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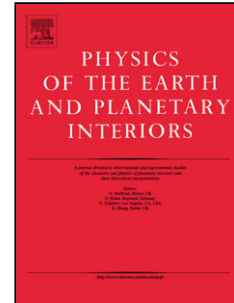
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Title: Environmental influence on relative palaeointensity estimates from Holocene varved lake sediments in Finland

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1. Introduction

Reconstructing past variations in geomagnetic palaeointensity provides information with various applications. These include e.g. modelling of the evolution of the geomagnetic field moment (Korte and Constable, 2005) and reconstructions of past solar activity by investigations of cosmogenic isotopes, whose production is in part modulated by the strength of the geomagnetic field (Thouveny et al., 1993; Beer 2000; Snowball and Muscheler, 2007). Importantly, globally synchronous variations in geomagnetic palaeointensity provide chronological markers for correlating different geological archives (Channell et al., 2009).

Variations in geomagnetic field intensity have been observed for the last two centuries (Courtillet and Le Mouél, 1988; Stern, 2002). In order to look further back in time, different archaeological and geological proxies have been employed to collect data on the variations in palaeointensity. These include extrusive rocks and baked archaeological artefacts carrying thermoremanent magnetisation (TRM), which allows the reconstruction of palaeointensity in absolute terms (Teanby et al., 2002; Kovacheva et al., 2004; Donadini et al., 2007). Unfortunately, the occurrence of these materials is scattered in space and time, and their precise dating may be ambiguous (Clark et al., 1988). Continuous information on the behaviour of the geomagnetic field can be obtained from investigations of marine and lacustrine sedimentary sequences, which may serve as records of relative palaeointensity (Meynadier et al., 1994; Williams et al., 1998; Guyodo and Valet 1999). Whereas marine sediments allow the reconstruction of long-term relative palaeointensity records, lacustrine and some river estuarine sediments provide more highly resolved palaeointensity data due to their generally higher deposition rates. The basic assumption underlying reconstruction of relative palaeointensity in sediments is that the measured natural remanent magnetisation (NRM) is in linear proportion to the concentration of magnetic minerals and the ambient magnetic field strength at the time of deposition (Kent, 1973; Tucker, 1981). To correct for the long-core variations in the magnetisability of sediments, laboratory-induced magnetisations and different types of remanence are applied to estimate the concentration of magnetic minerals. These include low-field magnetic susceptibility (κ), anhysteretic remanent magnetisation (ARM) and saturation isothermal magnetisation (SIRM). However, other physical factors such as hydrodynamic and gravitational processes, particle flocculation, changes in the concentration, type and mineralogy of clay minerals and salinity, may influence the acquisition of remanence, and thereby the intensity of magnetisation in sediments (Shcherbakov and Shcherbakova, 1983; Lu et al., 1990; Katari and Tauxe, 2000; Katari and Bloxham, 2001; Franke et al., 2004; Mitra and Tauxe, 2009).

Reconstruction of relative palaeointensity requires uniform magnetic properties, which have been reviewed by Tauxe (1993) and Valet (2003). Despite the rather strict constraints, relative palaeointensity records have been proposed in several recent studies, which have encouraged further investigations on relative palaeointensity using high-resolution sedimentary records (St-Onge et al., 2003; Richter et al., 2006; Snowball et al., 2007). In some cases, the reliability of relative palaeointensity reconstructions has been questioned due to unremoved climatic and/or environmental imprint (Weeks et al., 1995; Schwarz et al., 1996; Lund and Schwarz, 1999; Kok, 1999; Brachfeld and Banerjee, 2000; Nowaczyk et al., 2001; Frank et al., 2002).

This study presents the results of reconstructing relative palaeointensity from the sediments of two small neighbouring lakes in eastern Finland during the last 5100 years using conventional bulk normalisation procedures. The high quality of the palaeomagnetic directional records from these lakes has been recently discussed by Haltia-Hovi et al. (2010a). The investigated sediments are annually laminated, i.e. varved, providing an independent and precise chronology (Haltia-Hovi et al., 2007, Haltia-Hovi et al., 2010a). The results discussed document the complex relationship between relative palaeointensity estimates using standard normalisation techniques and unremoved environmental imprints, and the necessity of careful consideration of the environmental biases in the proposed relative palaeointensity estimates from similar sediments.

