c). The northward deflection of the magnetic equator toward Hawaii is similar to that in ALS3K, and is controlled primarily by inclination measurements from Hawaiian lava flows but also by inclination mea-

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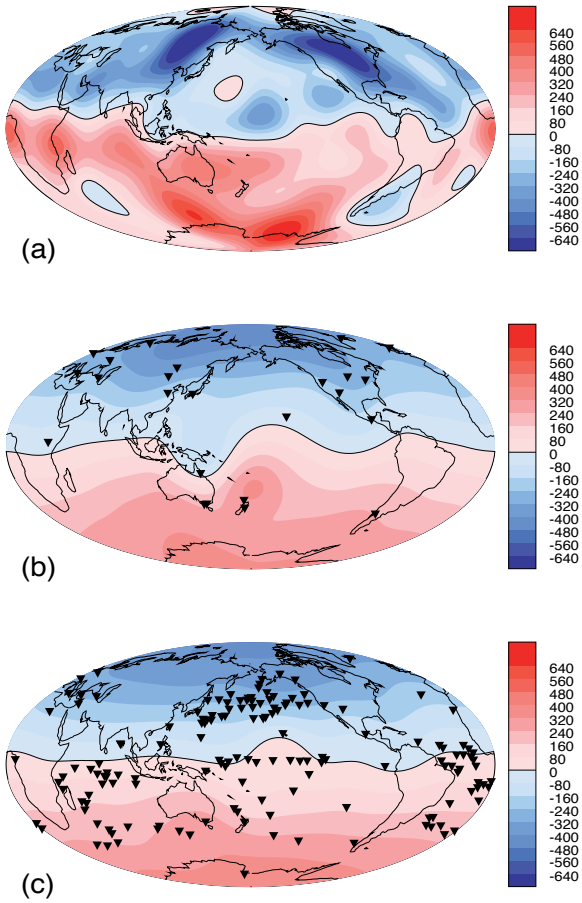

Figure 1. Radial magnetic field in mT at the CMB obtained from smooth inversions of geomagnetic data averaged over three time intervals. (a) Historical field model UFM1 (1840 AD–1980 AD), from a fully time-dependent inversion of field direction and intensity measurements [*BJ92*]. Data coverage is global. (b) 1800 AD–1000 BC field model from archeomagnetic and lake sediment paleomagnetic directions. Triangles give data locations. Variance reduction relative to a geocentric axial dipole model (GAD) is 80%. (c) 0–5 Myr normal polarity field model based on paleomagnetic directions from lava flows and deep-sea sediment cores. Variance reduction relative to a GAD is 40%.

surements from equatorial deep sea sediment cores and flow sites near the Pacific rim. Several lines of evidence indicate the feature is robust. First, if the feature results from crustal magnetic anomalies it reflects a large induced signal rather than remanent magnetization, since the sign of the inclination anomaly (inclination minus axial-dipole-predicted inclination) in the data reverses with field polarity. Second, the large inclination anomaly at Hawaii is unlikely to be caused by local tectonic effects (rotations) or serial correlation due to inadequate temporal sampling (*McElhinny et al.*, 1996; *JC97*) because the contributing data come from several islands. Third, larger spatial and temporal scale tectonic effects are negligible since plate motion corrections do not affect the resulting models.

Northern hemisphere flux lobes are not seen in LSN1; their presence cannot be ruled out however, since they are unlikely to be detected with the current spatial data distribution and associated uncertainties (see below).

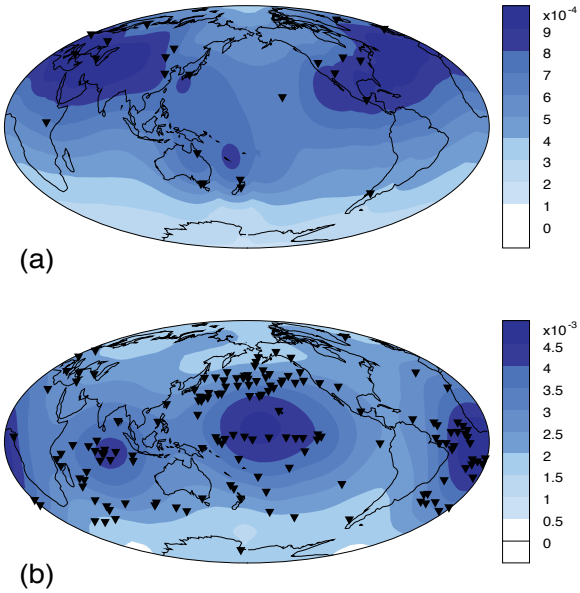

Figure 2. Sampling of the radial field at the core-mantle boundary (see text) for our two datasets (a) 1800 AD - 1000 BC and (b) 0–5 Myr. Deeper colours represent regions of maximal sampling. Data sites given by triangles. Although our data distribution is limited spatially the sampling kernels smooth out sampling of the CMB. The different data distributions for the two time periods result in quite different relative sampling of the CMB region.

