Assessing Holocene and late Pleistocene geomagnetic dipole field variability

Nilsson, Andreas

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Andreas Nilsson

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Abstract

Palaeomagnetic studies of continuous geological archives and archaeological artefacts are required to reconstruct geomagnetic field changes beyond the range of historical observations. In this thesis I assess the reliability of sedimentary palaeomagnetic data and Holocene dipole field reconstructions. New palaeomagnetic records are presented from a maar crater lake in New Zealand and a post-glacial lake in Sweden. The fidelity of the data is evaluated through comparisons with sediment parameters sensitive to environmental change and measurement of cosmogenic radionuclides. The results are used to date the sediments and to study regional and global geomagnetic field variations over the past 50,000 years. The Holocene dipole tilt variation is reconstructed by averaging virtual geomagnetic poles from five sedimentary palaeomagnetic records. The data are selected based on palaeomagnetic quality, chronologic constraint and location, with an emphasis on attaining a globally well-distributed data set. The results indicate a cyclical behaviour of the dipole tilt with a period of c. 1350 years. In addition, two preferred states of the dipole axis are identified with north geomagnetic pole longitudes confined to c. 120° West or 30° East. The performance of the dipole tilt reconstruction is compared to more complex geomagnetic field models. The comparison highlights inconsistencies within the sedimentary palaeomagnetic database that may smooth out variations of the dipole component and potentially shift power to higher degree components of the more complex field models. Independent geomagnetic field intensity data from western Eurasia and North America are shown to be consistent with the dipole tilt reconstruction. The cyclical tilt variation and the two preferred states of the dipole axis are interpreted in terms of displacement and/or distortions of high latitude flux lobes on the core mantle boundary. Based on palaeomagnetic directions and palaeointensity data, the two tilt maxima at 2650 and 1200 years BP are tentatively associated with the presence of high intensity magnetic flux beneath Europe. The dipole tilt reconstruction is highly correlated to millennial scale variations in the length of day, reconstructed from ancient records of eclipses, which suggests that the 1350-year cyclicity may constitute an important component of core flow dynamics.

Key words: Geomagnetic field, palaeomagnetism, the Holocene, dipole tilt, dipole moment, cosmogenic radionuclides

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Andreas Nilsson

Department of Earth and Ecosystem Sciences, Division of Geology, Quaternary Sciences, Lund University, Sölvegatan 12, 223-62 Lund, Sweden

This thesis is based on four papers listed below as Appendices I-IV. Paper I has been submitted to the journal indiated and is under consideration. Paper II is in press in the journal indicated. Paper III is reprinted with the permission of the American Geophysical Union. Paper IV has been submitted to the journal indicated and is under consideration.

Appendix I: Nilsson, A., Muscheler, R., Snowball, I., Aldahan, A., Possnert, G., Augustinus, P., Atkin, D. and Stephens, T. Multi-proxy identification of the Laschamp geomagnetic field excursion in Lake Pupuke, New Zealand. Manuscript submitted to Earth and Planetary Science Letters.

Appendix II: Stanton, T., Nilsson, A., Snowball, I. and Muscheler, R., In press. Assessing the reliability of Holocene relative palaeointensity estimates: a case study from Swedish varved lake sediments. Geophysical Journal International.

Appendix III: Nilsson, A., Snowball, I., Muscheler, R. and Bertacchi Uvo, C., 2010. Holocene geocentric dipole tilt model constrained by sedimentary palaeomagnetic data. Geochemistry Geophysics Geosystems 11(8), Q08018.

Appendix IV: Nilsson, A., Muscheler, R. and Snowball, I. Millennial scale cyclicity in the geodynamo inferred from a dipole tilt reconstruction. Manuscript submitted to Earth and Planetary Science Letters.

Contents

1. Introduction

The Earth is surrounded by a dynamic magnetic field, which originates in its deep interior. Studies of the geomagnetic field and how it varies in time and space contribute to the understanding of a wide range of geological processes. In addition, the geomagnetic field shields the Earth and its atmosphere from harmful cosmic radiation and solar particles. On geological time scales, the existence of the geomagnetic field has been vital for the continued existence and evolution of life on the planet. Without a magnetic field Earth's atmosphere would have been slowly eroded by the solar wind. It has also been suggested that geomagnetic field changes can have an influence on the Earth's climate. Reconstructions of past geomagnetic field changes have a wide range of Earth science applications; for example (i) global tectonics, (ii) the correlation and relative dating of geological archives and (iii) studies of the inner Earth.

The magnetic field is generated by fluid convection in the liquid iron-rich outer part of the core through a mechanism known as the geodynamo. At the Earth's surface today the field strongly resembles that of a geocentric dipole tilted about 11° from the rotational axis. The magnetic poles (i.e. points on Earth's surface where the inclination of the magnetic field is vertical) are separate from the geomagnetic poles, the intersections between a fitted dipole axis and the Earth's surface. This difference is due to the fact that the geomagnetic field also contain a significant non-dipole part that currently accounts for about 10-20% of the surface field expression. When magnetic field observations are projected down to the core mantle boundary (CMB) the effects of the non-dipole part become more apparent. The structure of the field at the CMB is characterised by several dip poles with strong magnetic flux concentrated away from the rotational axis in four approximately symmetric locations north and south of the equator (Bloxham and Gubbins, 1985, 1987). These patches of intense magnetic flux, or flux lobes, are the main contributors to the axial part of the dipole field (Gubbins and Bloxham, 1987) and have remained relatively stationary during the last four centuries (Jackson et al., 2000).

Studies of the geomagnetic field beyond the record of historical observations (c. 400 years) rely on palaeomagnetic data, primarily in the form of natural remanent magnetisations (NRMs) stored in different geological materials (e.g. lava flows, marine and lacustrine sediments, loess) and archaeological archives (e.g. burned ceramics, kilns). NRMs are acquired either through cooling of a magnetic material through its Curie (or Néel) temperature or during deposition of magnetic mineral grains in calm waters. The magnetic domains or grains are allowed to align themselves to the prevailing local geomagnetic field during a limited amount of time. The information regarding the intensity and direction of the palaeomagnetic field is stored in the material either through further cooling, preventing re-alignments of the magnetic domains, or in the case of the depositional remanence, through fixation of the mineral magnetic grains by neighbouring sediment particles.

Palaeomagnetic studies demonstrate the persistency of the dipole field on longer time scales. Time-averages over intervals of several millennia are generally sufficient to remove most of the effect of the dipole tilt and the non-dipole field, leaving a field that, to a first approximation, corresponds to a geocentric axial dipole (GAD) (Carlut et al., 1999). The palaeomagnetic data have also revealed dramatic changes, most notably the polarity reversals. During the most recent 83 million years the geomagnetic field has switch polarity state more than 150 times (Cande and Kent, 1995; Constable and Korte, 2006). In addition, numerous excursions have also been reported (Channell, 2006; Lund et al., 2006), which are large but brief ($<10^4$ years) magnetic field deviations from the GAD configuration, possibly representing aborted reversals (Valet et al., 2008b).

Several different approaches have been used to reconstruct the global Holocene geomagnetic field variations with significantly different results, even for the most basic (i.e. dipole) components of the field (e.g. Korte and Constable, 2005b; Valet et al., 2008a). Due to the large uncertainties and limited spatial distribution of palaeomagnetic data (Donadini et al., 2009), each method involves some form of compromise regarding the complexity of the model, the quality of the data used to constrain the model and/or the spatial and temporal resolution

of the reconstruction. Models based on spherical harmonic analysis (Hongre et al., 1998; Korte and Constable, 2003, 2005a; Korte et al., 2009) should theoretically provide the most comprehensive description of the field. However, such models require extensive data sets and risk shifting power to higher degree components of the field to accommodate for inconsistencies between different records (Valet et al., 2008a). Alternative reconstructions with limited complexity (e.g. Genevey et al., 2008; Knudsen et al., 2008; Ohno and Hamano, 1992; Valet et al., 2008a) could potentially provide better representations of the basic components (e.g. the dipole) by being more selective when choosing the data. On the other hand, such models will conversely only offer limited insight to the details of past changes in the geomagnetic field configuration and, therefore, into the processes within the core that generate the geomagnetic field.

As a complement to traditional palaeomagnetic methods, changes in the geomagnetic dipole field intensity can be estimated from measurements of cosmogenic radionuclides, e.g. ^{14}C, ^{10}Be and ^{36}Cl, deposited in high resolution archives such as ice cores and tree-rings (e.g. Muscheler et al., 2005a). Cosmogenic radionuclides are produced in the atmosphere through interactions between cosmic rays and atoms in the atmosphere. The production rates are inversely related to the magnitude of the dipole moment because the geomagnetic field shields the Earth from incoming cosmic rays (Lal and Peters, 1967). The solar wind modulates the production of cosmogenic radionuclides in a similar way. These variations are believed to be most important on decadal to centennial time-scales but little is known about long-term changes in the solar modulation. In addition, because modulation of cosmic rays takes place at high altitudes, outside the atmosphere, the effect of non-dipolar field components of the Earth's magnetic field can be neglected (Beer et al., 2002).

A better description of the Holocene geomagnetic field may help answer important questions regarding the significance of historic core field observations and improve our understanding of the processes governing the geodynamo: Is the current rapid dipole decay, partly associated with weak and reversed flux below the South Atlantic region, a precursor to a reversal (Hulot et al., 2002) or within the normal range of secular variation (Constable and Korte, 2006)? Are the high latitude flux lobes at the CMB and the low secular variation beneath the Pacific hemisphere, partly observed in long-term time-averaged global models based on palaeomagnetic data from the past 5 million years (Johnson and Constable, 1995; Kelly and Gubbins, 1997), persistent features of the Holocene geomagnetic field (Korte and Holme, 2010)? An accurate description of the dipole tilt variability during the Holocene would also provide a direct test of the GAD hypothesis. Furthermore, a better understanding of long-term changes in the dipole field is crucial for radionuclide-based reconstructions of solar activity and investigations of potential Sun-climate relationships (Muscheler et al., 2005b; Neff et al., 2001; Snowball and Muscheler, 2007) and to test hypotheses that suggest a causal relationship between geomagnetic field and climate change (Gallet et al., 2005; Knudsen and Riisager, 2009).

The objectives of this study are twofold. Firstly, new palaeomagnetic and cosmogenic radionuclide data are presented and compared to independent geomagnetic field reconstructions in attempts to date the sediments and to assess the reliability of the data. Secondly, sedimentary palaeomagnetic data from the Holocene are used to constrain the dipole tilt variability using an approach designed to minimise the amount of data required, thereby allowing for the application of more stringent data selection criteria. The results are used to assess the reliability of previous dipole field reconstructions and indirectly the fidelity of the records in the Holocene sedimentary palaeomagnetic database. Finally, the potential implications for the geodynamo are discussed.

