NON-DIPOLE FIELD

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The non-dipole (ND) field is that part of the internal geomagnetic field remaining after the major geocentric dipole contribution has been removed. It is distinct from the non-axial-dipole (NAD) field for which only the component of the geocentric dipole that is parallel to Earth's rotation axis is subtracted. Figure 1(a) shows the strength of the total scalar field at Earth's surface, with the spatial variations dominated by the dipole field, while in 1(b) the dipole contribution has been subtracted to reveal the substantially more complex non-dipole field. Two source regions contribute to the ND field: the dynamo in Earth's core that is also responsible for the dipole part of the geomagnetic field produces the largest part; the other source is Earth's lithosphere (see **crustal magnetic field**). Non-dipole field contributions are significant, but contribute only a small fraction of the average magnetic energy at the surface, as can be seen in Figure 2 (a) which shows $< \vec{B}_l \cdot \vec{B}_l >_{r=a}$, the squared average value of the field strength over the Earth's surface, average radius $r = a$, as a function of spherical harmonic degree, l. This **geomagnetic spatial power spectrum** (q.v.) falls off rapidly with increasing l (decreasing wavelength), up to about degree 12, then flattens out and remains roughly constant out to the shortest resolvable wavelengths. The ND field between degrees 2 and 11 is dominated by sources in Earth's core, while above degree 15 the core contribution is overwhelmed by that from lithospheric magnetic anomalies (see **modeling magnetic anomalies; magnetic anomalies, long wavelength; marine magnetic anomalies**). Between degrees 11 and 15, it is difficult to isolate the primary source, although time variations (Figure 2(b)) in the core part at these spatial scales will be better characterized with new high quality satellite data. Temporal variations in the lithospheric field occur on geological time scales, but direct measurements over the past few centuries will only sense changes in inducing fields. These are very small at time scales of the order of a year or longer.

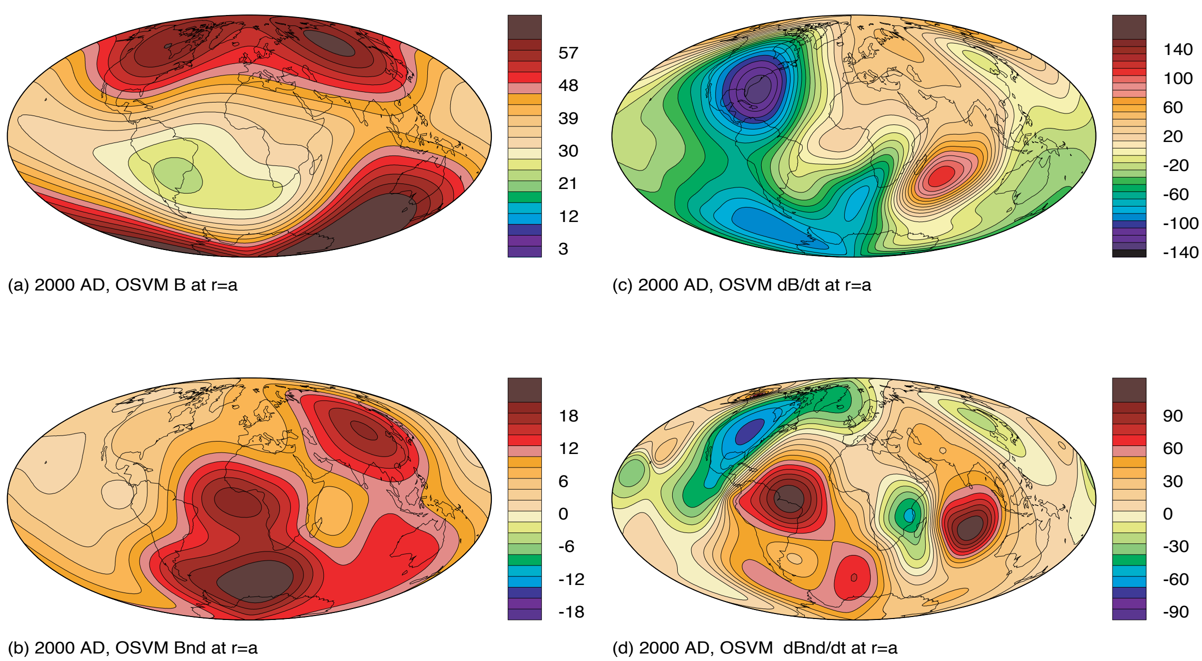

Figure 1: (a) Geomagnetic field strength B in μT and (b) its secular variation dB/dt in nT/yr, evaluated at Earth's surface (r = 6371.2 km) using the geomagnetic field model OSVM for the epoch 2000. Lower panels, (c) and (d) are the non-dipole field strength, B_{nd} in μT, and its rate of change, (nT/yr). Note different scales for each panel.