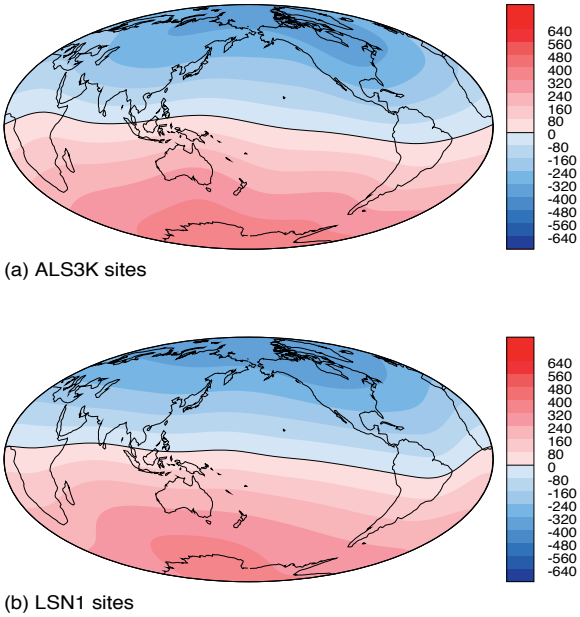

Figure 3. Inversions of synthetic data generated at (a) ALS3K sites, (b) L SN1 sites. D, I (flows) and I only (sediments) were predicted from UFM1, noise added (2° mean for 0-3kyr data, 5° mean for 0-5Ma data) and the synthetic data inverted. RMS misfit of model to synthetic data (a) and (b) is the same as that for our field models ALS3K and LSN1 respectively.

CMB Sampling and Time-Averaging

The limited data sets for ALS3K and LSN1 do not sample the CMB in a uniform manner. *JC97* defined a sampling function, by summing the magnitudes of the kernels relating changes in D and I to changes in B_r at the CMB for all

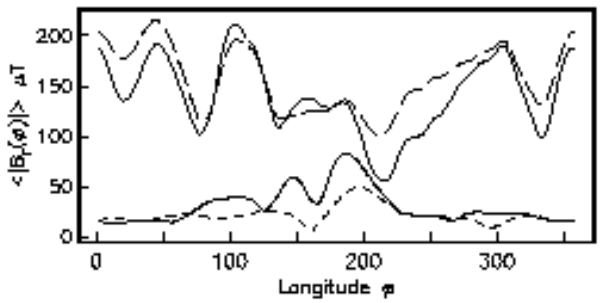

Figure 4. Average value of absolute NAD radial field at the CMB, $< |B_r| >$, as a function of longitude, ϕ. The average is computed over the band 60°N–60°S (as the high latitude resolution of the paleofield models is poor) for models LSN1 (dashed), ALS3K (dotted), UFM1 (solid). $< |B_r| >$ for UF M1 averaged over all latitudes is also shown (long dashed line). Restricting the latitude range makes little difference to $< |B_r| >$ for UFM1, except in the eastern Pacific where it highlights the low amplitude near-equatorial field.

available sites. The CMB sampling maps for ALS3K and LSN1 (Figure 2) are critical to comparisons of the paleo and historical fields.

For ALS3K, maximum sampling of the CMB occurs at mid northern latitudes (Figure 2a). On the basis of the sampling map alone, detection of northern hemisphere flux lobes should be possible; however, detection of the low flux polar region and the reverse flux patches in the southern Atlantic / Indian Oceans observed in *BJ92* seems unlikely. For LSN1, sampling of the CMB is best in the central Pacific, and central-southern Atlantic / Indian oceans (Figure 2b), due to the large number of inclination-only measurements from low-mid latitude deep-sea sediment cores. Detection of N. hemisphere flux lobes is difficult but possible with such a data distribution; however very high northern latitudes, and high southern latitudes are poorly sampled.