2. Study sites, varve formation and sediment coring

Lake Lehmilampi (hereinafter, Lehmilampi; 63°37'N, 29°06'E, surface area 15 ha, 95.8 meters a.s.l.) and Lake Kortejärvi (hereinafter, Kortejärvi; 63°37'N, 28°56' E, surface area 23 ha, 105.3 meters a.s.l.) are two small boreal lakes located in Northern Karelia, Eastern Finland (Fig. 1). The bedrock of the study area is part of the Fennoscandian Shield, which belongs to the multiply deformed late Archaean basement characterised by tonalites, trondhjemites and migmatites (Luukkonen, 2005). Climate has clear seasonal contrasts, and mean temperatures in January and July are -10 °C and +16 °C, respectively (Helminen 1987). The investigated sediments are annually laminated gyttja clay or clay gyttja sediments. Varve formation and preservation in these lakes results from the combined effects of climatically regulated seasonal changes in sediment sources together with deficiency of dissolved oxygen in the deepest areas of the basins. Flooding following snowmelt in the spring transports fine detrital matter to lakes, and from summer to winter, fine autochthonous and allochthonous organic matter deposits in the lake bottom. The absence of bottom-dwelling fauna in the oxygen-poor hypolimnion enables the preservation of distinctive clastic-organic varve couplets in these lakes (e.g. Haltia-Hovi et al., 2007). The sediment cores investigated have been retrieved using piston corers from an ice platform in spring in 2006 (Table 1). Cores were opened in laboratory and sediment was sampled into palaeomagnetic sampling cubes (6.8 cm³) at 2.5 cm intervals. Laboratory procedures relating to sediment core handling and sampling are described in detail in Haltia-Hovi et al. (2010a).

3. Magnetic measurements and mineral magnetic characteristics

Magnetic measurements were carried out in the Laboratory for Paleo- and Rock magnetism at the Helmholtz Centre Potsdam GFZ in Germany. Magnetic measurements are summarised in Table 2, and more detailed information on the measurements is presented in Haltia-Hovi et al. (2010a). The standard induced and installed magnetisations, including low-field magnetic susceptibility (κ), anhysteretic remanent magnetisation (ARM) and saturation isothermal remanent magnetisation, were employed to estimate the concentration of the magnetic minerals. The discussion on mineral magnetic and relative palaeointensity results is limited to the sediment core LL-I from Lehmilampi and to core KJ-A from Kortejärvi for the following reasons: 1) sediments are continuously varved, providing a highly resolved chronology; 2) sediments have apparently uniform mineral magnetic properties. Reconstructing relative palaeointensity requires a sediment magnetic assemblage dominated by pseudo single-domain (PSD) magnetite with concentration variations within an order of magnitude (King et al., 1983; Tauxe, 1993). Moreover, palaeomagnetic directional record should be of high quality, and the reconstructed relative palaeointensity record should not show correlation neither with the magnetic parameters nor lithological variations (Brachfeld and Banerjee, 2000; Lund and Schwarz, 1999). Stability of the NRM and palaeosecular directional variations recorded in the sediments of Lehmilampi and Kortejärvi during the last 10 000 years were recently discussed

by Haltia-Hovi et al. (2010a). Progressive NRM demagnetisation in ten alternating field (AF) steps (from 5 to 100 mT) showed univectorial decay towards the origin after the removal of secondary magnetisations in low fields, usually by the 20 mT AF demagnetisation step. Multiple cores yielded a highly consistent palaeomagnetic directional record in comparison with PSV records from Fennoscandia and Europe, allowing the building of North Karelian palaeomagnetic stacks of mean inclination and declination for the Holocene (Haltia-Hovi et al., 2010a). Variations recorded in the mineral magnetic parameters, mirroring changes in the concentration, grain size and mineralogy of magnetic minerals and their environmental interpretation in the Lehmilampi and Kortejärvi sediments during the Holocene, have been recently discussed in Haltia-Hovi et al. (2010a) and Haltia-Hovi et al. (2010b). A summary of selected mineral magnetic parameters drawn from these papers is briefly reviewed here for evaluating the suitability of the sediments for relative palaeointensity reconstructions.