2. Holocene palaeomagnetic data

The GEOMAGIA50v2 database (Donadini et al., 2006; Korhonen et al., 2008), which extends to 50,000 years before present (BP; defined as calendar years before 1950 AD) provides an overview of the available data from igneous rocks and archaeological artefacts (Fig. 1a). These data consist of spot readings in time and space of the direction and/or

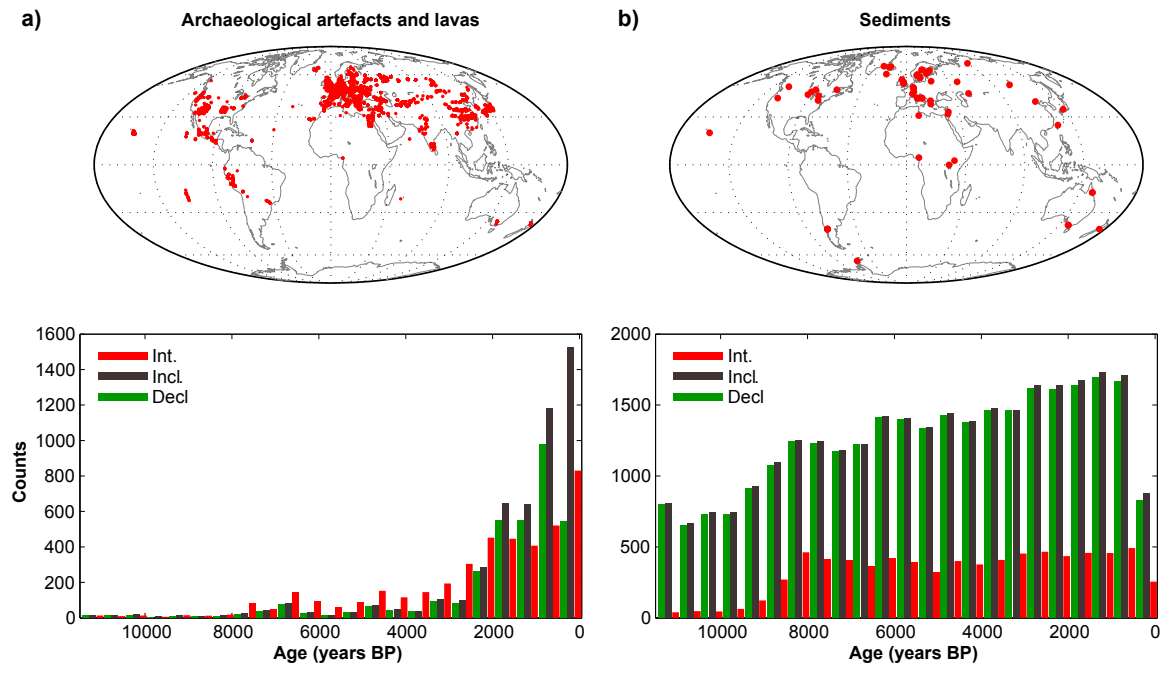

Figure 1. Top panel: the distribution of the archaeological artefacts and lavas (a) and sediment records (b) on the globe covering the past 11,500 years. Bottom panel: the temporal distribution of intensity, inclination and declination data from archaeological artefacts and lavas (a) and sediment records (b) during the past 11,500 years. All data are grouped in 500-year bins.

intensity of the magnetic field. About 54% of the data from the Holocene provide palaeointensity estimates, but 66% of these measurements lack directional information. More than 95% of the data come from the northern hemisphere, with the majority originating from western Eurasia and within the last three millennia. Beyond this time frame the main source of palaeomagnetic data is sedimentary archives.

The SED12k database (Donadini et al., 2009; Korte et al., 2005), including additions made in Appendix III, contain Holocene sedimentary palaeomagnetic data from 63 sites (Fig. 1b). As shown in Figure 1b, the sedimentary data are more evenly distributed in both time and space. About one third of the records provide relative palaeointensity (RPI) estimates, which in theory can be calibrated using absolute intensity measurements from archaeological artefacts or lava flows from the same region (Donadini et al., 2009) or even based on model predictions (Korte and Constable, 2006). The sedimentary data have the benefit of providing continuous records, which, in ideal circumstances, make it possible to build accurate and precise age-depth models using a variety of dating techniques. On the other hand, the gradual and often slow processes by which the palaeomagnetic signal is 'locked in' slightly below the sediment/water interface could result in a smoothing with time and potentially also an age offset between the sediment age and the age palaeomagnetic signal (Roberts and Winklhofer, 2004). In addition, the interpretation of the data is often complicated by weak and/or unstable magnetisations, leading to high degrees of noise (Creer et al., 1983).

3. Site descriptions

Sediments from two lakes were studied during the course of this project. Lake Pupuke was initially selected as part of the NZ-Maar project to investigate climate tele-connections between the northern and southern hemispheres using palaeomagnetic data to synchronise the record with other climate proxy data archives. Kälksjön ('sjön' is Swedish for 'lake') was selected during a systematic reconnaissance to find varved lake sediments in the province of Värmland (Zillén et al., 2003). Of the three varved sequences found during that survey, Kälksjön has the highest post-isolation sediment accumulation rate (0.7 mm/year for the last 9200

years) and was considered likely to produce a good palaeomagnetic secular variation (PSV) record.

3.1 Lake Pupuke

Lake Pupuke (36°47.25' S, 175°46.25' E) occupies a c. 250,000 year old maar crater (Hall and York, 1984) situated in the northern part of the Auckland Volcanic Field, New Zealand. The catchment is now covered by residential suburbia and is located only 200 m from the sea and 5 m above the present day sea level. The lake is surrounded by a tuff cone, which has protected it from erosion and seawater influx (Hayward et al., 2008). The characteristic shape of the crater produces a relatively small (1.1 km^2) and deep (57 m) lake with a limited catchment area (1.9 km^2) enclosed by the rim of the crater. The lake is closed hydrologically and the main source of water comes from rainfall into the catchment. The mean annual rainfall is 1119 mm, which is distributed evenly throughout the year (Tomlinson and Sansom, 1994). The surface waters have a pH of 8-9 indicating low levels of dissolved CO_2 and a predominance of bicarbonate and are separated from the anoxic hypolimnion by a well-defined thermocline with a lower boundary at around 21-25 m (Augustinus et al., 2006).

The lake sediments, as described for the greater part of the Holocene by Horrocks et al. (2005), consist of highly organic muds laminated at sub-millimetre scale. There are abundant macroscopic basaltic and rhyolitic tephra particles typical of the Auckland and Taupo Volcanic Zones respectively.

3.2 Kälksjön

Kälksjön (60°09.22' N, 13°03.38' E) is located in west central Sweden, in the province of Värmland, at an altitude of c. 98 m above sea level (a.s.l.). The present-day area of the lake is 30 ha while the catchment area comprises about 400 ha. There are four stream inlets entering from the northeast and one outlet in the west. The maximum lake water depth is 14.2 m (Zillén, 2003).

Kälksjön's sedimentary basin, initially part of the Ancient Lake Vänern, became isolated due to isostatic uplift in the early Holocene (Björck, 1995; Zillén et al., 2003). The fine-grained post-glacial silts and clays that were deposited on the bottom of Ancient Lake Vänern are still characteristic of the catchment area. The abundance of this fine-grained material, a significant number of stream inflows and strong seasonal variations have promoted the formation of biogenic-clastic varves in the Kälksjön sediments (Zillén et al., 2003). Anoxic bottom conditions in the deepest part of the lake prevent bioturbation of the sediments and ensures that the seasonal variations are preserved in the form of varves (Stanton et al., 2010).

4. Methods

4.1 Fieldwork and subsampling

The fieldwork at Kälksjön took place in March 2002 when the lake surface was frozen. A modified rod-operated fixed piston corer was used to recover four 5 m long cores for palaeomagnetic analyses (Snowball and Sandgren, 2002). The core barrel consisted of PVC tubes with an internal diameter of 67 mm. The total recovered sediment thickness was 6.75 m.

The sediment cores from Lake Pupuke were collected in February 2007 using a fixed piston 'Niederreiter' corer from a Uwitec floating platform. Seismic profiles and an echo sounder were used to locate the deepest part of the lake. A sediment sequence of 16 m was retrieved in 16 overlapping 3 m long core segment PVC tubes with a diameter of 60 mm.

All cores were split longitudinally into two sections. Standard sized palaeomagnetic sampling boxes (2.2 x 2.2 x 2.2 cm external dimensions and an internal volume of 7 cm^3) were carefully oriented and gently pushed into the centre of the core cross section, minimizing the disturbed edge effects from the coring. The samples, collected in 3 cm intervals, were then cut out with a non-magnetic knife and stored in a cool and moist environment.

4.2 Mineral magnetism

Several different mineral magnetic techniques were used during the course of this study. A short description of the parameters is provided below. For

a comprehensive overview the reader is referred to Thompson and Oldfield (1986). Unless stated otherwise, all measurements were carried out on discrete palaeomagnetic samples.

Magnetic susceptibility of the split core surfaces was measured at a resolution of 4 mm using a Bartington Instruments MS2E1 surface-scanning sensor coupled to a TAMISCAN conveyor. Mass (χ) or volume (κ) specific susceptibility was measured on discrete samples using a Geofyzica Brno Kappabridge KLY-2. Magnetic susceptibility reflects in general the concentration of ferrimagnetic minerals in the sample but it is also sensitive to magnetic grain size and the influence of diamagnetic and paramagnetic minerals.

Saturation isothermal remanent magnetisation (SIRM) was induced with a DC field at 1T using a Redcliffe 700 BSM pulse magnetizer and measured with a Molspin Minispin magnetometer. SIRM reflects primarily the concentration of ferrimagnetic minerals but it is also sensitive to changes in magnetic grain size (domain state). S-ratios were determined by dividing backfield isothermal remanent magnetisations (IRMs), induced and measured with the same equipment, with the SIRM providing a measure of the magnetic coercivity, i.e. the magnetic hardness of the measured material.

Anhysteretic remanent magnetisation (ARM) was induced by subjecting samples to a decreasing alternating field (AF) (100-0 mT) in the presence of a DC bias field of 0.05 mT using the coils of a 2G-Enterprises model 755-R SQUID magnetometer and measured using the same equipment. This parameter provides an alternative measure of the concentration of ferrimagnetic minerals and is particularly sensitive to the fine-grained magnetic fractions.

Magnetic hysteresis loops, with a saturation field of 500 mT, were measured using a Princeton Measurements Corporation alternating gradient magnetometer (AGM M2900-2). Small (circa 100 mg) amounts of selected samples were dispersed within a diamagnetic Araldite epoxy resin and a small drop of the mixture placed on thin (<0.1 mm) square diamagnetic plastic sheets. The hysteresis loops were corrected for high magnetic field susceptibility, thus providing the ratio of saturation remanent magnetisation to saturation magnetisation (M_{RS}/M_S) and coercivity of remanence to coercive force [$(B_0)_{CR}/(B_0)_C$]. The magnetic hysteresis ratios are useful indicators of magnetic grain size (Day et al., 1977), but only provide information about the bulk composition. First-order reversal curves (FORCs) measured using the same equipment and analysed with the FORCinel algorithm (Harrison and Feinberg, 2008), can be used to unmix the magnetic components and to detect non-interacting single domain (SD) particles (Egli et al., 2010).

4.3 Palaeomagnetism

The natural remanent magnetisations (NRMs) were measured using a 2G-Enterprises model 755-R SQUID magnetometer equipped with an automatic three-axis AF demagnetisation system. Pilot samples were progressively AF demagnetised with increments of 5-10 mT up to a maximum AF of 100 mT. The results from the pilot samples were used to select shorter demagnetisation routines for quicker processing of the bulk samples.

The highest stability component of the NRM, generally referred to as the characteristic remanent magnetisation (ChRM), was determined using PCA analysis (Kirschvink, 1980). The maximum angular deviation (MAD) as defined by Kirschvink (1980) provides a measure of how well the determined line (direction) fits the data and, more indirectly, can be used to assess the stability of the magnetisation.

Relative palaeointensities (RPIs) were determined by normalising the NRM with artificial remanences (NRM/ARM or NRM/IRM) and susceptibility (NRM/κ). The objective is to compensate for changes in mineral magnetic concentration by using a normaliser that activates the same magnetic fraction responsible for the ChRM (King et al., 1983; Tauxe, 1993). A more sophisticated, but also more time-consuming, pseudo-Thellier technique (Tauxe et al., 1995) was applied to the Kälksjön data using both ARM and IRM as normalisers (Appendix II).

Virtual geomagnetic poles (VGPs) were determined from palaeomagnetic field directions according to Butler (1992). VGPs are used to illustrate the position of the NGP assuming that the geomagnetic field is purely dipolar and geocentric. In a similar way palaeointensity

measurements (F) can be expressed as virtual dipole moments (VDMs) or as virtual axial dipole moments (VADMs), assuming in the latter case that the geomagnetic field is also aligned with the rotational axis. VADMs were determined using the following equation (e.g. Merrill and McElhinny, 1983):

$$VADM = \frac{4\pi R^3}{\mu_0} \frac{F}{\sqrt{1+3\cos^2\theta}}$$

where μ_0 is the permeability of free space, R the average radius of the Earth and θ the geographic colatitude. VDMs were determined by substituting θ with the magnetic colatitude θ_m derived from:

$$\tan I = 2\cot\theta_m$$

where I is the magnetic field inclination. In addition an alternative VDM_p was determined by substituting the θ_m with θ_p, representing the great circle distance between the NGP, estimated independently, and the geographic coordinates of the site.

4.4 Cosmogenic radionuclides

Plant macrofossils and bulk sediment samples were selected for accelerator mass spectrometry (AMS) radiocarbon datings, which were performed at (i) the Radiocarbon Laboratory of Lund University, Sweden, (ii) the Ångström Laboratory of Uppsala University, Sweden, (iii) the Australian Nuclear Science and Technology Organisation in Canberra, Australia, and (iv) the Rafter Stable Isotopes Centre, GNS Science, New Zealand. All ^{14}C ages were calibrated using the INTCAL09 calibration curve (Reimer et al., 2009) and the Oxcal 4.1 software (Bronk Ramsey, 2009). Alternative age depth models were constructed by interpolating between the calibrated radiocarbon ages using different deposition models (Bronk Ramsey, 2008). In addition, $\Delta^{14}C$ values were calculated based on the formula from Stuiver and Polach (1977) and the variations were used as an indirect proxy for geomagnetic field intensity changes.