The maps of Figure 2 show only the effect of data distribution, not data uncertainties. We investigated how well our paleo data distributions and uncertainties allow us to recover model UFM1. Inversions of synthetic data plus noise, generated from UFM1 at our ALS3K and LSN1 data sites are shown in Figures 3a and 3b respectively. The figures show the reduced power in the non-axial-dipole terms in the paleo fields relative to the historical field; an effect noted previously (*Johnson & Constable*, 1995) and due to time-averaging, the reduced spatial distribution and noise. The data distributions and uncertainties for both 0–3 kyr and 0–5 Ma do not permit us to resolve the low flux near the poles nor most of the southern hemisphere structure present in UFM1. The N. hemisphere lobes and one S. Hemisphere lobe of UFM1 are now represented by broader regions of flux concentration in Figure 3a; further smoothing is evident in Figure 3b. Thus the lack of structure in our models ALS3K and LSN1 in general reflects temporal averaging and secular variation. However, if our data uncertainties (especially for LSN1) also reflect poor quality or inconsistent data, then features such as the high latitude flux lobes in UFM1, which might persist over longer time scales, would not be detected by our current data set. New high quality high latitude paleomagnetic data can resolve this issue.

Discussion

Figure 1 shows that the non-axial-dipole (NAD) structure of the field changes dramatically as the temporal averaging is increased from 140 years to 5 Myr. We have quantified this by computing the average absolute value of the NAD field as a function of longitude for UFM1, ALS3K and LSN1 (Figure 4). In UFM1 the NAD field is highly variable, but on average lower and less variable in the Pacific, than elsewhere. Over time scales of 3 kyr and especially 5 Myr, the NAD field is averaged out everywhere except the Pacific. In the historical field the Pacific has low secular variation and low NAD field. However, over timescales of $10^3 - 10^6$ years the Pacific appears anomalous in having large average NAD contributions to the field, presumably because the high amplitude longitudinal variations in the historical NAD field have short time constants. Apparently there is large variance in the Atlantic hemisphere, but persistent bias in the Pacific hemisphere. This is not incompatible with previous paleomagnetic studies using VGP dispersion (*e.g.*, *McElhinny et al.*, 1996); however direct comparisons are hindered by differences in the sampling kernels for directions and VGPs: VGP kernels have too large a footprint to resolve our result.

These observations and inferences of field behavior may reflect the influence of long-term lateral variations in the physical properties of lower mantle near the CMB. Lateral thermal or electrical conductivity variations in the lower mantle might affect the geomagnetic field observed at the surface either indirectly (by affecting flow patterns in the outer core via the Lorentz force) or directly (*e.g.*, screening of field variations).

Screening of field variations by a conductive layer (about $10^3 Sm^{-1}$) at the base of the mantle has been argued to explain low historical secular variation in the Pacific [*Runcorn*, 1992]. However, electrical conductivity estimates for the lower mantle are $1 - 10 Sm^{-1}$ [*Petersons & Constable*, 1996; *Shankland et al.*, 1993]; neither lateral temperature variations, nor compositional heterogeneities of lower mantle materials are likely to produce the large electrical conductivity variations required for screening of even the historical field.

Field attenuation over hundreds to thousands of years requires lower mantle electrical conductivities approaching core conductivities in a thick layer. Whilst mechanisms for enhancement of lower mantle electrical conductivity have been proposed [*Knittle & Jeanloz*, 1991], they are extremely controversial [*Poirier & le Mouël*, 1992], and unlikely to result in a stable highly conductive layer. We therefore rule out electromagnetic screening as a viable process for the longer time scales.

We turn instead to indirect effects of lateral heterogeneities in the CMB region on the observed geomagnetic field. Although electromagnetic coupling due to a variable highly conductive layer has been suggested to account for confined VGP paths during reversals [*e.g.*, *Runcorn*, 1992], such mechanisms are subject to the criticisms mentioned above. Lateral variations in temperature at the CMB have been invoked to explain aspects of the historical geomagnetic field [*Bloxham et al.*, 1989]. The effects of lateral variations in heat flux at the CMB on the geodynamo have been modeled, though such models are still some way from representing the real earth [*e.g.*, *Olson & Glatzmaier*, 1996]. Results from global and regional seismology indicate long wavelength lateral variations in seismic velocities in the lower

mantle, generally thought to reflect long wavelength temperature variations. Recent work based on long period travel time residuals [*Bolton & Masters*, 1996], precursors to P-wave reflections from the CMB [*Mori & Helmberger*, 1995], and diffracted P-waves [*Garnero & Helmberger*, 1996] suggests that locally, particularly in the central Pacific, such temperature variations may be extreme, leading to regions of partial melt [*Williams & Garnero*, 1996] possibly with associated compositional heterogeneities.

Seismology provides a picture of lower mantle structure today; but characteristic timescales for convection in the lower mantle suggest that long wavelength velocity heterogeneities have persisted over similar timescales. Thus the most likely candidate to explain long-lived anomalous NAD fields in the Pacific is modification of core-flow due to lateral variations in temperature in the CMB region of the lower mantle. However, it is clear that significant progress in understanding the non-axial dipole part of the geomagnetic field over timescales of $10^4 - 10^6$ years requires new high quality paleomagnetic and archeomagnetic data.

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