3.1. Mineral magnetic characteristics of Lehmilampi

Selected mineral magnetic parameters for Lehmilampi are shown in Fig. 2. Judging from the similarity of the NRM, κ , ARM and SIRM profiles, the intensity of NRM mainly responds to the concentration of magnetic minerals. Concentration of magnetic minerals varies by a factor of less than 2, 2.5 and 2 for κ , ARM and SIRM, respectively. The S-ratio, calculated here as $0.5 \cdot [1 - (\text{IRM}_{100\text{mT}} / \text{SIRM}_{1000\text{mT}})]$, is conventionally interpreted to indicate relative variations in low and high coercivity minerals, where 0 (1) indicates the sole presence of haematite (magnetite) (e.g. Frank and Nowaczyk, 2008). The high values in S-ratio, nearly throughout ≥ 0.9 , and the median destructive field of ARM (MDF_{ARM}) ranging between 38 and 43 mT support the interpretation of magnetic assemblage dominated by fine PSD sized magnetite (Maher, 1988). Stepwise acquisition of IRM of selected samples from the core LL-I indicated that about 90% of the IRM is obtained after exposing samples to magnetising fields ranging from 100 to 130 mT, suggesting magnetic mineralogy dominated by a ferrimagnetic mineral, most probably magnetite (Haltia-Hovi et al., 2010b). The interparametric ratio $\kappa_{\text{ARM}}/\text{SIRM}$ serves as a magnetic grain size proxy, and it is sensitive to the concentration of single domain (SD) magnetite. Higher (lower) values in $\kappa_{\text{ARM}}/\text{SIRM}$ denote relatively finer (coarser) magnetic grain size in a magnetic assemblage dominated by magnetite (Maher, 1988). Values in $\kappa_{\text{ARM}}/\text{SIRM}$ are high, which indicate contribution of SD sized magnetite in the magnetic assemblage. Variations in the magnetic grain size proxies and mass normalised ARM (not shown here) closely respond to the concentration of organic matter as defined by measuring total organic carbon (TOC) in Lehmilampi (Haltia-Hovi et al., 2010b). The similarity of mineral magnetic properties of Lehmilampi sediments in comparison with other lakes, where SD sized magnetosomes produced by magnetotactic bacteria have either been shown (Snowball, 1994; Kim et al., 2005) or suspected (Ojala and Saarnisto, 1999; Snowball et al., 2002; Geiss et al., 2004; Paasche et al., 2004) to be a part of the sediment magnetic assemblage, is believed to mirror the contribution of magnetosomes in the Lehmilampi sediments. The fairly uniform magnetic properties in the deep basin of Lehmilampi, as represented by core LL-I, are assumed to be suited for reconstructing variations in relative palaeointensity.

3.2. Mineral magnetic characteristics of Kortejärvi

Fig. 3 presents the same magnetic parameters from Kortejärvi as was shown for Lehmilampi. The concentration of magnetic minerals, as indicated by κ , ARM and SIRM, varies by factors less than 2.5, 2.5 and 2, respectively. NRM shows a general decreasing trend, corresponding to variations in ARM and SIRM. According to hysteresis parameters, bulk magnetic grain size tightly clusters in the finer end of the PSD range, with $M_{\text{sr}}/M_{\text{s}}$ and $B_{\text{cr}}/B_{\text{c}}$ ranging from 0.27 to 0.34 and from 1.8 to 2.1, respectively (Haltia-Hovi et al., 2010a). Parameters

indicating coercivity, or H_r (coercivity of remanence; 35.7-38.2 mT), MDF_{ARM} (42-46 mT) and S-ratio (mostly ≥ 0.9), showed only small variations, which was interpreted to indicate a uniform magnetic assemblage dominated by SD to fine PSD magnetite (Maher, 1988; Peters and Dekkers, 2003). The grain size indicative parameter $\kappa_{ARM}/SIRM$ shows varying but consistently high values, indicative of SD magnetite (Maher, 1988). Unfortunately, the lack of TOC data from Kortejärvi precludes making detailed inferences of the relationship between magnetic parameters and concentration of organic matter in sediments. However, such homogenous mineral magnetic properties may suggest that at least part of the magnetic minerals in the sediments is of bacterial origin. In the light of mineral magnetic properties, KJ-A has potential to yield a relative palaeointensity record.

4. Varve chronology of Lehmilampi and Kortejärvi sediments

Varve chronologies for Lehmilampi and Kortejärvi sediments have been established by semi-automatic varve counting using x-ray densitometry in combination with digital image analysis (Haltia-Hovi et al., 2007; Haltia-Hovi et al., 2010a). Relative mean x-ray density provides information on annual compositional variations in the deposited sediment. This parameter responds to sediment compositional variations, with higher (lower) density values relating to higher (lower) relative proportion of detrital matter in the sediment. On average, Lehmilampi and Kortejärvi varve chronologies cover 5122 and 3902 years, respectively. For the whole sediment sequence, cumulative calculation errors in varve counting are estimated as +104 (+2.1 %) and -114 (-2.2 %) varves for Lehmilampi and +60 (+1.5 %) and -59 (-1.5 %) for Kortejärvi. On average, annual sedimentation rate in the investigated sediments is 0.81 mm/yr in both lakes. Precision in varve counting is good and comparable to those from other high-quality varved lake sediments (e.g. Renberg et al., 1984; Zolitschka, 1991; Snowball et al., 1999; Ojala and Tiljander, 2003).