Bulk sediment samples from Lake Pupuke were sent for ^{10}Be analyses at the Uppsala Tandem Laboratory AMS facility, Sweden. The majority of the samples were taken from 2-3 palaeomagnetic sub-samples and mixed to average out effects of ^{10}Be production caused by the 11-year and 207-year solar cycles (Beer et al., 1990; Damon and Sonett, 1991). All samples were prepared and measured using the procedures described by Berggren et al. (2010). ^{10}Be flux (atoms/cm^2/year) was calculated by multiplying the ^{10}Be concentration (atoms/g) with sediment dry density (g/cm^3) and sediment accumulation rate (cm/year). Geomagnetic dipole field intensity changes were estimated from both ^{10}Be concentration and ^{10}Be flux using two different transfer functions (Lal, 1988; Masarik and Beer, 1999).

4.5 Tephrochronology

Macroscopic tephra, sampled from the Lake Pupuke sediments, were identified by chemical finger printing using an electron microprobe at the University of Auckland, New Zealand (Molloy et al., 2009). The tephra marker layers were used both to correlate the cores with each other, adjust for cracks, and to synchronise the Lake Pupuke record with other regional stratigraphic data.

5. Summary of papers

5.1 Appendix I

Nilsson, A., Muscheler, R., Snowball, I., Aldahan, A., Possnert, G., Augustinus, P., Atkin, D. and Stephens, T. Multi-proxy identification of the Laschamp geomagnetic field excursion in Lake Pupuke, New Zealand. Manuscript submitted to Earth and Planetary Science Letters.

New palaeomagnetic and cosmogenic radionuclide data are presented from Lake Pupuke, a maar crater lake in Auckland, New Zealand. The aim of the study is to identify the Laschamp geomagnetic field excursion and the associated dipole moment minimum (e.g. Bonhommet and Babkine, 1967; Bonhommet and Zahringer, 1969; Laj et al., 2000; Lund et al., 2005), which could help to synchronise the Pupuke climatic record to, for example, the ice core archives in both Greenland

and Antarctica.

Preliminary age estimates based on radiocarbon dating and tephrochronology suggest that the sediment sequence recovered extends beyond 50,000 years BP. Despite the location in a volcanically active region the concentrations of magnetic minerals in the mostly organic-rich lake sediments are low. Weak magnetisations and frequent interferences from tephra complicate the interpretation of the palaeomagnetic signal. Nevertheless, we find evidence for a minimum in the relative palaeointensity around the timing of the Laschamp excursion and transitional directions at c. 32,000 years BP potentially related to the Mono Lake excursion (e.g. Cassata et al., 2008; Denham and Cox, 1971).

As a complement to the palaeomagnetic data ^{10}Be concentrations were measured over the expected age range of the Laschamp excursion. Besides a brief anomaly associated with high magnetic susceptibility, the results are largely consistent with the ^{10}Be data from the GRIP ice core (Muscheler et al., 2004; Wagner et al., 2000; Yiou et al., 1997) according to the GICC05 age model (Svensson et al., 2008). The geomagnetic field intensity minimum associated with the Laschamp excursion is identified as a peak in ^{10}Be flux at c. 41,000 years BP. The peak flux of ^{10}Be is synchronous with the relative palaeointensity minimum and an anomaly in the ^{14}C data and shows that the data and the adopted time scales are internally consistent.

The study demonstrates the potential of combining traditional palaeomagnetic measurements with cosmogenic nuclides to reconstruct palaeointensity. The multi-proxy approach could also be used to study older excursions providing an indirect method to date the sediments beyond the limit of the radiocarbon method.

5.2 Appendix II

Stanton, T., Nilsson, A., Snowball, I. and Muscheler, R., In press. Assessing the reliability of Holocene relative palaeointensity estimates: a case study from Swedish varved lake sediments. Geophysical Journal International.

New palaeomagnetic data are presented from Kälksjön, a varved lake in central west Sweden. The data are compared to regional PSV reconstructions and potential environmental influence on the RPI estimates is investigated. The sediment chronology was established by Stanton et al. (2010) based on varve counting, radiocarbon dating, lead pollution isochrons and PSV data.

Magnetic hysteresis data of the post-isolation sediments, including first order reversal curves, suggests a bimodal grain size distribution with a mixture of primary multi-domain grains originating from the catchment and secondary single-domain (SD) grains produced within the lake basin, most likely by magnetotactic bacteria (Snowball et al., 2002). Alternating field demagnetisation reveals a strong stable single component magnetisation carried mainly by the fine-grained SD magnetic fraction. The RPI was estimated using a pseudo-Thellier approach (Tauxe et al., 1995) and ARM as the normalisation parameter. The millennial-scale features of the inclination, declination and RPI data are in good agreement with the Fennoscandian master curves, FENNOSTACK and FENNORPIS, a recently published North Karelian Finnish stack (Haltia-Hovi et al., 2010; Haltia-Hovi et al., 2011) and a dipole moment reconstruction (Knudsen et al., 2008).

There is evidence for environmental bias in the RPI estimates, particularly during the early part of the record following the isolation of the lake. Similar fluctuations on time scales on the order of 200-1000 years are observed in both the RPI and different magnetic and non-magnetic parameters sensitive to environmental change. These variations in the RPI are likely related to the relative proportions of fine-grained (SD) autochthonous magnetic particles associated with organic matter and catchment derived, coarser (PSD, MD) magnetic particles and become less important as the organic content of the sediment increases.

By low-pass filtering the RPI data using a cut-off frequency of 1/500 years^{-1} we remove most of the environmental bias in the early part of the record. The data are compared to ^{14}C-based geomagnetic field reconstructions treated the same way (Muscheler et al., 2005a). We detect similar short-term variations in both records, particularly a

maximum at 8700 years BP and a minimum at 7500 years BP, suggesting that they may be related to the changes in geomagnetic dipole field.

5.3 Appendix III

Nilsson, A., Snowball, I., Muscheler, R. and Bertacchi Uvo, C., 2010. Holocene geocentric dipole tilt model constrained by sedimentary palaeomagnetic data. Geochemistry Geophysics Geosystems 11(8), Q08018.

In this study we use a classic palaeomagnetic method of estimating dipole tilt by averaging VGP positions (e.g. Merrill and McElhinny, 1983; Ohno and Hamano, 1992, 1993; Valet et al., 2008a). Four versions of a Holocene time-varying geocentric dipole model are determined from five sedimentary records selected based on: (i) the palaeomagnetic quality, (ii) chronologic constraints and (iii) the location, aiming for a globally uniform distribution. The reliability of the reconstructions is evaluated using modern observatory data for the year 2000 AD. The results highlight the need for globally well-distributed data showing potential misfits of more than 6° resulting from using data from one hemisphere only.

All four dipole estimates show fairly similar variations with a pronounced dipole tilt maximum at c. 2650 years BP representing a rapid westward pole movement from Scandinavia to Greenland. The NGP movement from the preferred dipole estimate, DE_{FNBKE} (the subscript denotes the first letter of the lake records used to constrain the model), is compared to independent geomagnetic field models. In general DE_{FNBKE} appears to be characterised by relatively larger amplitude variations than predicted by spherical harmonic models based on palaeomagnetic data (Korte and Constable, 2005a; Korte et al., 2009). The range of variation exhibited by DE_{FNBKE} is, however, in good agreement with the changes observed during the last four centuries (Jackson et al., 2000). We argue that the lower degrees of dipole tilt exhibited by some models are due to problems with the sedimentary palaeomagnetic data that has been used to constrain them.

The predictions of DE_{FNBKE} in terms of directional variations is tested against palaeomagnetic data from 63 different sedimentary sites and also compared to the same palaeomagnetic models as above. The results show that, apart from two regions (Mediterranean-Africa and South America), there is little or no significant difference between the performances of DE_{FNBKE} and CALS3k.3, the preferred spherical harmonic model (Korte et al., 2009). We conclude that better palaeomagnetic data and associated time control are needed to improve more complex global geomagnetic field models.

5.4 Appendix IV

Nilsson, A., Muscheler, R. and Snowball, I. Millennial scale cyclicity in the geodynamo inferred from a dipole tilt reconstruction. Manuscript submitted to Earth and Planetary Science Letters.

An updated dipole estimate for the Holocene (see Appendix III) is presented and compared to independent dipole moment reconstructions (Genevey et al., 2008; Knudsen et al., 2008; Korte et al., 2009; Muscheler et al., 2005a) and changes in length of day (LOD) reconstructed from ancient records of eclipses (Morrison and Stephenson, 2001; Stephenson and Morrison, 1995).

By including new and improved data from South America, an area previously noted for the large inconsistencies between data sets, we are able to distinguish features that were only partly resolved in the previous dipole estimates. We identify a dominant 1350-year periodicity in the dipole tilt and two preferred states of the dipole axis with north geomagnetic pole longitudes confined to either c. 120° West or c. 30° East. The uncertainty of the dipole estimate, introduced by chronologic uncertainties is further investigated using new Monte Carlo simulation based analyses. The results indicate that both the dipole tilt periodicity and the two preferred states are robust features allowing for dating errors of up to ±300 years.

The dipole tilt estimates and regional intensity reconstructions from western Eurasia (Genevey et al., 2008) are shown to be mutually consistent. We observe generally higher intensities when the dipole is tilting towards western Eurasia and lower intensities during periods when the dipole is tilting

away from it. Similar variations are also seen in alternative dipole moment reconstructions based on more data (Knudsen et al., 2008; Valet et al., 2008a) but are not detected in the arguably more global signal of ^{10}Be data from the GRIP ice core (Muscheler et al., 2004). We argue, therefore, that these millennial scale variations may be caused by a geographic bias in the data and are likely not representative of the global dipole moment.

The two preferred states of the dipole axis suggests a persistent non-zonal structure in the field, which may be related to the semi-stationary high latitude flux lobes observed in the historic data (Jackson et al., 2000). We speculate that the dipole tilt variation is partly related to the displacement and/or distortions of these features and that dipole tilts towards 30° East, at 2650 and 1200 years BP, may correspond to a flux lobe beneath western Eurasia.

The dipole tilt reconstruction is highly correlated to millennial scale variations in the LOD. It has previously been suggested that changes in LOD may be associated with azimuthal core flow through exchange of angular momentum between the mantle and the core (e.g. Dumberry and Bloxham, 2006). There is no straightforward way to link east-west component core flows to variations in dipole tilt, but the similar periodicity and the fixed phase relationship between both records suggests that the common variations may be related to similar flow structures in the core. Based on these observations, and the consistent variations observed in the intensity data, we argue that this 1350-periodicity constitutes a dynamic component of core flow dynamics.

