



RECONSTRUCTING THE GLOBAL GEOMAGNETIC FIELD OF THE HOLOCENE

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Abstract

Archeomagnetic results and high resolution sedimentary records have been used to reconstruct the global geomagnetic field for millennial time-scales. Here I present a series of models named *CALSxk*, Continuous models based on Archeomagnetic and Lake Sediment data of the past x kyrs, and in particular *CALS10k.1b*, the first regularized spherical harmonic field model for the past 10 kyrs. The effects of uncertainties in both magnetic elements and their ages and of uneven global data distribution are assessed by a bootstrap resampling scheme. I discuss the evolution of the dipole moment and tilt and features of the radial field component at the core-mantle boundary. The model also provides estimates for field directions and intensity for any location at Earth's surface. However, as the presently available data distribution is uneven and strongly biased towards the northern hemisphere and Europe in particular, the accuracy and resolution of global models remains limited. More high resolution lake or marine paleomagnetic sediment records and archeomagnetic results from the southern hemisphere, e.g. the South American countries, are necessary to improve global field reconstructions.

Archeomagnetic resultados y registros de alta resolución sedimentarias se han utilizado para reconstruir el campo magnético global para escalas de tiempo del milenio. Aquí presento una serie de modelos llamado *CALSxk*, los modelos Continua basados en datos Archeomagnetic y de Sedimentos Lacustres de x kyrs, y en particular *CALS10k.1b*, la primera regularizó modelo esférico campo armónico de los últimos 10 kyrs. Los efectos de la incertidumbre tanto en los elementos magnéticos y sus edades y la distribución desigual de los datos globales son evaluadas por un esquema de remuestreo bootstrap. Discutir la evolución del momento dipolar y sus inclinación y las características de la componente del campo radial en la frontera entre el núcleo y el manto. El modelo también proporciona las estimaciones de las direcciones y la intensidad de campo de cualquier lugar de la superficie terrestre. Sin embargo, como la distribución de los datos disponibles en la actualidad es desigual y muy sesgada hacia el hemisferio norte y Europa en particular, la precisión y resolución de los modelos globales sigue siendo limitada. Más resultados alta resolución paleomagnéticos de sedimentos des lagos o del mar y datos archeomagnetic desde el hemisferio sur, por ejemplo, los países de América del Sur, son necesarias para mejorar la reconstrucción de campo magnético global.

Introduction

The past evolution of the global geomagnetic field is of interest in order to gain a better understanding of the geodynamo process in the Earth's core and to estimate the geomagnetic shielding against galactic cosmic rays. The amount of published archeomagnetic results and high resolution lake or marine paleomagnetic records over recent decades has become sufficient to attempt global modelling of magnetic field evolution on millennial time-scales (Ohno and Hamano, 1993, Hongre et al., 1998, Constable et al., 2000). Over recent years, a series of models has been developed, attempting to give the highest possible resolution for studying the geomagnetic field evolution at the core-mantle boundary and Earth's surface (Korte and Constable, 2003, Korte and Constable, 2005, Korte et al., 2009). The models are named



CALS_{xk}, Continuous models based on Archeomagnetic and Lake Sediment data of the past *x* kyrs. Here I give an overview over the available global data compilations and the series of *CALS_{xk}* models, and I present some results shown by the latest and longest term model version, *CALS10k.1b* (Korte and Constable, *subm. to Earth Planet. Sci. Lett.*).

Global Holocene data compilations

The global compilation of archeomagnetic data goes back to the IAGA archeomagnetic directional database ARCHEO00 assembled by D. Tarling (<http://www.ngdc.noaa.gov/geomag/paleo.shtml>). Global intensity data have been compiled by Genevey et al. (2008) and Donadini et al. (2006). The latter database, GEOMAGIA (<http://geomagia.ucsd.edu/>), has since been improved to include all previously compiled and newly published archeomagnetic and lava directional and intensity data that became known to us (Donadini et al., 2009). The global distribution of data included in the GEOMAGIA database up to August 2009 is shown in Fig. 1a. It is obvious that most data come from low to mid latitudes in the northern hemisphere with the highest concentration in Europe. Data from high latitudes but also the southern hemisphere continents are clearly lacking for a good global coverage. The majority of these data come from the most recent 3 kyrs.