5. Results of different normalisation methods for reconstructing relative palaeointensity

In a sediment sequence with homogenous magnetic properties, normalisation of NRM by using any of the three concentration dependent parameters (κ , ARM and SIRM) should yield a similar profile. Following Tauxe (1993) and Valet (2003), three relative palaeointensity estimates were calculated. The data after the 30 mT AF demagnetisation step were used for NRM (NRM_{30mT}) and ARM (ARM_{30mT}), by which secondary magnetisation components were completely demagnetised (Haltia-Hovi et al., 2010a). For normalisation by SIRM, the remanent magnetisation imparted at DC field of 1000 mT ($SIRM_{1000mT}$) was used. The resulting relative palaeointensity estimates, NRM_{30mT}/κ , NRM_{30mT}/ARM_{30mT} and $NRM_{30mT}/SIRM_{1000mT}$, were normalised by the average of the core to allow comparisons between the different estimates. The three different relative palaeointensity candidates from Lehmilampi and Kortejärvi are shown in Fig. 4 and Fig. 5, respectively. Mean x-ray density reflecting sediment compositional variations, which appears critical for the interpretation of the relative palaeointensity results, is also presented. To provide a measure of the correlation between sediment composition and relative palaeointensity estimates, moving cross correlation was applied to determine the relation between the RPI estimates and relative mean-x-ray density (Fig. 6). Correlation coefficients (CCs) were calculated using a window of 200 years, and moving the window in 20 year increments along the time axis.

In Lehmilampi, NRM_{30mT}/κ and $NRM_{30mT}/SIRM_{1000mT}$ show largely similar millennial trends, where values increase between 5100 and 4000 yrs BP, with maximum intensity found between 2500 and 2600 yrs BP and rapidly decreasing values after 1000 yrs BP. The centennial variations have similar profiles, but the amplitude of changes is more pronounced in NRM_{30mT}/κ . Correlation between sediment density and the palaeointensity estimates normalised by κ is mostly negative correlation with moderate values (Fig. 6).

NRM_{30mT}/ARM_{30mT} shows somewhat differing behaviour, with smoothly increasing millennial trend until 2200 yrs BP, and thereafter decreasing values until present. The normalisation based on ARM_{30mT} shows rapid centennial oscillations, which appear to follow the variations in the sediment composition, where centennial peaks in the deposition of detrital matter coincide with higher values in NRM_{30mT}/ARM_{30mT} (Fig. 4). CCs indicate moderate to high positive correlation between sediment density and NRM_{30mT}/ARM_{30mT} (Fig. 6). In Kortejärvi (Fig. 5), NRM_{30mT}/κ and $NRM_{30mT}/SIRM_{1000mT}$ indicate increasing values until around 2600 yrs BP, after which intensity shows a slowly and then at 800 yrs BP a rapidly decreasing trend. Moreover, NRM_{30mT}/κ indicates another small maximum at 900 yrs BP. Millennial and centennial variations are of larger amplitude and the centennial variations appear more pronounced in NRM_{30mT}/κ , which shows a moderate to high negative correlation with sediment density as in Lehmilampi (Fig. 6). NRM_{30mT}/ARM_{30mT} records moderate increase in palaeointensity between 3600 and 3000 yrs BP, and cyclic variations between 2800 and 1000 yrs BP. After this, this relative palaeointensity estimate indicates rapidly decreasing values until present. As in Lehmilampi, comparison of this relative palaeointensity estimate with sediment compositional variations indicates clearly positive correlation (Fig. 6). Such simple comparison provides preliminary evidence of environmental influence over the proposed relative palaeointensity records, which, instead of reflecting a purely geomagnetic signal, incorporate a lithological signal as well (Schwartz et al., 1996; Lund and Schwartz, 1999). Consequently, the coherence of the potential relative palaeointensity profiles with their normalisers was further tested with AnalySeries 2.0 software (Paillard et al., 1996), where Blackman-Tukey cross-spectral analysis with a Bartlett window was applied (Fig. 7). As expected, coherence above the 95% confidence limit between the palaeointensity estimate and the respective normaliser is observed in a broad range of frequencies especially in the relative palaeointensity estimates based on normalisation by κ in both lakes. This indicates that NRM_{30mT}/κ should be excluded from further considerations on relative palaeointensity. NRM_{30mT}/ARM_{30mT} appears to be more successfully normalised, but it is nevertheless coherent in several frequencies with ARM_{30mT} . In the light of the results from cross-spectral analysis, the palaeointensity estimate $NRM_{30mT}/SIRM_{1000mT}$ is the least coherent with its normaliser in Lehmilampi. In Kortejärvi, the results from cross-spectral analysis suggest an incomplete normalisation of NRM_{30mT}/ARM_{30mT} and $NRM_{30mT}/SIRM_{1000mT}$. Due to this evidently large-scale environmental bias, the value of the relative palaeointensity estimates from Kortejärvi is considered ambiguous, and therefore their use is avoided altogether. On the grounds of the results from cross-spectral analysis, $NRM_{30mT}/SIRM_{1000mT}$ appears to be the most reliable relative palaeointensity estimate from the sediments of Lehmilampi.