Inferences about the historical ND field rely on **time-dependent models of the main magnetic field**

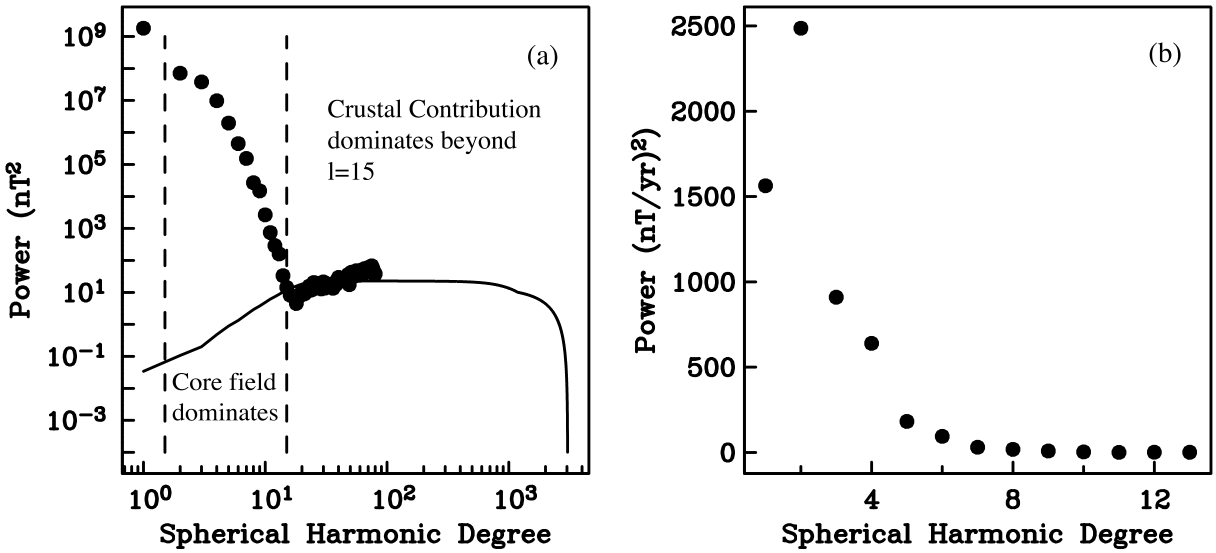

Figure 2: The spatial power spectrum of the geomagnetic field (a) and the spatial power spectrum of the secular variation (b) evaluated at Earth's surface (r = 6371.2 km). In (a) black dots are for a satellite field model for epoch 2000 as a function of degree l, solid line gives the crustal power spectrum derived from **Project Magnet** (q.v.) aeromagnetic data after removal of core field contributions.

(q.v.), extending from 1590 to the present (the GUFM model of Jackson et al., 2000). Recently developed paleofield models (CALS7K.2 (Continuous Archeomagnetic and Lake Sediment for 0-7 ka, version 2) model of Korte and Constable, 2005) extend to millennial time scales and are likely to improve as more data become available. The Oersted Secular Variation Model (OSVM) for epoch 2000.0 of Figure 1 (Olsen, 2002) is based on recent satellite and observatory data with excellent spatial coverage, and has much higher resolution than historical or paleofield models.

For the year 2000, the ND field is lower in the Pacific than the Atlantic/Asian hemisphere (Figure 1(b)). Major ND contributions are in the central and South Atlantic, where the total field seems anomalously low (Figure 1(a)), and beneath Australia and Eastern Asia, where it is on average rather high. The South Atlantic anomaly is of some concern since the relatively low geomagnetic field results in diminished geomagnetic shielding from cosmic radiation, presenting a hazard to low-Earth-orbiting satellites.