6. Challenges with sedimentary palaeomagnetic data

Sedimentary palaeomagnetic data can provide the ideal foundation for the development of Holocene geomagnetic field models due to the possibility of obtaining long and continuous sequences that are well dated and have a reasonable global distribution. The pioneering work of Mackereth (1971) lead to the construction of a

Table 1. Author contributions to Appendices I-IV

	Appendix I	Appendix II	Appendix III	Appendix IV
Fieldwork/Sampling	*A. Nilsson* *I. Snowball* *T. Stephens* *D. Atkin*	*T. Stanton* *I. Snowball* *A. Nilsson*	-	-
Mineral magnetic and palaeomagnetic measurements	*A. Nilsson*	*T. Stanton* *I. Snowball*	-	-
Palaeomagnetic data treatment	*A. Nilsson*	*A. Nilsson* *T. Stanton*	*A. Nilsson*	*A. Nilsson*
^{14}C/^{10}Be analyses	*G. Possnert* *A. Aldahan*	-	-	-
^{14}C/^{10}Be data treatment	*A. Nilsson* *R. Muscheler*	*R. Muscheler*	-	*A. Nilsson* *R. Muscheler*
Dipole model development	-	-	*A. Nilsson*	*A. Nilsson*
Data interpretation	*A. Nilsson* *R. Muscheler* *I. Snowball* *A. Aldahan* *G. Possnert* *P. Augustinus*	*T. Stanton* *A. Nilsson* *I. Snowball* *R. Muscheler*	*A. Nilsson* *I. Snowball* *R. Muscheler* *C. Bertacchi Uvo*	*A. Nilsson* *R. Muscheler* *I. Snowball*

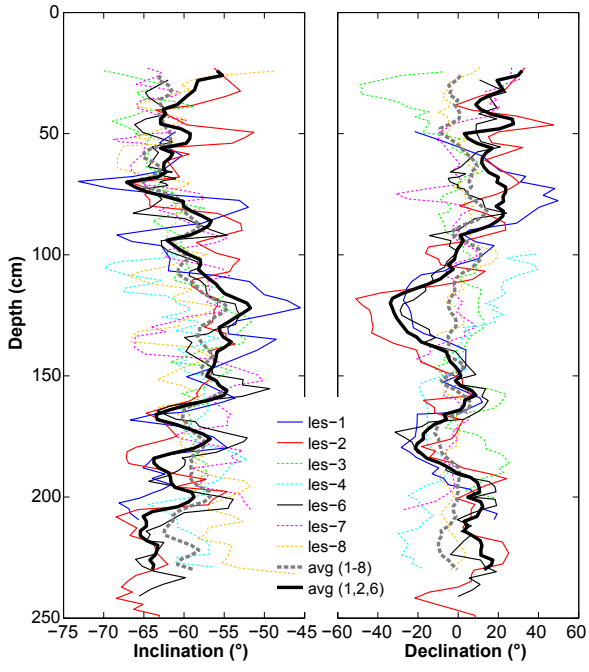

Figure 2. Inclination and declination data, from Lake Escondido (Gogorza et al., 1999), of seven parallel cores (3-point running averages), the published arithmetic averages based on data from all cores (dotted grey line) and averages based on data from les-1, les-2 and les-6 (thick black line) plotted against depth below the sediment surface.

several Holocene palaeomagnetic records in the late 1970's and 1980's, which still account for more than 40% of the database (Fig. 1). These studies demonstrated the great potential of the sedimentary palaeomagnetic archive, but also acknowledge a wide range of potential problems associated with both the magnetisations and the dating of the sediments. While the sensitivity of the equipment keeps improving, leading to more accurate measurements, the fundamental issues still remain the same, particularly with dating. If not properly dealt with, these problems will produce contradictory results in the database (Appendix III). The following section will be focused on specific problems encountered during the course of this study, how they have been addressed and suggestions of potential solutions.

6.1 Directional data

When reconstructing the geomagnetic field direction from sediments the main challenge is to isolate the geomagnetic field signal from noise related to (i) the acquisition of the detrital remanent magnetisation (DRM), (ii) post depositional processes such as chemical overprinting (Snowball and Thompson, 1990) and (iii) physical disturbance during coring (Bowles, 2007) and sub-sampling (Gravenor et al., 1984). By collecting several parallel cores it is possible to detect and possibly correct for many of these problems by checking for reproducibility within the data.

The palaeomagnetic record from Lake Escondido (Gogorza et al., 1999), Argentina, was used in the study presented in Appendix III to constrain the dipole tilt reconstruction. Based on objective criteria it is probably the lowest quality record used to constrain the model, however, there is no apparent better-quality alternative from South America. Therefore, it is a good example how one can try to extract a consistent signal from a record. All data from the individual cores were digitised from the original publication. In Figure 2 the stacked inclination and declination data are plotted on top of the 3-point running averages of the individual core data. The data are characterised by a high degree of scatter and inconsistencies between the cores, which tend to remove any large variability in the smoothed data. This scatter is particularly evident in the declination data, between 100-150 cm and below 200 cm depth, suggesting that some of the cores may have rotated during sediment penetration. If the core rotated uniformly during descent this would be detected as a westward (clockwise) or eastward (anticlockwise) trend in the declination data superimposed on the shorter-term variability, as for example seen in 'les-4'. Such rotational deviations could theoretically be corrected for by linearly detrending the data (e.g. Ali et al.,

Table 2. Correlation coefficient matrix for declination data shown in Figure 2

	les-1	les-2	les-3	les-4	les-6	les-7
les-2	*0.56*					
les-3	*-0.38*	*-0.43*				
les-4	*-0.27*	*-0.55*	*x*			
les-6	*0.64*	*0.62*	*-0.49*	*-0.51*		
les-7	*-0.25*	*x*	*-0.47*	*x*	*x*	
les-8	*0.36*	*x*	*x*	*0.43*	*x*	*x*

'*x*' denotes non-significant correlations according to the bootstrap significance test.

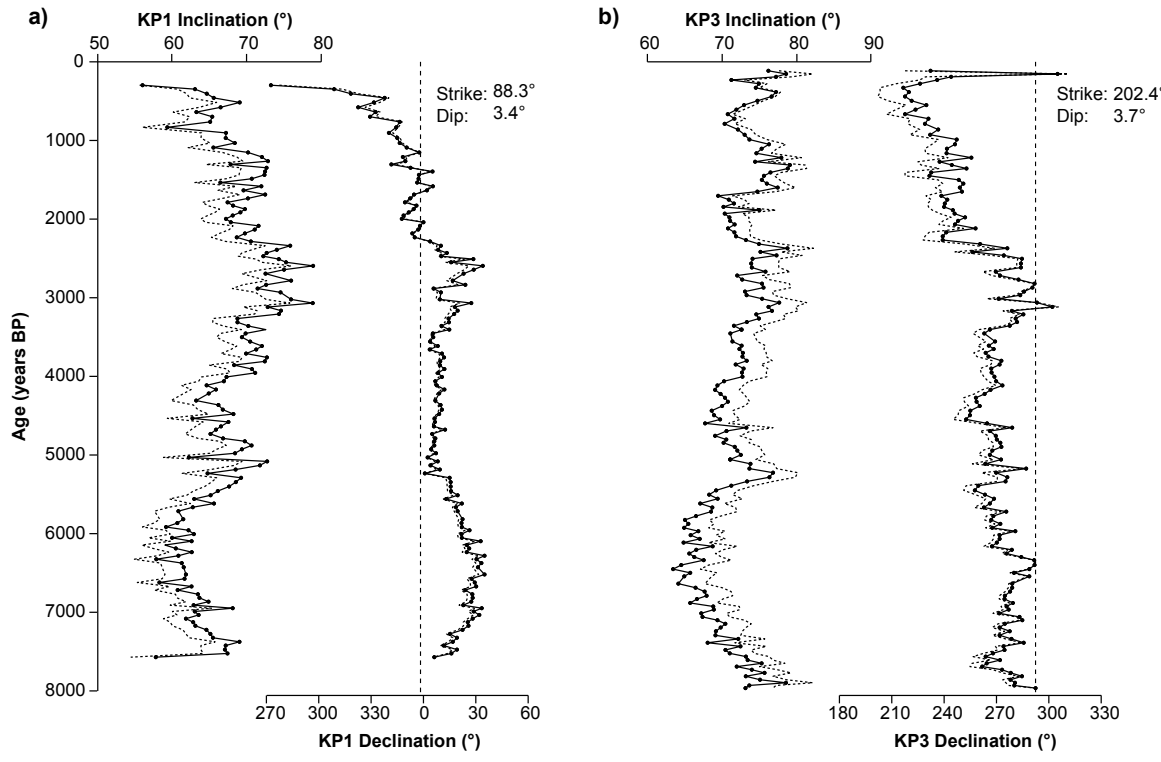

Figure 3. Inclination and declination for (a) KP1 and (b) KP3 from Kälksjön before (dotted lines) and after (solid lines and circles) the correction for the dip of the varve bedding planes plotted against varve years BP. Vertical dashed lines indicate the direction of maximum dip, i.e. 90° relative to the strike of the bedding planes.

1999). If, however, the core rotated irregularly with alternating directions it would be impossible to restore the true variations.

An alternative approach is to look for data showing similar variations. Whether the problem is core rotation or perhaps inadequate synchronisation of the individual core depth scales it is reasonable to suggest that, if several cores show the same pattern of change, these changes are likely reflecting true geomagnetic field variations. To look for such common signals the 3-point averaged declination data were interpolated at 2 cm and correlated with each other. The significance levels of the correlation coefficients were evaluated using a bootstrap significance test based 100 randomly re-sampled data sets, see table 2. This correlation exercise highlights three cores in particular (les-1, les-2 and les-6) that show similar variations. Based on the interpolated data from these three cores an alternative average is calculated, which shows considerably more pronounced variability than the original data (see Fig. 2). As noted in Appendix IV the same variations can be seen in a newer study from Lake Escondido (Gogorza et al., 2002) supporting the conclusion that the data from the three internally consistent cores are mainly showing changes in the geomagnetic field.

In the Kälksjön study (Appendix II) core rotation was mostly observed in the top 1 m of each core. However, systematic offsets between the inclination data from mainly two cores, KP1 and KP3, suggest that the cores may have penetrated the sediments at an oblique angle. Since the sediments are varved it was possible to investigate this problem directly by measuring the relative orientation of the bedding planes. The measurements were carried out on all four cores at roughly 0.5 m intervals utilising the surface of the split core section and the cleaned trench walls, created after extracting the sample cubes, to determine the strike and dip of the laminations. An average strike and dip was calculated for each core and used to adjust the inclination and declination data by rotating them on a unit sphere. The results of this procedure for KP1 and KP3 are shown in Figure 3 along with dashed lines marking the direction of maximum dip on the declination axis. The strikes are relative to the magnetometer axis and not a geographic

longitude because the cores were not oriented to an azimuth during collection. The correction considerably reduces the difference in inclination between the two cores but it does not remove the offset completely. However, the remaining discrepancies can be considered to be within the measurement uncertainty of the strike and dip determinations of the varve bedding planes.

Besides potential coring related problems the two examples illustrate the signal-to-noise ratio than can be expected from different studies, related to the stability of the natural magnetisations, and the limitations of single core studies.

6.2 Relative palaeointensity

Estimates of RPI rely on the assumption that the chosen normalisation parameter activates the same magnetic fraction as the NRM in a proportional way. This is complicated by temporal variations of the (i) magnetic mineral concentration, (ii) grain size and (iii) mineralogy, which may influence the effectiveness of the DRM acquisition and that of the normalisation parameter differently (King et al., 1983; Tauxe, 1993). In addition, tendencies of clay particles to stick together (flocculate) during deposition (Tauxe et al., 2006) and post depositional processes such as chemical overprinting or selective magnetite dissolution (Karlin and Levi, 1983) may further complicate the interpretation. While great success has been achieved estimating relative palaeointensities using deep marine sediments (e.g. Guyodo and Valet, 1999; Laj et al., 2000), lacustrine records have often proven more difficult due to their higher sensitivity to environmental change.

As described in Appendix I the Lake Pupuke sediments are characterised low concentrations of ferrimagnetic minerals. Magnetic hysteresis data indicate the presence of a high coercivity magnetic mineral in addition to a dominant magnetic fraction probably represented by titanomagnetite. In general the sediments would not be considered suitable for RPI reconstructions (King et al., 1983). However, as shown through comparisons with independent ^{10}Be and ^{14}C reconstructions, it might still be possible to detect long-term changes in the geomagnetic field intensity over limited sections of the sediment sequence characterised by relatively low mineral magnetic variability.

In contrast, the Kälksjön sediments (Appendix II) possess a strong and stable magnetisation and would according to classical magnetic grain size analyses (Day et al., 1977) be considered suitable for RPI analyses (King et al., 1983). However, more detailed analyses indicate that the grain size distribution of the magnetic mineral assemblage is probably bimodal, characterised by a mixture of fine-grained (SD) magnetic particles associated with organic matter and coarser catchment-derived (PSD-MD) magnetic particles. Centennial-scale environmental bias in the RPI was detected through correlation analyses with ARM and dry density. The bias is likely related to the relative proportions of SD and coarser PSD-MD magnetic particles in the sediments. However, as noted by King et al. (1983) ARM, which was used as a normaliser, is highly sensitive to minor variations in the magnetic particle size distribution in the sub-micrometre range suggesting, alternatively, that the bias could be caused by subtle variations in the fine-grained (SD) magnetic fraction. Two different biases are observed, before and after 7800 years BP, which is interpreted to reflect a shift in the dominant carrier of the NRM. Such a shift could mean that the RPI levels before and after this time might not be mutually comparable. In addition, a long-term Holocene trend towards a fining of the mineral magnetic assemblage could also be responsible for part of the general increase in RPI.