6. Relative palaeointensity records with respect to magnetic grain size and lithological variations

The difficulties encountered in isolating relative palaeointensity signal from the investigated sediments demonstrate that the fulfilled criteria of magnetic uniformity may not always result in a palaeointensity record of purely geomagnetic origin. Different factors may contribute to the complications encountered when applying the conventional normalisation techniques. Subtle shifts in magnetic grain size have been postulated to cause problems in reconstructing relative palaeointensity (Brachfeld and Banerjee, 2000). The deviations between the different normalisations reconstructed from sediments from Lehmilampi and Kortejärvi may derive from changes in magnetic grain size, the details of which are beyond the resolution of the set of magnetic analyses used in this work. Variations in sedimentary magnetic grain size may change in response to palaeoenvironmental changes, and they are influenced by several factors, such as the characteristics of detrital magnetic minerals derived from the catchment (Stockhausen and Zolitschka, 1999) and authigenic (in)organic formation of ferrimagnetic minerals (Pan et al., 2005; Ariztegui and Dobson, 1996).

Magnetic susceptibility is largely free of grain size dependence in the SD fraction and larger, but yields considerably higher values in the superparamagnetic (SP) size fraction (Maher, 1988; Heider et al., 1996; Peters and Dekkers, 2003). Moreover, when the concentration of ferrimagnetic minerals is low, κ may be controlled by paramagnetic minerals, which do not display remanence. The inverse relation between $\text{NRM}_{30\text{mT}}/\kappa$ and sediment density variations (Fig. 7) probably reflects the presence of SP and MD magnetite and paramagnetic minerals in the magnetic record of these lakes. These minerals are presumed to originate from the catchment and are transported during periods of maximum discharge in spring. Use of isothermal remanent magnetisation as a normaliser is justified by the absence of paramagnetic contributions in it. Nevertheless, range of values in $\text{SIRM}_{1000\text{mT}}$ is approximately an order higher than those found in NRM, indicating that $\text{SIRM}_{1000\text{mT}}$ has activated magnetic fractions, such as large PSD and MD magnetite and/or other iron oxides, most likely haematite (Fe_2O_3), which are not contributing to the stable NRM, but instead cause over-correction in normalisation.

In previous studies involving relative palaeointensity reconstructions from similar varved lake sediments in Finland and Sweden, the investigators have preferred the normalisation of NRM at a chosen demagnetisation step by ARM (Saarinen, 1998; Ojala and Saarinen, 2002; Snowball and Sandgren, 2002). This approach is appealing, because ARM activates the same magnetic grain population (SD to fine PSD) which carries the stable NRM signal (Levi and Banerjee, 1976). On the other hand, ARM is highly dependent on the magnetic grain size in submicron sized magnetite (King et al., 1983) and on the concentration of SD magnetite due to magnetic interactions (Sugiura, 1979). Higher concentration of single-domain magnetite in the more organic-rich parts of the sediment cause the positive correlation between $\text{NRM}_{30\text{mT}}/\text{ARM}_{30\text{mT}}$ sediment density in Lehmilampi and Kortejärvi. Magnetic assemblage in Lehmilampi sediments is postulated to be a mixture of magnetite of larger grain size derived from the catchment and SD bacterial magnetite, and the respective proportions of these components vary with time (Haltia-Hovi et al., 2010b). In a recent study, the accumulation of organic matter in Lehmilampi was suggested to respond to solar forcing during the last 2000 years (Haltia-Hovi et al., 2007). The correlation of mass-specific ARM and TOC in Lehmilampi, with high values found e.g. during the High Medieval (1100-900 yrs BP), may indicate a climatic control over magnetosome production (Haltia-Hovi et al., 2007). In case the regional climate is indirectly controlling the relative proportions of detrital and organic matter depositing in the lake bottom, the mineral magnetic assemblage mirrors the prevailing climate regime. Such subtle climatically driven shifts in bulk magnetic grain size may complicate normalisation of sediments for relative palaeointensity. $\text{SIRM}_{1000\text{mT}}$ may provide a more efficient normalisation for palaeointensity in these sediments, because it incorporates different magnetic grain sizes providing a more blurred estimate of magnetic concentration, whereas variations in $\text{ARM}_{30\text{mT}}$ may be dependent on climatic variations. Snowball and Sandgren (2004) adopted normalisation by pseudo-Thellier technique in reconstructing relative palaeointensity from homogenous gyttja sediments in a Swedish lake. An advantage of this approach is that it allows observing discreet changes in coercivity and making of internal checks for reliability (Tauxe et al., 1995). Another aspect, by which the sediment compositional variations may influence relative palaeointensity, is that the processes related to the acquisition of NRM can be biased by changes in sediment physical properties and deposition rates, resulting in a filtered geomagnetic signal (Valet and Meynadier, 1998; Mitra and Tauxe, 2009).