The global compilation of sediment records started with records taken from the IAGA database SECVR00 (<http://www.ngdc.noaa.gov/geomag/paleo.shtml>), and we have consecutively added additional data that became known and available to us (Korte et al., 2005, Donadini et al., 2009, Korte and Constable, *in press*). The global distribution of all records used in the construction of the latest models is shown in Fig. 1b. The temporal distribution of sedimentary data is better, but the southern hemisphere coverage is only slightly better than for archeomagnetic and lava data.

The series of *CALS_{xk}* models

The *CALS_{xk}* models are based on continuous magnetic field modelling techniques optimised for mapping the main field at the core-mantle boundary as pioneered by Bloxham and Jackson (1992) and adapted for archeo- and paleomagnetic application by Korte and Constable (2005), Korte et al. (2009) and Korte and Constable (2011), where details of the method are given. The field is described by a spherical harmonic expansion in space with the Gauss coefficients expanded in cubic B splines for temporal continuity. The expansion in both space and time allows for more structure/faster variations than can be expected to be resolved by the data, and a physically motivated regularization is applied to trade a simple, smooth model against the fit to the data. The idea is to find the model with minimum structure required to explain the data. By applying the spatial smoothing, in our case minimising the Ohmic dissipation, at the core-mantle boundary, smaller features are damped much more efficiently than large-scale field contributions. For temporal smoothness, the second derivative of the field integrated over the global surface is minimised. The choice of the strength of regularization is somewhat subjective, but comparisons of geomagnetic power spectra provide a guidance. They also suggest that with the presently available data basis the millennial scale models can provide a resolution of approximately spherical harmonic degree 4 in space and in the order of about 100 yrs in time.

The first widely used model was *CALS3kK.1* (Korte and Constable, 2003), covering the time span 1000 BC to 1950 AD. This model was based on a rather limited data set of directional data only and therefore did not provide an independent estimate of the axial dipole strength, that information was taken from archeomagnetic virtual axial dipole moments. *CALS3k.1* clearly is outdated now. The next version, *CALS3K.2*, was practically included in the 7 ka model *CALS7K.2* (Korte and Constable, 2005). Here, individual archeomagnetic data instead of composite curves, including intensities, were used for the first



time, together with 41 sedimentary directional records. Intensity data were still underrepresented in these models. *CALS3k.3* (Korte et al., 2009) was the first model to include calibrated relative intensity records from sediments, and for the large scales was constrained to agree with the *gufm1* model, describing the field between 1590 and 1990 based on historical and modern field observations (Jackson et al., 2000).

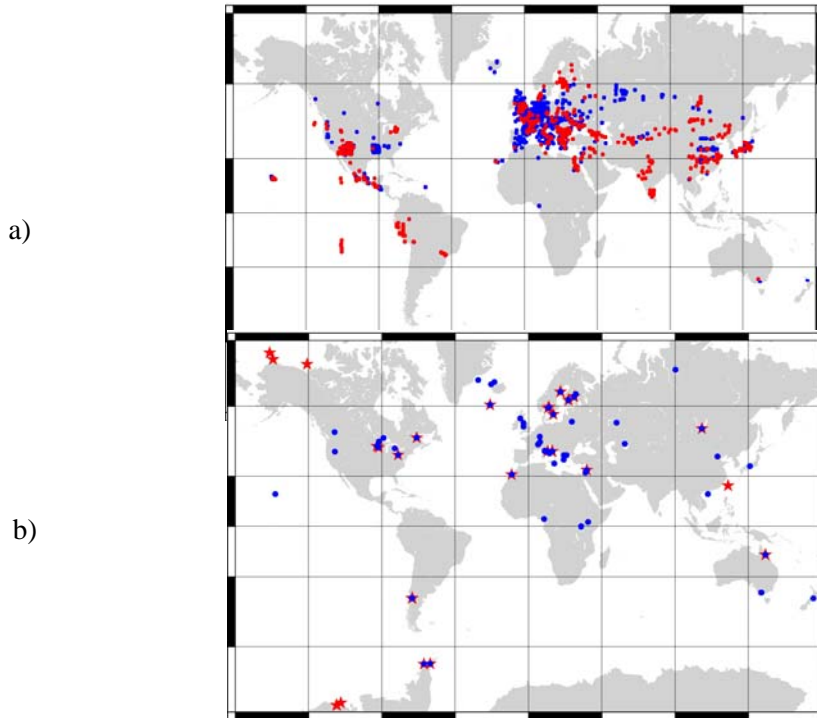


Figure 1: Global data distribution. a) Archeomagnetic directional (blue) and intensity data (red) included in the GEOMAGIA database by August 2009. b) Sedimentary directional (blue) and relative intensity (red) records as compiled for the CALS10k.1b model.