The studies highlight the importance of checking for environmental bias in RPI data. If the bias is isolated to a relatively narrow frequency range the effects can be removed by band-pass filtering the data. In the case of Kälksjön it was found that a low-pass filter with a cut-off frequency of 1/500 years^{-1} was able to remove the bias in the RPI before 7800 years BP. The long term-trend present in the Kälksjön RPI data could potentially be a bias related to the gradual stabilisation of catchment soils during the Holocene. This development of the catchment is typical for many Scandinavian lakes (Snowball and Sandgren, 2004; Zillén et al., 2003), which implies that similar environmental biases could be present in other RPI records as well (Snowball et al., 2007).

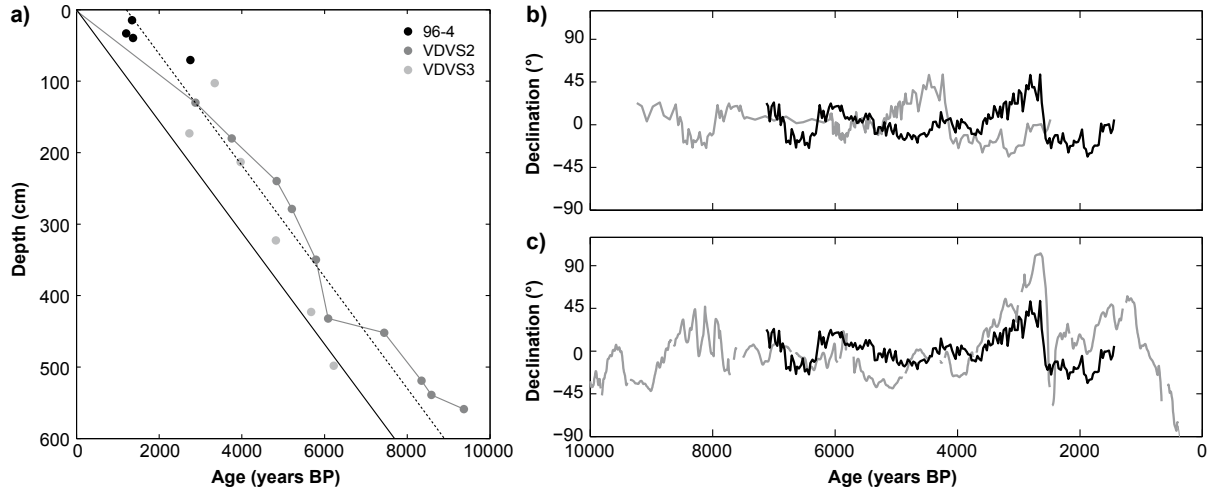

Figure 4. (a) Calibrated radiocarbon ages from core 96-4 (Doner, 2003) and VDVS2-3 (Thompson and Turner, 1985) from Vatndalsvatn plotted versus depth. The thick grey line shows the original age-depth relationship based on linear interpolation between the dates from VDVS2 and the sediment water interface. The black lines shows the alternative age models based on linear regression of all dates (Doner, 2003) before (dotted) and after (solid) removal of the mean age offset of 1200 years. All dates have been calibrated using the INTCAL09 calibration curve (Reimer et al., 2009). Note that slight differences in the depth scales between VDVS2 and VDVS3 are not taken into account. (b) Declination data plotted versus the alternative (black line) and the original (grey line) age-depth relationship. (c) Declination data plotted versus the alternative (black line) age depth relationship compared to declination data from core MD99-2269 (Stoner et al., 2007).

6.3 Chronology

Much of the early palaeomagnetic work of Holocene sediments was hampered by dating difficulties associated with the radiocarbon technique. It was often found that sediments rich in mineral detritus with the best palaeomagnetic properties were difficult to date due to the low organic content, particularly with the radiocarbon detectors available at the time. On the other hand, organic rich sediments were normally found to acquire a weak palaeomagnetic signal (Creer, 1985).

Several records in the palaeomagnetic database are subject to chronological uncertainties related to the dating of bulk sediments that contain 'old' carbon from the bedrock and soil, or recycled from within the lake (Stanton et al., 2010), 'diluting' the contemporary ^{14}C in the sediments and causing too old ages. A good example of this problem is the palaeomagnetic study from Vatndalsvatn (Thompson and Turner, 1985), Iceland, which originally relied on 16 radiocarbon dates based on bulk sediment samples. The site was revisited in 1996 and the surface sediments were re-dated using a combination of lead isotope, caesium and radiocarbon analyses (Doner, 2003). The new results indicated that the bulk radiocarbon ages are affected by the variable influx of old carbon resulting in a mean age offset of c. 1200 years (Fig. 4a) between calibrated ^{14}C age and true age. In Figure 4b the declination data from one core (VDVS2), digitised from the original publication by Korte et al. (2005), are plotted versus time using the original age-depth relationship suggested by Turner and Thompson (1985) and the alternative age-depth relationship from Doner (2003) determined by calculating a linear regression using all radiocarbon dates and then subtracting 1200 years. The data plotted using the updated age-depth relationship show good agreement with the palaeomagnetic data from a regional marine record (Stoner et al., 2007), also shown for comparison (Fig. 4c).

The example from Vatndalsvatn illustrates that unrecognised dating uncertainties may be present in the palaeomagnetic database. It also demonstrates how different methods of interpolating between dated horizons could significantly alter the appearance of the data. One way to approach this problem is to use the palaeomagnetic data by comparing PSV features to neighbouring and independently dated records or model predictions.

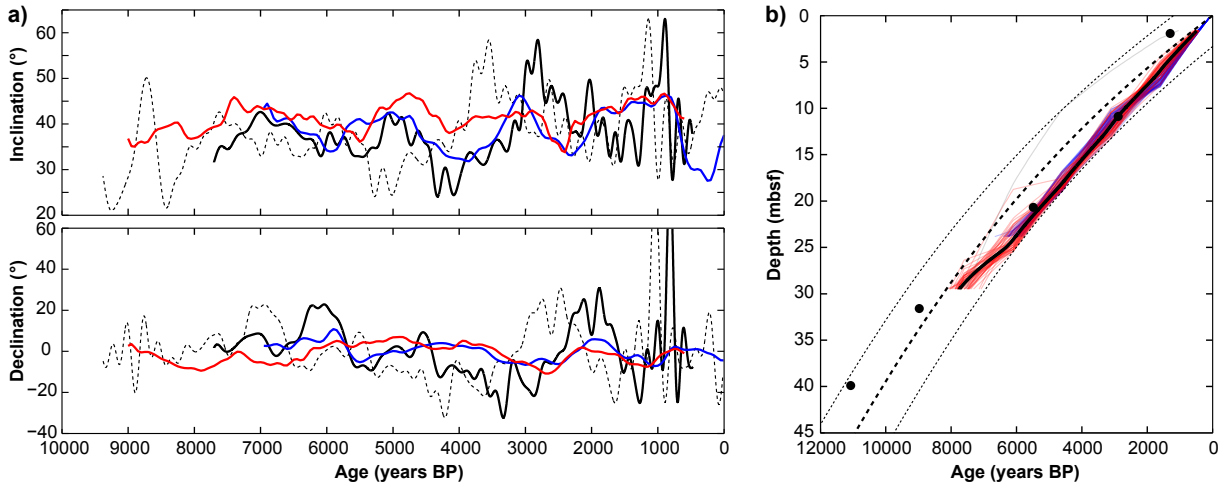

Figure 5. (a) Band-filtered inclination and declination of data from ODP Hole 1202B plotted versus the original (dashed black line) and preferred (solid black line) age-depth relationship compared to predictions from DE_{FNBKE} (red line) and CALS7K.2 (blue line). (b) Calibrated radiocarbon ages (black dots), the original age-depth model (thick dashed black line), the maximum and minimum limit of the stretch and compress routine (thin dotted black lines), the age-depth solutions with highest mean correlation coefficients for DE_{FNBKE} (red lines) and CALS7K.2 (blue lines) and the preferred age-depth model (solid black line) based on the correlation with DE_{FNBKE} plotted versus depth below seafloor. One age-depth solution from the correlation with DE_{FNBKE}, which did not conform to the rest, was removed from before calculating the mean (thin grey line).

Such an approach could potentially be used to assist the definition of a preferred age-depth relationship (Stoner et al., 2007), to help to identify outliers or other chronology related errors (Stanton et al., 2010) or to even date a sediment sequence (Barletta et al., 2010). Field modellers must be aware of how PSV data were secured to a time scale: for instance, there is a danger that palaeomagnetic data entered into the database were initially tuned to model predictions and their use could incorrectly reinforce models.

The technique for stretching and compressing the data described in Appendix IV offers a way to objectively synchronise the palaeomagnetic data with, for example, geomagnetic field model predictions. A high-resolution marine palaeomagnetic record from ODP Hole 1202B (Richter et al., 2006) in the southern Okinawa Trough can be used to illustrate this (Fig. 5). The original age-depth model was established from 11 AMS radiocarbon ages fitted with a third-order polynomial. The younger part of the record is shown in Figure 5b. In order to compare geomagnetic variations on similar time-scales both model predictions and data were low-pass filtered with a cut-off frequency of 1/200 years^{-1} before the analyses. Following the methodology outlined in Appendix IV, the palaeomagnetic data from ODP Hole 1202B were randomly stretched and compressed with 5000 iterations using a sliding window of 1200 years and a maximum perturbation of 1000 years. For each solution the inclination and declination data were compared to the predictions of both the dipole tilt reconstruction and CALS7K.2 and the agreement of the data was evaluated through correlation analyses. The results were used to search for the age-depth solutions with the on average best agreement between inclination and declination data from ODP Hole 1202B and model predictions. A preferred age-depth model was determined by averaging the top 1% of the age-depth solutions with the highest mean correlation coefficients (Fig. 5b). Note the removal of one age-depth solution, marked in grey in Figure 5b, which did not conform to the rest. The results from using the dipole tilt reconstruction or CALS7K.2 are very similar and both suggest a nearly linear age-depth relationship down to c. 25 m below the sediment surface, which is in good agreement with two of the radiocarbon samples. For simplicity the analysis had fixed starting conditions and, therefore, the modelled time scale was also constrained by the method, which might explain the discrepancy towards the top radiocarbon age.

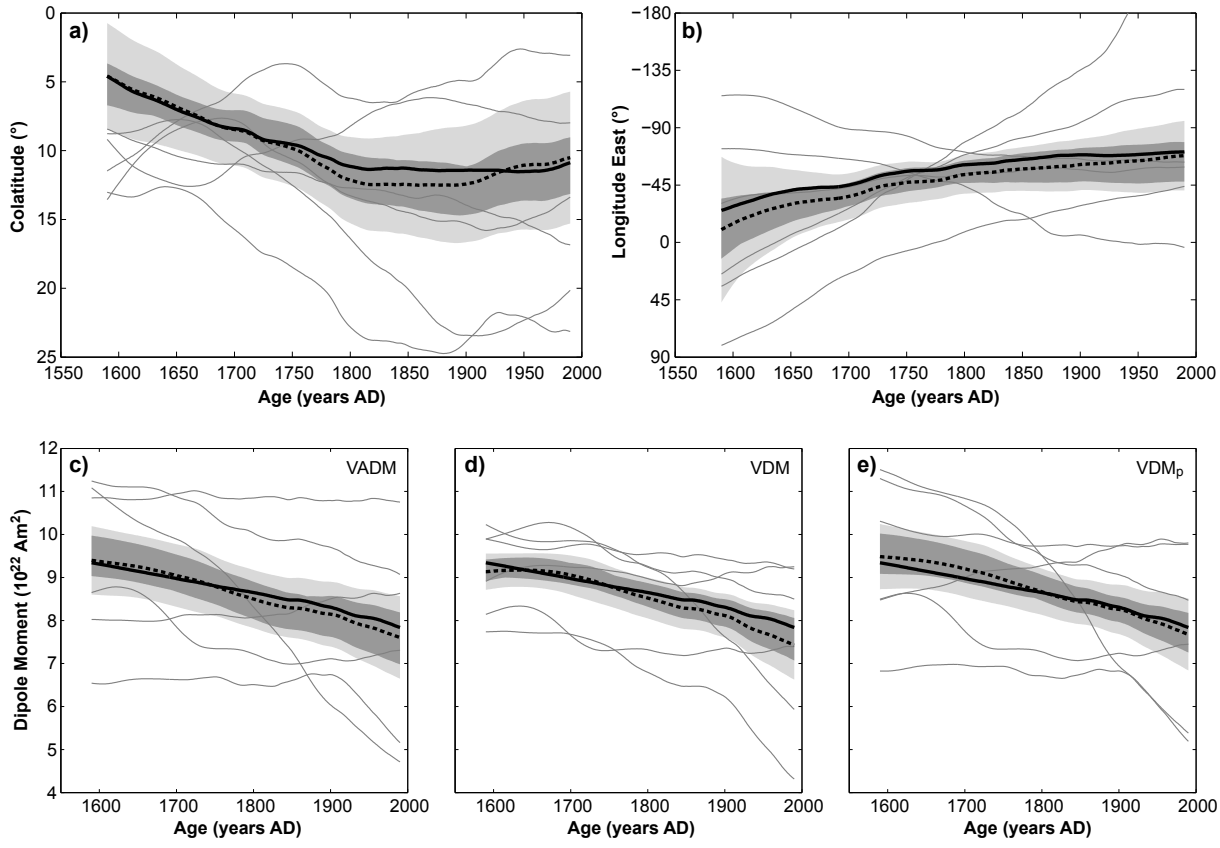

Figure 6. (a) Colatitude and (b) longitude of VGPs (thin light grey lines) from gufm.1 predictions at the coordinates of the five sites used to constrain the dipole tilt reconstruction and the addition of a sixth site from South Africa, the NGP derived directly from the gufm.1 model (solid black line) and the NGP estimated by averaging the VGPs (dashed black line). The light grey shaded area represents the error of the mean and the dark grey shaded area shows the minimum and maximum prediction from six different configurations based on five sites each. (c-e) The same as (a-b) but for VADM, VDM and VDM_p estimates compared to the dipole moment derived from the gufm.1 model.