Selective dissolution of magnetite, which has been reported in anoxic and organic-rich lacustrine and marine environments, has been shown to cause complications in reconstructing relative palaeointensity records (Nowaczyk et al., 2001; Frank et al., 2002; Hayashida et al., 2007). In such environments, dissolution of magnetite can be suspected, when concentration of magnetic minerals descends with simultaneous shift to larger magnetic grain size, which may also coincide with a visible change in sediment lithology (Karlin and Levi, 1983; Karlin,

1990; Anderson and Rippey, 1988; Snowball, 1993; Jelinowska et al., 1997). The available magnetic evidence from Lehmilampi does not suggest magnetite dissolution, but rather the opposite: organic-rich sediment sections are enriched in fine ferrimagnetic material, probably reflecting proliferation of magnetotactic bacteria during periods of abundant supply of nutrients. However, the contrast in magnetic properties in two sets of duplicate cores, KJ-A and KJ-B vs. KJ-I and KJ-II, from two coring sites in the same deep basin in Kortejärvi may point to selective dissolution of magnetite in the sediments in KJ-I and KJ-II (Haltia-Hovi et al., 2010a). Small but frequent occurrence of vivianite ($\text{Fe}_3(\text{PO}_4)_2$) concretions in the sediments of both lakes indicates early reductive iron diagenetic changes (Berner, 1981), but its extent and influence over the sediment magnetic assemblage is not quantified.

The noise produced by unremoved local lithological effects in relative palaeointensity records may be smoothed out by stacking of records from different study sites (Snowball et al., 2007). Since Saarinen (1998), palaeomagnetic research in Finland and Sweden has been focused on varved sediment sequences deposited in small boreal lakes, with characteristics very similar to Lehmilampi and Kortejärvi. In case the response of these lakes to climatic variations would result in correspondent variations in lithology and consequently mineral magnetic properties, it is possible that some lithological biases could remain in the stacked record. However, other factors than climate influence mineral magnetic properties in lake sediments, such as the availability and characteristics of magnetic minerals in the catchment, airborne magnetic input, and authigenesis and dissolution of magnetic minerals, which complicate direct comparisons between different sediment records.

7. Comparison of Lehmilampi relative palaeointensity estimate with absolute and relative palaeointensity records

Environmental bias in the relative palaeointensity record $\text{NRM}_{30\text{mT}}/\text{SIRM}_{1000\text{mT}}$ from Lehmilampi, imprinting the centennial variations, has been clearly acknowledged. The competence of the millennial-scale relative palaeointensity variations can be tested by comparing it with other records, preferably those holding absolute palaeointensity. The record from Lehmilampi was compared with relative and absolute palaeointensity records from Europe (Fig. 8). The relative palaeointensity records are compiled from varved lake sediments as well, and they include a) Lake Pohjajärvi $\text{NRM}_{30\text{mT}}/\text{ARM}_{30\text{mT}}$ record from eastern Finland ($62^\circ 82' \text{N}$, $28^\circ 04' \text{E}$; Saarinen, 1998), b) Lake Nautajärvi $\text{NRM}_{20\text{mT}}/\text{ARM}_{20\text{mT}}$ record from central Finland ($61^\circ 48' \text{N}$, $24^\circ 41' \text{E}$; Ojala and Saarinen, 2002), and c) FENNORPIS, which is constructed by stacking NRM/ARM records from six varved lake sediment sequences (including the Lake Nautajärvi record) and one non-laminated sediment sequence, where relative palaeointensity was reconstructed by pseudo-Thellier technique (57° - 64°N , 12° - 24°E ; Snowball et al., 2007). In addition, archaeomagnetic data compilation presenting absolute palaeointensity data from e) Bulgaria and other countries in Europe and northern Africa (Kovacheva et al., 2009), f) Finland (Pesonen et al., 1995), and g) CALS7K.2 model output for Northern Karelia (Korte and Constable, 2005) were used in the comparison.

Comparing the morphologies of the different palaeointensity profiles reveals a largely similar trend of increasing intensity from 5000 yrs BP onwards with highest intensity found between 2800 and 2200 yrs BP. Another high intensity feature occurs around 1000 yrs BP, and it is particularly visible in the archaeomagnetic datasets and in Lake Pohjajärvi record. In Lehmilampi this palaeointensity feature seems subdued. Except for Lake Nautajärvi, all the records show a decreasing trend in palaeointensity starting approximately at 1000 yrs BP. The decreasing relative palaeointensity in Lehmilampi during the last millennia is largely in line with archaeomagnetic palaeointensity results in Finland (Pesonen et al., 1995). CALS7K.2 model output compares favourably with Lehmilampi relative palaeointensity record. The general similarity, in particular when compared with the archaeomagnetic datasets, indicates that the sediments from Lehmilampi record the millennial trends in the geomagnetic

palaeointensity during the last 5100 years. However, the centennial variations are responding to sediment lithology, which hampers their use as a relative record of geomagnetic field moment and comparisons with cosmogenic isotope records (St-Onge et al., 2003).