Figures 1(c) and (d) show the **geomagnetic secular variation** (q.v.), the rate of change with time, in the total and non-dipole parts of the scalar field for the year 2000. The ND field is increasing in some regions and decreasing in others, with the largest rates of change in the Atlantic/Asian hemisphere. At present the secular variation in the geomagnetic field is predominantly in the ND part of the field. Figure 2 (b) shows the maximum power is at degree 2. In time-varying historical models much of the secular variation is manifest by **westward drift** (q.v.) of features in the ND field, but the westward drift is confined to the Atlantic/Asian hemisphere, with features modified or dying away before reaching the Pacific region. Paleofield records from distant sites are uncorrelated, supporting the view that the longevity of drifting ND features is insufficient to carry them for a full global circuit. For the second half of the twentieth century variations in the ND field are well fit by dynamical models that comprise steady fluid flow in the outer core, and **torsional oscillations** (q.v.): such models predict observed **length of day variations** (q.v., see also Jault, 2003), as well as the sudden changes known as **geomagnetic jerks** (q.v.). Westward drift of features in the ND field is well documented for the Atlantic/Asian hemisphere (Bloxham et al., 1989), but definitive identification of pole-ward propagation in the ND field has proved elusive, perhaps because longer time scales are involved and the quality as well as the temporal and spatial distribution of records deteriorates with increasing age.

The longevity of both static and drifting features in the ND field is poorly documented, but both paleofield records and global models derived from them indicate substantial variations on time scales of hundreds to several thousands of years and probably longer. These variations are large in spatial scale, exhibiting substantial coherence over continental size geographic regions.

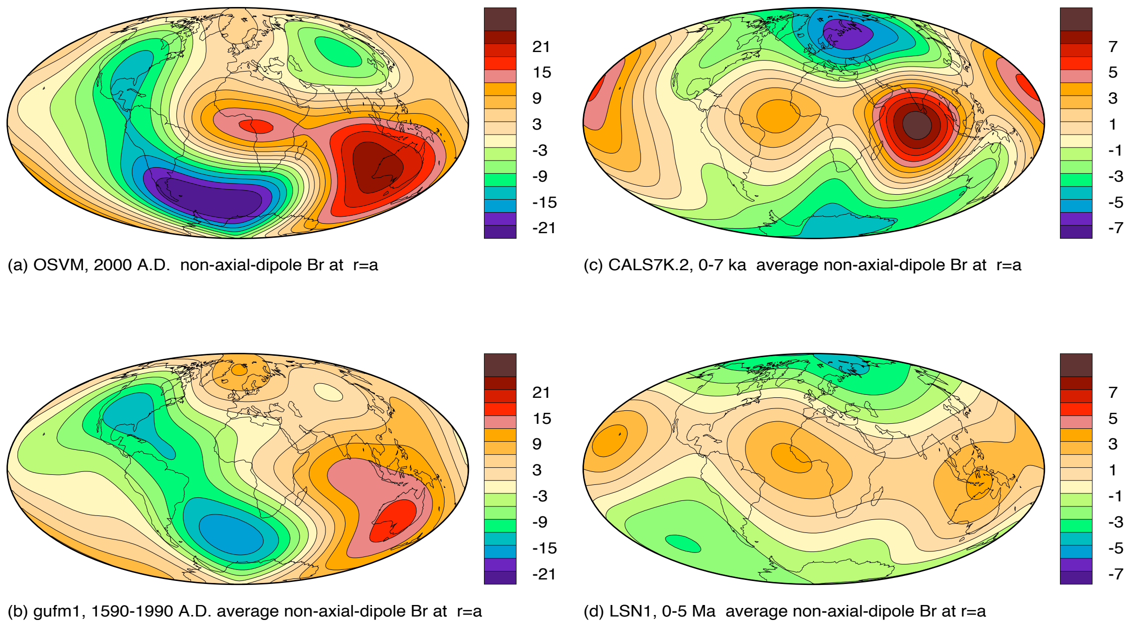

Figure 3: (a) Vertical component of the non-axial dipole filed in μT evaluated at Earth's surface (r = 6371.2 km) using the geomagnetic field models OSVM for 2000A.D., (b) GUFM averaged over 400 years, (c) CALS7K.2 averaged over 7 kyr and (d) LSN1 (Johnson & Constable, 1997), from normal polarity lava and marine sediment directions averaged over 5 Myr. Note scales for (c) and (d) differ by factor of 3 from (a) and (b).