It was recently updated with additional data and the agreement with the *gufm1* model was intensified to include smaller scales. This new *CALS3k.4* model currently is the highest resolution magnetic field model for the time interval 1000 BC to 1990 AD (Korte and Constable, 2011). At the same time, a model spanning the past 10 kyrs was developed, based on the same data set of all archeomagnetic data included in the GEOMAGIA database by August 2009 and 75 sediment records, some of them including relative intensity information. For times prior to around 1000 BC the model predominately relies on the sediment data. We followed the previous approach to include all available data without prior data selection, but for the early time of the model we noticed some apparent inconsistencies among the records. It was not straightforward to identify any erroneous data. Further work to better assess the quality of individual records is in progress. For the first 10 ka model we decided to apply bootstrap techniques, varying the data within their data and dating uncertainties and drawing randomly from the global data set, to take into account the uncertainties and uneven distribution. *CALS10k.1b* is an average of 2000 bootstrap models with uncertainty estimates for the model provided by their standard deviation (Korte et al., submitted to Earth Planet. Sci. Lett.). For the sediments, however, the age bootstraps are not performed individually for each datum, but in order to preserve the stratigraphy the whole records are shifted in time. These correlated samples in the bootstrap lead to a strong temporal smoothing in the resulting average model. For studies of the past 3 kyr, *CALS3k.4* currently seems the best available model, while the longer term *CALS10k.1b* is particularly suited to study the general field evolution at the core-mantle boundary for studies of geodynamo processes. All models are available from the EarthRef Digital Archive at <http://earthref.org>.



Holocene geomagnetic field features

The dipole moment estimate of *CALS10k.1b* (Fig. 2a) shows the well-known pattern of higher values for the time interval 2000 BC to present and lower values for earlier times. The change appears rather gradual. The strong variation at the earliest part of the model around 8000 BC should be regarded with some caution as intensity data are scarce between 8000 BC and 7000 BC. Virtual axial dipole moment averages from archeomagnetic data only tend to overestimate the dipole moment due to their strongly biased geographical distribution. The previous *CALS7K.2* underestimates the dipole moment from 5000 BC to 1000 BC due to the scarcity of intensity data for this time interval in this model. The higher resolution variations shown by *CALS3k.3* are nicely included in the uncertainty estimates of the longer-term model.