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Table and figure captions

Table 1. Information on sediment cores from Lehmilampi and Kortejärvi discussed in the present study. *PP-corer is a lighter type of Kullenberg piston corer **only the upper and varved part of the core LL-I (total length 748 cm) from Lehmilampi is discussed here

Table 2. Summary on magnetic measures and procedures

Figure 1. A) Location of the investigated lakes in Eastern Finland, B) Kortejärvi and C) Lehmilampi. Coring sites for the individual cores are marked in B) and C). Numbers denote depth (m) in the deepest point of the basin.

Figure 2. Mineral magnetic properties of core LL-I from Lehmilampi during the last 5100 years. See subsection 3.1 for explanation of the magnetic parameters. Total organic carbon (TOC), expressed in weight percentage, is also shown to facilitate comparison between magnetic parameters and concentration of organic matter.

Figure 3. Mineral magnetic properties of core KJ-A from Kortejärvi during the last 3700 years. See subsection 3.1 for explanation of the magnetic parameters.

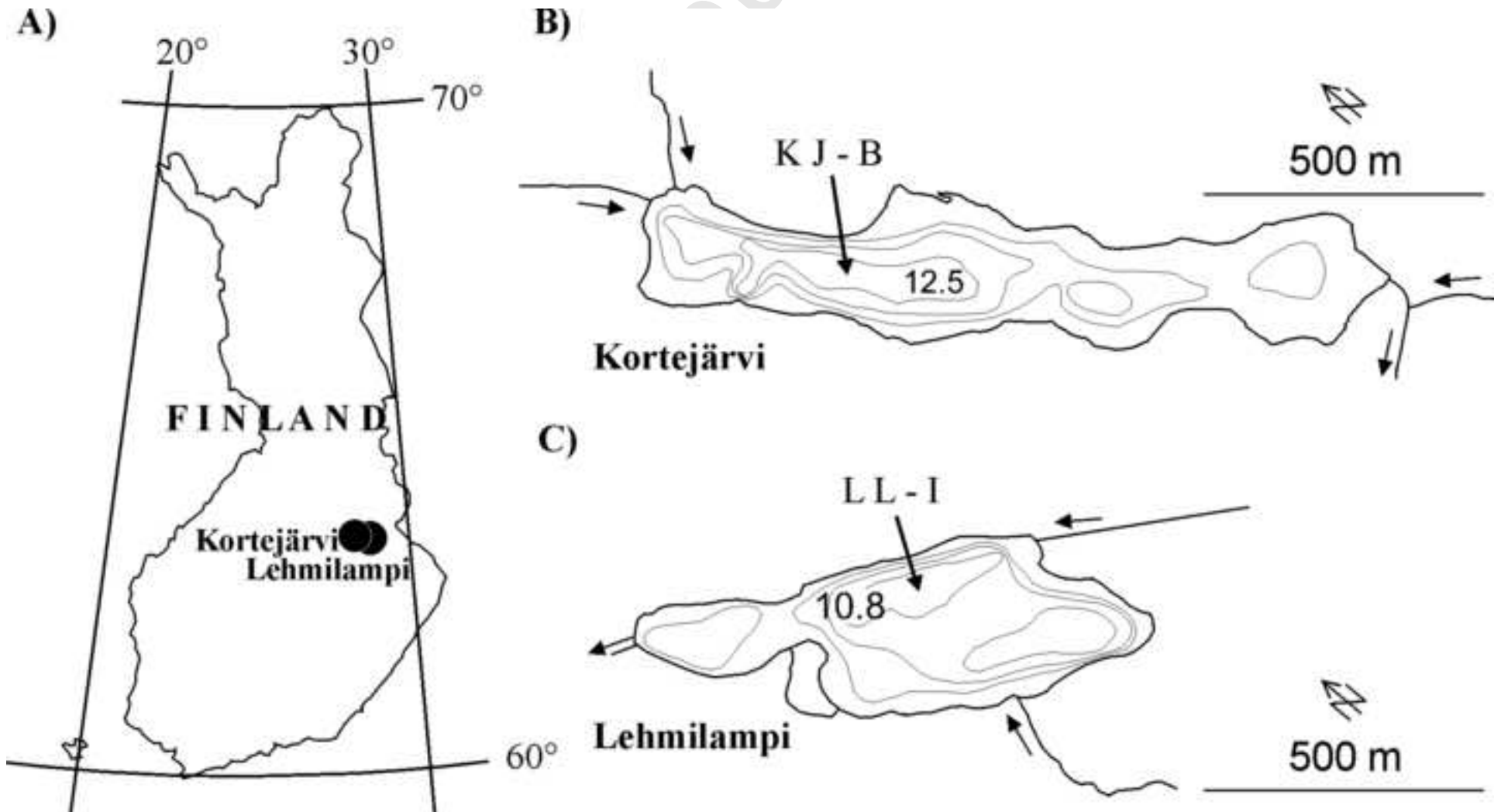
Figure 4. Relative palaeointensity estimates from Lehmilampi core LL-I together with sediment relative mean x-ray density, where annual data is shown as a grey line and the superimposing black line is a 31-year running average to provide smoothing for the high-frequency variations in the annual deposition.