7. Implications of Holocene dipole tilt reconstructions

7.1 Reliability of dipole field reconstruction

In Appendix III and IV the Holocene dipole tilt variation is reconstructed by averaging VGPs from five strategically selected sedimentary records; (i) Fish Lake in western USA (Verosub et al., 1986), (ii) Lake Nautajärvi in Finland (Ojala and Saarinen, 2002), (iii) Lake Biwa in Japan (Ali et al., 1999), (iv) Lake Keilambete in Australia (Barton and McElhinny, 1981) and (v) Lake Escondido in Argentina (Gogorza et al., 1999; Gogorza et al., 2002). The approach differs from other similar studies (Merrill and McElhinny, 1983; Ohno and Hamano, 1992, 1993; Valet et al., 2008a) by putting the greatest emphasis on attaining an equal spatial data distribution rather than choosing the data by availability. For comparison a dipole estimate was also constructed using the predictions of the gufm.1 model (Jackson et al., 2000) for the last four centuries (fig. 6a-b) at the coordinates of the selected sedimentary records and a sixth site in South Africa, added to fill the data gap in the southern hemisphere. The results demonstrate the level of accuracy that can be expected from these reconstructions. Differences between the estimated positions of the NGP and the positions determined directly from the gufm.1 model are well within the confidence limits of the dipole estimate. An additional uncertainty is introduced by using five records instead of six, shown by the dark grey band in Figure 6 representing the maximum and minimum limit of the result from six possible configurations, removing one record at the time.

In Figure 6c-e the dipole moment is estimated by averaging VADMs, VDMs or VDM_ps

(determined using the NGP derived directly from gufm.1) from the same six sites. The results illustrate that the method used for the directional data, could, theoretically, also be used to constrain the dipole moment with uncertainties in the range of 0.5×10^{22} Am^2.

Given the simplicity of the approach and the minimal amount of data required, it is perhaps surprising how well the method works. This success could be related to the fortunate locations of four of the records, which happen to coincide approximately with the stationary high latitude flux lobes at the core mantle boundary. It is possible that these locations provide a strategic advantage for reconstructing variations in the dipole field. A similar comparison to the above (see Appendix III, table 1), using two different distributions of observation station data rotated approximately 60° in longitude with respect to each other, hints at such a potential relationship but has not been investigated further.

7.2 Holocene dipole field variations

As shown in Appendix IV, the reconstructed dipole tilt variations are characterised by recurrent tilt maxima every c. 1350 year separated by periods with almost no tilt. The dipole axis appears to exhibit two preferred states with NGP longitudes confined to c. -120° and 30° East. During the relatively short time span of the record the dipole has shifted between these two states roughly every 2700 years. Large and well-defined tilt maxima, which are in phase with the 1350-year periodicity signal, are found to coincide mainly with NGP longitudes around 30°, the current tilt being the exception. Comparisons between the dipole tilt variation and eclipse-based reconstructions of changes in LOD (Morrison and Stephenson, 2001; Stephenson and Morrison, 1995) show a remarkable in-phase relationship during the last 2500 years (Appendix IV). These millennial scale variations in Earth's rotation rate, inferred from the LOD record, are considered to be caused by exchange of angular momentum between the mantle and the core due to time-dependent azimuthal core flow (Dumberry and Bloxham, 2006). The good agreement between the records implies that the 1350-year periodicity may constitute a dynamic component of core flow dynamics.

The dipole tilt reconstruction can explain a large part of the variation in the Holocene directional data on the millennial scale (Appendix III). Significant non-dipole contributions are observed in the data, sometimes varying in phase with the variations predicted by a geocentric dipole. In other cases the non-dipole influence appear to give rise to persistent offsets in the data, such as generally lower inclinations in Lake Nautajärvi around 7500-5500 years BP and in Fish Lake around 5000-3000 years BP (see Fig. 9 in Appendix III). Model-data comparisons suggest that some regions, particularly Mediterranean-Africa and South America, show less agreement with the dipole tilt predictions, which implies that these regions may have been comparatively more dominated by non-dipole field components during the Holocene. However, to some degree these differences are probably related to poor palaeomagnetic data quality and/or the lack of accurate and precise time control characteristic to some of the records.

In Appendix IV, VADM averages from western Eurasia (Genevey et al., 2008), the region with highest density of palaeointensity data, are compared to a tilt modulated ^{10}Be based dipole moment reconstruction. The comparison shows that the palaeointensity data are consistent with the dipole tilt reconstruction, showing generally higher intensities when the dipole axis tilted towards western Eurasia and lower intensities when the dipole tilted away. In Figure 7 the same comparison is made for VADM averages of absolute palaeointensity data from three equally large regions chosen to achieve an approximately even distribution in longitude (Fig. 8a): (i) Europe-Near East (30-60° latitude, 10°W-50°E longitude), (ii) eastern Eurasia-Far East (20-50° latitude, 95-155°E longitude) and (iii) southern part of North America (15-45° latitude, 225-285°E longitude). The selected VADM data, which were retrieved from the online GEOMAGIA50v2 database (Donadini et al., 2006; Korhonen et al., 2008), constitute c. 70% of the available data for the last 9000 years. No sedimentary palaeointensity data were used in this comparison due to the difficulty in assessing the uncertainties of such records. The VADM data averages were

calculated using a sliding window of 500 years shifted by 250 years. In accordance with Knudsen et al. (2008) data from Sun dried objects and iron slags (30 values) were omitted from the study as these materials have been found to be unsuitable for palaeointensity experiments (Donadini et al., 2007). The tilt modulated VADMs were determined in the same way as in Appendix IV using a ^{10}Be based dipole moment reconstruction, low-pass filtered with a cut-off frequency of 1/3000 years^{-1} and normalised to Holocene average VADM from Knudsen et al. (2008).

The uncertainties in the data used in this comparison, represented by the standard deviations, are noticeably larger than the data compilation used to construct the VADM averages for western Eurasia (Genevey et al., 2008). This is due to the stringent selection criteria applied by Genevey et al. (2008), which removed almost 50% of the data that did not fulfil the minimal reliable standards. Even so the data presented here from Europe-Near East (Fig. 7b) are almost identical to the compilation of western Eurasia from Genevey et al. (2008) when compared over the same time window. Both data sets show the same millennial-scale variations in agreement with the tilt-modulated reconstruction, particularly the intensity peaks at 2650 and 1200 years BP. It is noted that the data for all three regions in Figures 7 and 8 are associated with such large errors that most of the millennial-scale variations investigated here cannot be considered significant. However, since other studies based on more selected data from the same regions show similar variations (Genevey et al., 2008), these errors are ignored for this comparison.

The data from eastern Eurasia-Far East show much more variability than predicted by the dipole tilt modulated VADM (Fig. 7c). In fact, the tilt modulated VADM does not show any major variability in this region besides a dip in intensity associated with the dipole tilt maxima at 2650 years BP, which is partly reflected in the data. From this comparison, it would appear that non-dipole field contributions have been relatively more important in this region during the Holocene. However, it is also possible that some of these variations may also be associated with changes in the dipole moment on time scales shorter than 3000 years, which would

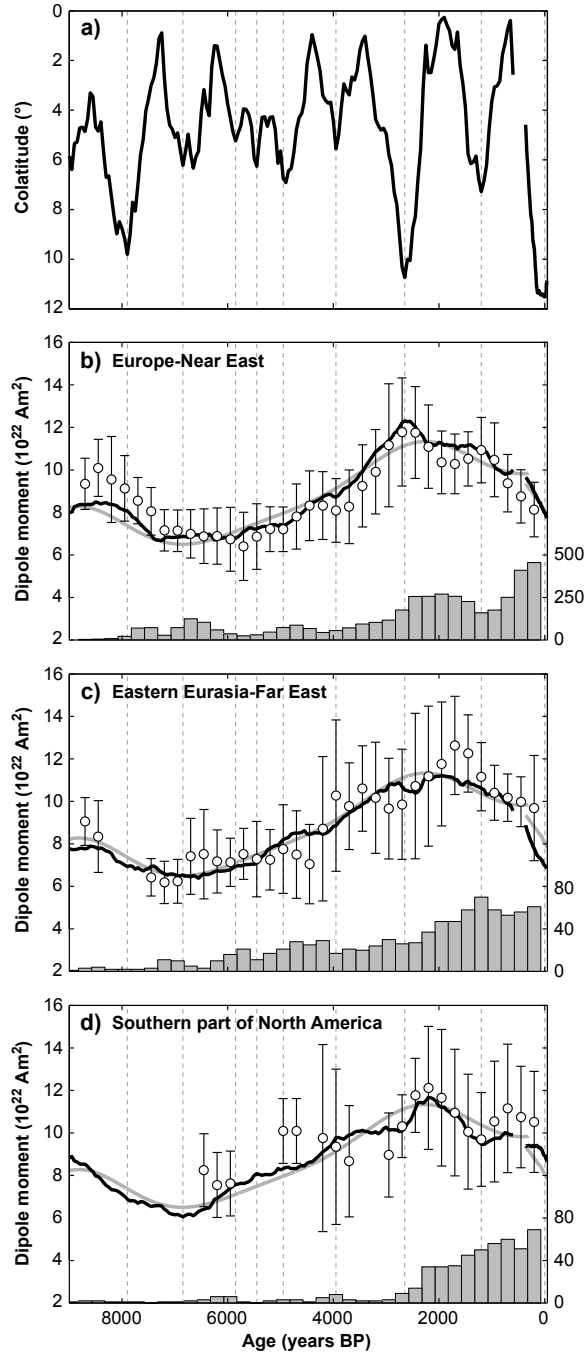

Figure 7. (a) NGP colatitude of DE_{FNBKE} and gufm.1. VADM averages (open black circles) from (b) Europe-Near East, (c) eastern Eurasia-Far East and (e) southern part of North America calculated using a 500-year sliding window shifted by 250 years. Mean values are reported only when at least three independent results are available per time window. The number of data points used for each average is depicted by the grey bar plots in the bottom of each panel, note different y-scale on the right side of the plot. Also shown is the dipole moment estimate based on the ^{10}Be data from the GRIP ice core and the gufm.1 dipole moment (grey lines) and the tilt-modulated ^{10}Be- and gufm.1-based VADM (black lines) for each region. Peaks in dipole tilt are highlighted throughout the figure with vertical thin grey dotted lines.