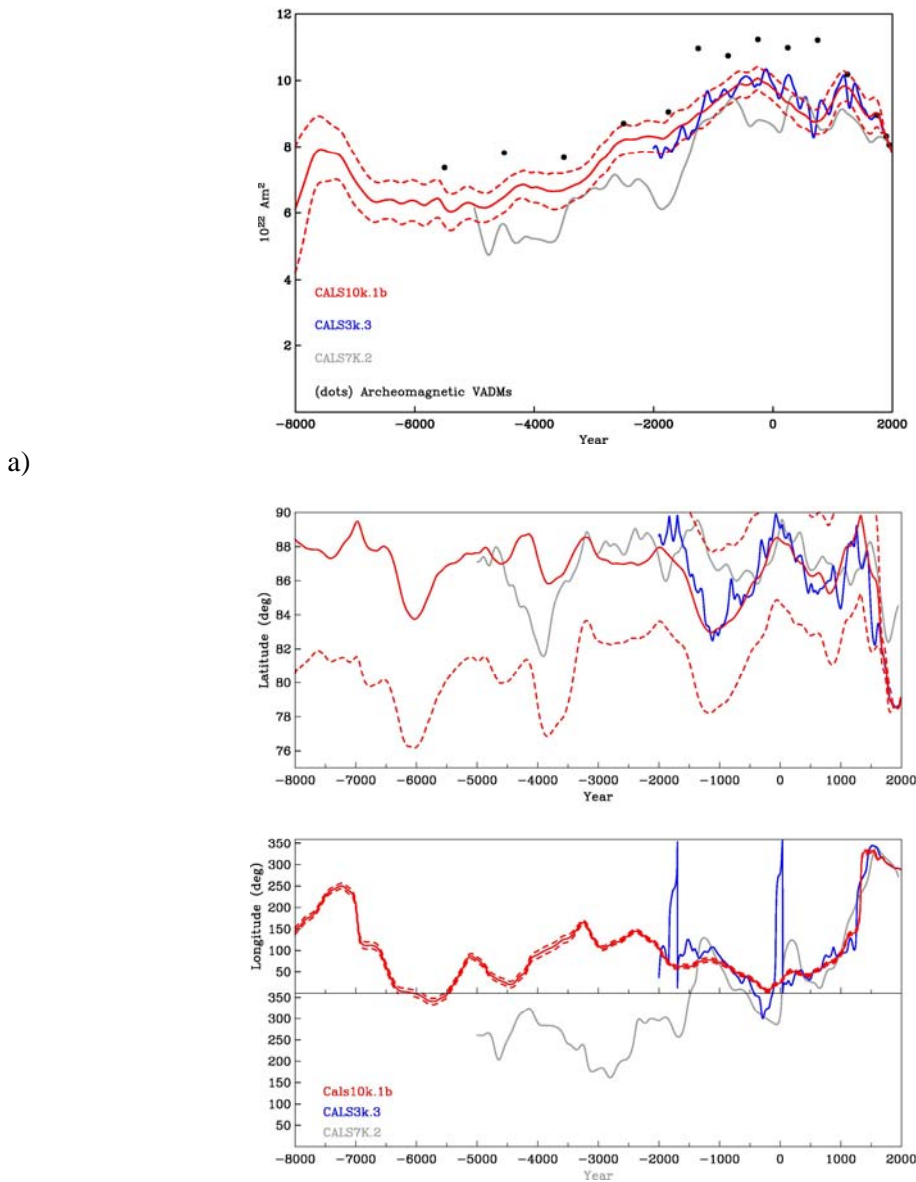


Figure 2: Dipole moment (a) and orientation of the dipole axis in latitude (b upper panel) and longitude (b lower panel) as given by three models. Uncertainty estimates for the bootstrap average *CALS10k.1b* predictions are shown by dashed lines.



The dipole axis estimate shows a somewhat periodical tilt (Fig. 2b). The present dipole tilt appears exceptionally large, but the uncertainty ranges reach similar values. It might be that rather strong tilts cannot be fully resolved by the models. The agreement in dipole tilt (latitude) in general is good among the different models. For longitude one eastward and one westward swing appear opposite in *CALS10k.1b* and the previous *CALS7K.2*. With a highly increased number of data and the small uncertainty estimates in the order of a few degrees the new model should predict the dipole axis movement more reliably. Two apparently very abrupt longitudinal changes in *CALS3k.3* occur at time when the dipole axis is nearly at the geographic pole, so that longitudes are nearly meaningless.

Pairs of maxima of magnetic flux concentration which appear nearly hemispherically symmetric in the radial field downward-continued to the core-mantle boundary (CMB) are known from the historical field (Gubbins and Bloxham, 1987) and time-averages of the paleomagnetic field (Johnson and Constable, 1995, Kelly and Gubbins, 1997). Their variability or persistence is of interest for the understanding of the geodynamo process and possible core-mantle interaction. The earlier *CALSxk* models indicated preferred locations for flux concentrations at least in the northern hemisphere, but lacked resolution in the southern hemisphere. *CALS3k.3*, its update *CALS3k.4* and *CALS10k.1b* for the first time also indicate preferred locations for southern hemisphere flux maxima and suggest an average lifetime of flux patches in the order of a thousand years (Korte et al., submitted to Earth Planet. Sci. Lett.). Improvements to the global data coverage are important to study the evolution of these features in more detail.

Conclusions

The millennial scale *CALSxk* geomagnetic field models are a useful tool to study geomagnetic secular variation, processes of the geodynamo in the Earth's core and to take into account the shielding effect of the magnetic field in studies involving galactic cosmic rays and cosmogenic nuclides. Accuracy and resolution of the models, however, are limited by the quality and distribution of available data. Archeo- and paleomagnetic laboratory procedures are constantly improving, providing higher quality data and a better understanding of data uncertainties. The amount of data from the southern hemisphere included in the global compilations at present still is sparse. Archeomagnetic and sediment data e.g. from the South American countries are urgently needed to improve global geomagnetic field reconstructions for the Holocene.

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