A fundamental tenet of paleomagnetism, embodied in the **geocentric axial dipole hypothesis**, is that when the geomagnetic field is averaged over long time scales, non-axial-dipole contributions can be considered negligible. That this is approximately true can be seen in Figure 3, where the vertical component of the non-axial-dipole (NAD) field is shown for the year 2000 A.D., along with averages for the most recent 400 years, 7 kyr and 5 Myr. The magnitude diminishes with increasing averaging interval, but there remain small (apparently time-varying) non-axial-dipole field contributions on all time scales. The spatial scale of the residual contributions increases with averaging interval, supporting the idea that short wavelength features are associated with shorter time scales. The short term averages in Figure 3(a) and (b) exhibit a number of similarities to one another, which seem quite distinct from the similarities between the longer term averages in (c) and (d).

The similarities in structure for the long term averages are generally positive NAD radial fields at equatorial and low latitudes and generally negative NAD radial fields at high latitude. This overall latitudinal variation in NAD radial field contributes to the persistent "far-sided effect" in **virtual geomagnetic poles** derived from paleomagnetic directional observations and detected in early work that identified small departures from the geocentric axial dipole hypothesis. This reflects a (latitudinally varying) negative deviation of the inclination from that predicted by a geocentric axial dipole field (Merrill *et al.*, 1996). For a several million year average such an effect can be largely explained by a persistent axial magnetic quadrupole with a moment of the order of a few percent of that of the axial dipole. The influence of any axial quadrupole on paleomagnetic directions is largest at the equator, generally visible at low to mid latitudes, and basically so small as to be undetectable at high latitudes. The existence of a small but persistent geocentric axial quadrupole contribution in addition to the axial dipole is the only feature on which all magnetic field models for the interval 0-5 Ma agree: however, the size of the estimated contribution varies by about a factor of three (McElhinny, 2004).

Although it is often supposed that non-zonal (longitudinally varying) contributions to the field will average out on long time-scales, this remains controversial. Small contributions persist in the model in Figure 3(d), and statistical models of **paleosecular variation** for the time interval 0-5 Ma invoke significant variations attributed to non-zonal quadrupolar fields. Some researchers attribute all of the non-zonal structure to poor quality and spatial distribution of the data (McElhinny, 2004). Others (including the author) believe that the persistent quadrupole is over-emphasized in many models because of the poor geographic coverage (see Gubbins,1998, 2003; Gubbins and Gibbons, 2004), and that one might expect hemispheric differences arising from thermal **core-mantle coupling** (q.v.). It is notable that the persistent non-zonal structures in (c) and (d) do have a number of similarities, despite the fact that they are derived from very different kinds of data. It is likely that much of the detail in (c) and (d) will change as new modeling efforts take advantage of improved data sets. It remains unclear whether field behavior in the Pacific hemisphere is persistently different over thousands or millions of years: paleofield models for 0-7 ka indicate substantial secular variation, but they are not yet good enough to allow a definitive determination of whether the ND field is consistently anomalous there. The same holds true for longer time intervals. More effort needs to be invested in discriminating among the various data sets and viable models.

The temporal evolution of the South Atlantic anomaly from the historical to the present field has given rise to speculation that complex field structures in this region may be a sign of impending geomagnetic reversal. The longevity of this feature is unknown, making it an interesting target for future study. There is no evidence that the non-dipole field is substantially increased or diminished during a reversal: most reversal records indicate field strengths around 10-20% of the pre-reversal field at their lowest point. It is possible that the NAD field may differ for successive polarity chrons, but this remains at the limit of current data resolution. The possibility of larger non-dipole field contributions in the ancient past is widely discussed (van der Voo and Torsvik, 2004; Courtillot and Besse, 2004), and for Pre-Cambrian times it cannot be ruled out with currently available data (Dunlop and Yu, 2004).

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Cross references: Crustal magnetic fields, dipole field, geomagnetic spatial spectrum, Pacific low in secular variation, geodynamo, spherical harmonics, paleosecular variation, westward drift, geomagnetic jerks. geocentric axial dipole hypothesis, Project Magnet, virtual geomagnetic poles, torsional oscillations, variations in length of day, core-mantle coupling, thermal.