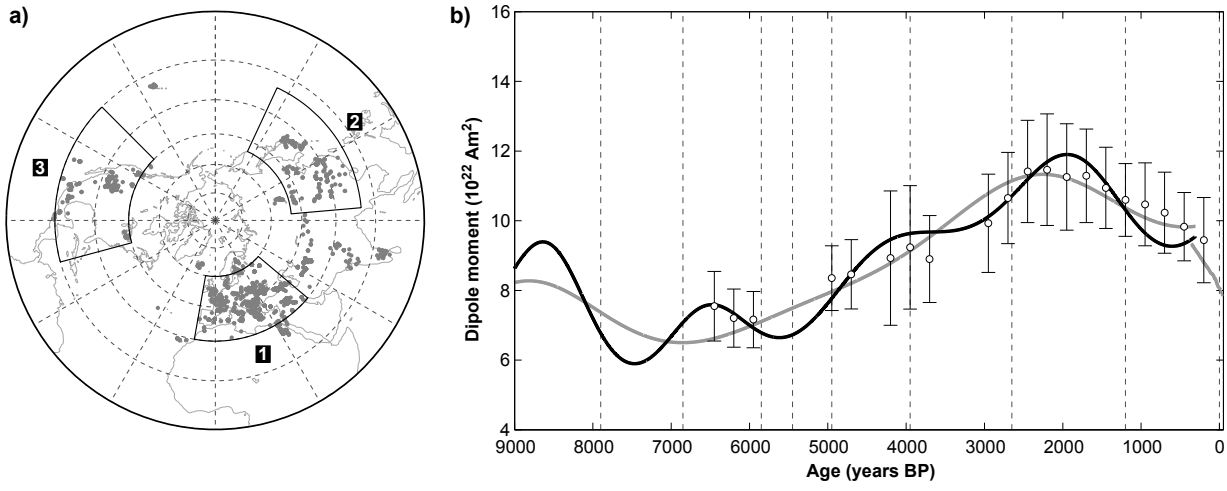

Figure 8. (a) Map of the northern hemisphere showing the limits of the three zones (black 'squares') defined in the text and the distribution of the intensity data (grey dots). (b) Dipole moment estimate based on the VADM data in Figure 7 (open black circles) and based on the GRIP ^{10}Be data low-pass filtered with cut-off frequencies of 1/3000 years^{-1} (grey line) and 1/1500 years^{-1} (black line).

have been removed by the low-pass filter of the ^{10}Be data. The potentially large influence of the non-dipole field at a given site is exemplified in Figure 6c-e.

The comparison with the data from the southern part of North America and the tilt-modulated VADM for this region shows a reasonably good agreement on millennial scales during the last 3000 years for which there are continuous data (Fig. 7d). The data show that the peak intensities between the three latest dipole tilt maxima appear to be almost perfectly anti-correlated to the data from Europe-Near East, in accordance with the tilt modulated VADM prediction.

Similar to the comparison with directional data it appears that the intensity data from both Europe-Near East and southern part of North America, between 3000 and 500 years BP, co-vary with the dipole tilt prediction, but with larger amplitude variations. This difference in amplitude is particularly evident in the comparison with the higher resolution compilation from western Eurasia (Appendix IV). The observed relationship implies that the local changes in the regional magnetic field beneath these two regions may have been intimately linked with the processes causing the dipole tilt variation during these periods.

The high intensities observed in the data from western Eurasia, which coincide with the dipole tilt maxima at 2650 and 1200 years BP, have been attributed to variations of the dipole moment (Knudsen et al., 2008; Valet et al., 2008a). Considering the large geographic bias in the distribution of the data towards western Eurasia, it could be argued that the reconstructions fail to remove the influence of the equatorial component of the dipole field, i.e. the dipole tilt, as well as non-dipole field contributions (Appendix IV). To test this possibility the binned data from the three regions in Figure 7b-d were used to calculate a regionally weighted VADM average, thus providing an estimate of the dipole moment (Fig. 8b). The approach constitutes a direct analogue to the dipole tilt reconstruction DE_{FNB} (Appendix III) and should remove the effects of a geographical bias in the northern hemisphere data. However, similarly to DE_{FNB}, the results will also mainly reflect the geomagnetic field in the northern hemisphere and could systematically overestimate (Korte and Constable, 2005b) or underestimate the dipole moment. The weighted VADM averages predict highest geomagnetic field intensity at roughly 2000 years BP, i.e. between the dipole tilt maxima at 2650 and 1200 years BP. This is in good agreement with the peak found in the ^{10}Be data low-pass filtered with a higher cut-off frequency (1/1500 years^{-1}) implying that it may be a real feature of the dipole moment. However, part of this high frequency ^{10}Be variation may be due to solar modulation. None of the data sets suggests increased intensity at the dipole tilt maxima at either 2650 or 1200 years BP, which supports the assessment that these features

seen in the western Eurasian data are rather local than global characteristics of the dipole field intensity.

7.3 Dipole tilt contributions

Amit and Olson (2008) argue that changes in dipole tilt correspond to re-organisations of magnetic field structures on the CMB associated with – and augmented by – changes in the flow structure. The rapid tilt increase before 1800 AD and the decrease after 1960 AD are identified as being mainly caused by north-south displacements of high latitude flux lobes and westward drift of equatorial flux. The tilt increase prior to 1800 AD involved generally equatorward motions of the flux lobes below North America and the Indian Ocean and southward motion of the flux lobe below South America. At present the tilt is mainly controlled by magnetic field asymmetry in the southern hemisphere of the core, which is largely related to the weak and reversed flux beneath the South Atlantic (Amit and Olson, 2008).

From the observations of the recent tilt it is possible to hypothesise that the reconstructed dipole tilt variations may, to a large degree, have been related to displacement and/or distortions of high latitude flux lobes. However, tilt variations could potentially also result from relatively small changes in the magnetic field that perturb a delicate balance of positive and negative tilt contributions (Amit and Olson, 2008). Therefore, one needs to be cautious when interpreting the reconstructed tilt in terms of magnetic field structures on the CMB. Nevertheless, this hypothesis is supported by recent analyses of Dumberry and Finlay (2007) who, based on calculations of the CALS7K.2 model (Korte and Constable, 2005a), observe variations in the azimuthal motions of northern hemisphere high latitude flux lobes for the last 3000 years that are in phase with changes of the reconstructed dipole tilt. It could be argued that the apparent preferred states of the NGP with longitudes, confined to either 120° West or 30° East, might be related to two different preferred configurations of the high latitude flux lobes, perhaps involving a third pair beneath Europe. The occurrence of such strong flux below Europe has been detected in time-averaged palaeomagnetic field models (Johnson and Constable, 1995; Kelly and Gubbins, 1997; Korte and Holme, 2010). To investigate different configurations of the flux lobes and their relation to the dipole tilt, one would ideally require spherical harmonic models that can be projected down to the CMB. However, a detailed analysis of the VGP data used to constrain the dipole tilt could, due to the favourable locations of the sites in relation to the high latitude flux lobes, potentially also provide some valuable insights of the magnetic field structures governing the tilt.

Figure 9 shows the dipole tilt reconstruction divided into its northern and southern hemispherical components by calculating VGP averages of the data from the respective regions. Also shown is an estimate of the tilt contribution from the individual records, evaluated over a 300-year window centred on different dipole tilt maxima, which were chosen rather subjectively (see Fig. 9). The tilt contribution of a record is defined as the angular decrease (positive contribution) or increase (negative contribution) in the estimated dipole tilt resulting from the removal of this record from the calculation compared to the original estimate based on all five records. A positive tilt contribution could either be a sign of strong regional magnetic flux if the dipole is tilting towards the region or weak and even reversed flux if the dipole is tilting away from it.

For comparison the same calculations were made using the predictions from the gufm.1 model (Jackson et al., 2000), shown in Figure 6, with the addition of a sixth site from South Africa. The results show, as expected, a relatively larger tilt contribution from the southern hemisphere. The tilt increase is rather consistent in data from both hemispheres up to 1800 AD after which the northern hemisphere component starts to decrease. This is around the same time as the South Atlantic Anomaly started to develop and the tilt became more controlled by structures in the southern hemisphere, which is arguably reflected by the increasing difference between the hemispherical tilt estimates.

Most of the dipole tilt maxima reconstructed from palaeomagnetic field data do not exhibit a difference between the northern and southern hemispherical VGP data that is as large as the

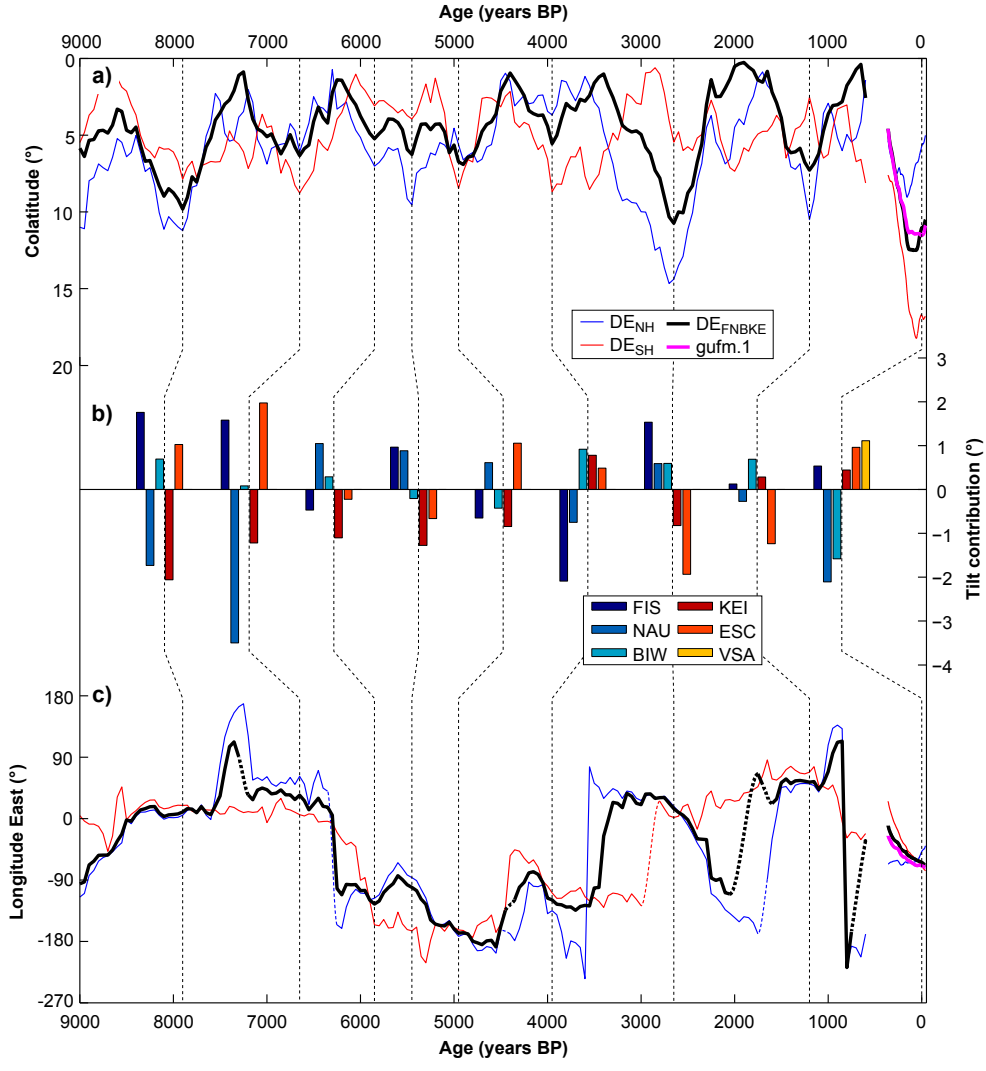

Figure 9. (a and c) NGP colatitude and longitude of DE_{FNBKE} (black line), tilt estimates based on VGP data from the northern (blue line) and southern hemisphere (red line) and gufm.1 (magenta line). (b) Tilt contributions from the individual sites calculated over 300-year window covering peaks in dipole tilt (highlighted with vertical dotted lines). FIS = Fish Lake, NAU = Lake Nautajärvi, BIW = Lake Biwa, KEI = Lake Keilambete, ESC = Lake Escondido and VSA = site in South Africa. Note that large deviations in longitude associated with colatitudes below 1° were removed and interpolated using a cubic spline.

difference associated with the current field morphology. However, the lack of data from South Africa may complicate the interpretation. The closest analogue appears to be the tilt maxima at 2650 years BP, which contrary to the current field, is characterised by a larger tilt contribution from the northern hemisphere. There is no obvious connection between the four tilt maxima associated with NGP longitudes around 30° East. While the tilt maxima at 2650 and 1200 years BP are observed mainly in data from the northern hemisphere, the maxima at 7900 and 6650 years BP appear to be mostly apparent in data from North America (Fish Lake) and South America (Lake Escondio). The dipole tilt variation between 6250 and 3400 years BP, which is associated with NGP longitudes around 120° West, is not as easily characterised by minima and maxima and it is consequently harder to evaluate the spatial origin of the tilt contribution. It is possible that both the reconstruction and interpretation of the tilt variation during this period are more affected by the lack of data from the southern hemisphere. This seems like a plausible explanation considering the longitudes of the predicted south geomagnetic poles, ranging from 0-90° East, and the geographical gap in the data distribution (e.g. South Africa located at c. 30° East).

The improved spatial and temporal distribution of the intensity data for the last 3000 years allow for a more detailed examination of the tilt variation. As shown in Figure 7 both the tilt maxima at 2650 and 1200 years BP towards western Eurasia are associated with high intensities in this region, which suggests that they may be related to the appearance of high intensity flux beneath Europe. In addition, low intensities in North America may indicate a synchronous weakening or displacement of the Canadian flux patch. A set of new models from Korte and Holme (2010) were constructed specifically to investigate the occurrence of high latitude flux lobes. These models were constrained using the same data as CALS7K.2 (Korte and Constable, 2005a) but with different a priori conditions based on time-averages of the gufm.1 (Jackson et al., 2000) and CALS3k.3 (Korte et al., 2009) models. The predicted flux distributions are generally in agreement with the current analysis for the tilt maxima at 1200 years BP. For the tilt maxima at 2650 years BP the flux on the CMB is distributed more diffusely and less easily characterised by specific flux lobes. Interestingly the models also predict the presence of reversed flux in the north-western Pacific associated with both tilt maxima, which disappears briefly in between. Considering the similar VGP signatures (Fig. 9) with the current tilt it is tempting to draw analogues between these reversed flux patches and similar features beneath the South Atlantic today and their role in controlling the current tilt. This consideration would imply that both the tilt maxima at 2650 and 1200 years could have been characterised by magnetic field asymmetries in the northern hemisphere – similar to the current asymmetry in the southern hemisphere.

The two tilt maxima at 7900 and 6650 years BP are characterised by negative tilt contributions from Europe (Lake Nautajärvi), due to generally lower inclinations, which appear to contradict the presence of high intensity flux beneath Europe during these times. On the other hand, the VADM compilation from western Eurasia (Genevey et al., 2008) show slight increases in intensity related to the tilt maxima (Appendix IV), which might suggest the opposite. Positive tilt contribution from South America imply northward movement and/or intensification of the flux lobe beneath Patagonia while negative tilt contribution from North America may indicate a similar weakening or displacement of the Canadian flux lobe which has been suggested for the more recent tilt maxima. The models from Korte and Holme (2010), arguably not as well constrained for this earlier time period, hint that strong flux below Europe and reversed flux patch in the north-western Pacific at 6650 years BP (the models only cover the last 7000 years) but do not show any significant deviations of the Patagonian and Canadian flux lobes.

To summarise, the palaeomagnetic data suggests that the dipole tilt variation associated with NGP longitudes around 30° could be related to the appearance of strong magnetic flux beneath Europe, but the evidence is not conclusive. It appears that a weakening or displacement of the Canadian flux lobe may have been equally or more important. In addition, the model results from Korte and Holme (2010) suggest that the occurrence of reverse flux beneath the north-western Pacific could potentially also have contributed to the observed tilt variation. The reconstructed dipole tilt variation associated with NGP longitudes of around 120° West does not exhibit similar consistent patterns and have therefore not been studied in detail.

7.4 Future prospects

The development of the sedimentary palaeomagnetic database will improve Holocene geomagnetic field models. Work is currently in progress by the palaeomagnetic community (Fabio Donadini et al.) to update the GEOMAGIA50v2 database to include sedimentary data. By importing the data from individual cores it will be possible to objectively rank each record based on the criteria of reproducibility described in section 6.1. Similarly the dating control could be ranked by methodology and number of independent dating horizons. New age-depth models should be constructed for records with large known uncertainties (e.g. due to radiocarbon dating problems) or they should be discarded altogether. Sites with proven palaeomagnetic properties but questionable age control could be re-sampled and re-dated with newer equipment and techniques possibly also

yielding new RPI data. As shown by the comparative analyses, using gufm.1 predictions, the dipole estimates and geomagnetic field models in general would greatly benefit from new palaeomagnetic data from the southern hemisphere, particularly from Southern Africa.

Radiocarbon 'wiggle-match' dating of the palaeomagnetic feature "f" in Kälksjön, related to the dipole tilt maxima at 2650 years BP, is currently in progress. Extending this approach to date the corresponding events in different palaeomagnetic records around the world could significantly improve our understanding the spatial and temporal description of magnetic features related to the tilt variation. Dating uncertainties associated with individual reconstructions are arguably the biggest challenges for geomagnetic field models. To address these uncertainties a Bayesian model approach, similar to that used by Leonhardt et al. (2009) for the Laschamp excursion, could potentially be employed for the Holocene. In this context the stretch and compress technique described in section 6.3 could be used to synchronise records with preliminary model predictions.

The dipole modelling approach outlined in this study could potentially be used to extend the dipole tilt reconstruction to longer time periods provided enough widespread palaeomagnetic records with sufficient high resolution (e.g. Lund et al., 2005) are available. With such a reconstruction it would be possible to evaluate the significance of the 1350-dipole tilt cyclicity and the preferred states in NGP longitude. In addition, potential relationships between dipole tilt maxima and preferred VGP paths during geomagnetic field excursions (Laj et al., 2006) and reversals (Clement, 1991) could be investigated.

8. Conclusions

The discussion in this synthesis lead to the following main conclusions:

- The current sedimentary palaeomagnetic database has to be reviewed carefully when used to constrain new and improved geomagnetic field models.
- A reasonable estimate of the dipole tilt variation can be inferred from a selection of limited but high quality data with a good spatial distribution.
- The reconstructed dipole tilt variation shows two apparent preferred states in NGP longitude, which implies a persistent non-zonal structure in the Holocene geomagnetic field.
- A dominant 1350-year cyclicity is identified in the tilt variation, which is highly correlated to millennial scale variations in the length of day, suggesting that it may constitute a dynamic component of the core flow dynamics.
- Reconstructions of dipole moment can be improved through combined studies of palaeomagnetic and cosmogenic radionuclide data.

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Svensk sammanfattning

Det jordmagnetiska fältet kan till stor del (80-90%) beskrivas av ett dipolfält, producerat av en magnet i mitten av jorden med en lutning på 11° från rotationsaxeln. Magnetfältet genereras av konvektionsströmmar i den flytande järnrika yttre delen av kärnan i form av en jättelik dynamo, och tros ha varit aktivt sedan kärnan bildades för ungefär 4.5 miljarder år sedan. Det jordmagnetiska fältet är långt ifrån statiskt, utan förändras kontinuerligt på tidskalor som sträcker sig från millisekunder till miljontals år. Så kallade polomvändningar, då nord- och sydpol byter plats, tillhör de mest kända och dramatiska förändringarna. Den senaste polomvändningen inträffade för ungefär 780 000 år sedan.

Jordens magnetfält utgör ett viktigt skydd mot strålning från bland annat solen. Utan ett aktivt magnetfält skulle jordens atmosfär successivt ha blåst bort av solvinden, och planeten hade varit obeboelig för människor. Det har även föreslagits att förändringar i det jordmagnetiska fältet indirekt kan påverka jordens klimat. Traditionellt sett har rekonstruktioner av förändringar i jordens magnetfält använts inom geovetenskapen för att: (i) spåra rörelser av kontinentalplattor, (ii) korrelera och datera geologiska arkiv och (iii) studera jordens inre.

Historiska mätdata från magnetiska observatorier i kombination med framförallt kompassavläsningar noterade i loggböcker från olika rederier har gjort det möjligt att rekonstruera förändringar i jorden magnetfält de senaste 400 åren. Längre bak i tiden baseras studier av det jordmagnetiska fältet huvudsakligen på paleomagnetiska data. Naturliga remanenta magnetiseringar i olika geologiska och arkeologiska arkiv bevarar information om det forna magnetfältets riktning och intensitet. De remanenta magnetiseringarna förvärvas vid avsvalnad av ett magnetiskt material (t.ex: lavaflöden, bränd keramik, stenugnar) genom dess curietemperatur (580° C för magnetit) eller vid deposition av magnetiska mineralkorn i vatten under lugna förhållanden (sjö- eller havssediment).

I den här studien har jag fokuserat framförallt på paleomagnetiska analyser av sjösediment. Naturliga processer såsom vittring och erosion medför en kontinuerlig tillförsel material till sjöar som förr eller senare avlagras som bottensediment. Magnetiska mineral är vanligt förekommande i framförallt basiska bergarter (t.ex. diabas), men kan även produceras av så kallade magnetotaktiska bakterier som använder de magnetiska kristallerna för att orientera sig i vattenkolumnen. När de magnetiska mineralen sjunker till sjöbotten, där det råder lugna och relativt strömfria vattenförhållanden, riktar de in sig efter jordens magnetfältet. Orienteringen av mineralkornen fixeras och bevaras i sedimenten genom att de magnetiska mineralkornen kilas fast av omgivande mineralkorn. Sjösedimenten fungerar på så sätt som ett naturligt arkiv av magnetfältet. Under flera årtusenden kan metervis av sediment deponeras, och genom att mäta den remanenta magnetiseringen i sedimentprover från olika sedimentdjup går det att återskapa lokala förändringar i det jordmagnetiska fältet.

En alternativ metod för att rekonstruera förändringar i jordens magnetfält baseras på koncentrationsmätningar av kosmogena nukleider (t.ex. ^{14}C och ^{10}Be) i sediment, iskärnor eller trädringar. Kosmogena nukleider bildas i atmosfären genom interaktioner mellan kosmisk strålning och atomer i atmosfären. Eftersom jordens magnetfält agerar som ett skydd mot kosmisk strålning är produktionen av kosmogena nukleider omvänt

relaterad till styrkan av magnetfältet, dvs ett svagare magnetfält leder till att mer kosmogena nukleider bildas.

I jämförelse med historiska mätdata är informationen om jordens magnetfält som erhålls från paleomagnetisk data och kosmogena nukleider förknippad med relativt stora osäkerheter. Det genomgående syftet med den här avhandlingen har varit att granska tillförlitligheten av paleomagnetiska rekonstruktioner från enskilda studier och globala modeller.

I den första delen av studien valdes två sjöar ut för paleomagnetiska analyser: Lake Pupuke i Nya Zeeland och Kälksjön i Sverige. Datakvaliteten utvärderades genom att jämföra de paleomagnetiska resultaten med klimatkänsliga sedimentparametrar och oberoende rekonstruktioner baserade på kosmogena nukleider. Målet med studierna var att datera sedimenten genom att identifiera kända regionala eller globala variationer i jordens magnetfält, och att studera variationer i det jordmagnetiska fältets intensitet.

I den andra delen av studien presenteras nya modeller av jordens dipolfält för de senaste 9000 åren. Rekonstruktionerna är baserade på paleomagnetiska studier från fem sjöar, strategiskt utvalda med hänsyn till datakvalitet, osäkerheter i åldersbestämning och geografiskt läge. Resultaten antyder att dipolfältets lutning varierar i cykler med 1350 års intervall. Rekonstruktionerna indikerar även att dipolfältet har karakteriseras av två olika konfiguartioner de senaste 9000 åren; antingen med en lutning mot Nordamerika (dagens fält inkluderat) eller mot Europa. Ett sådant bestående asymmetriskt mönster kan ses som en indikation på att magnetfältet påverkas av en eller flera externa faktorer (utanför kärnan) , t.ex. temperaturskillnader i den nedre manteln.

De cykliska variationerna i dipolfältets lutning överensstämmer väl med rekonstruktioner av jordens rotationshastighet de senaste 2500 åren. Sådana variationer har tolkats som ett utbyte av rörelsemängdsmomentum mellan manteln och kärnan på grund av longitudinella flödesvariationer i den yttre kärnan. Med andra ord, om kärnans rotationshastighet ökar måste manteln (och jordskorpan) rotera långsammare för att bevara jordens totala rörelsemängdsmomentum. Det utmärkta sambandet mellan de båda rekonstruktionerna antyder att 1350-års periodiciteten kan utgöra en viktig komponent i kärnans flödesdynamik.

Resultaten från den här avhandlingen demonstrerar potentialen av att använda sedimentära paleomagnetiska data för att rekonstrura förändringar i jordens magnetfält, men påpekar även brister i den nuvarande databasen och vikten av en nogrann granskning vid urvalet av data.

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