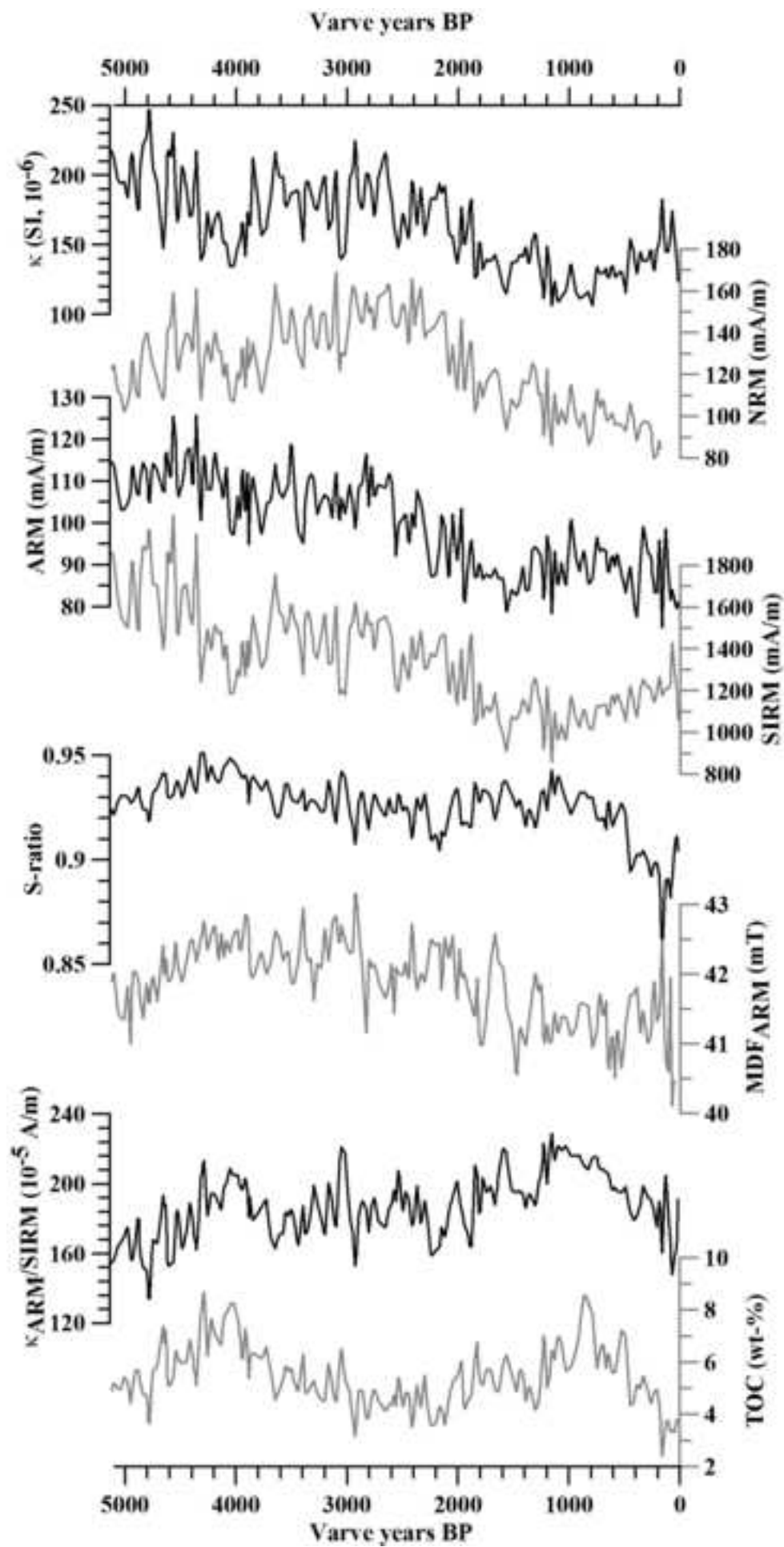
Figure 5. Relative palaeointensity estimates from Kortejärvi core KJ-A together with sediment relative mean x-ray density, where annual data is shown as a grey line and the superimposing black line is a 31-year running average to provide smoothing for the high-frequency variations in the annual deposition.

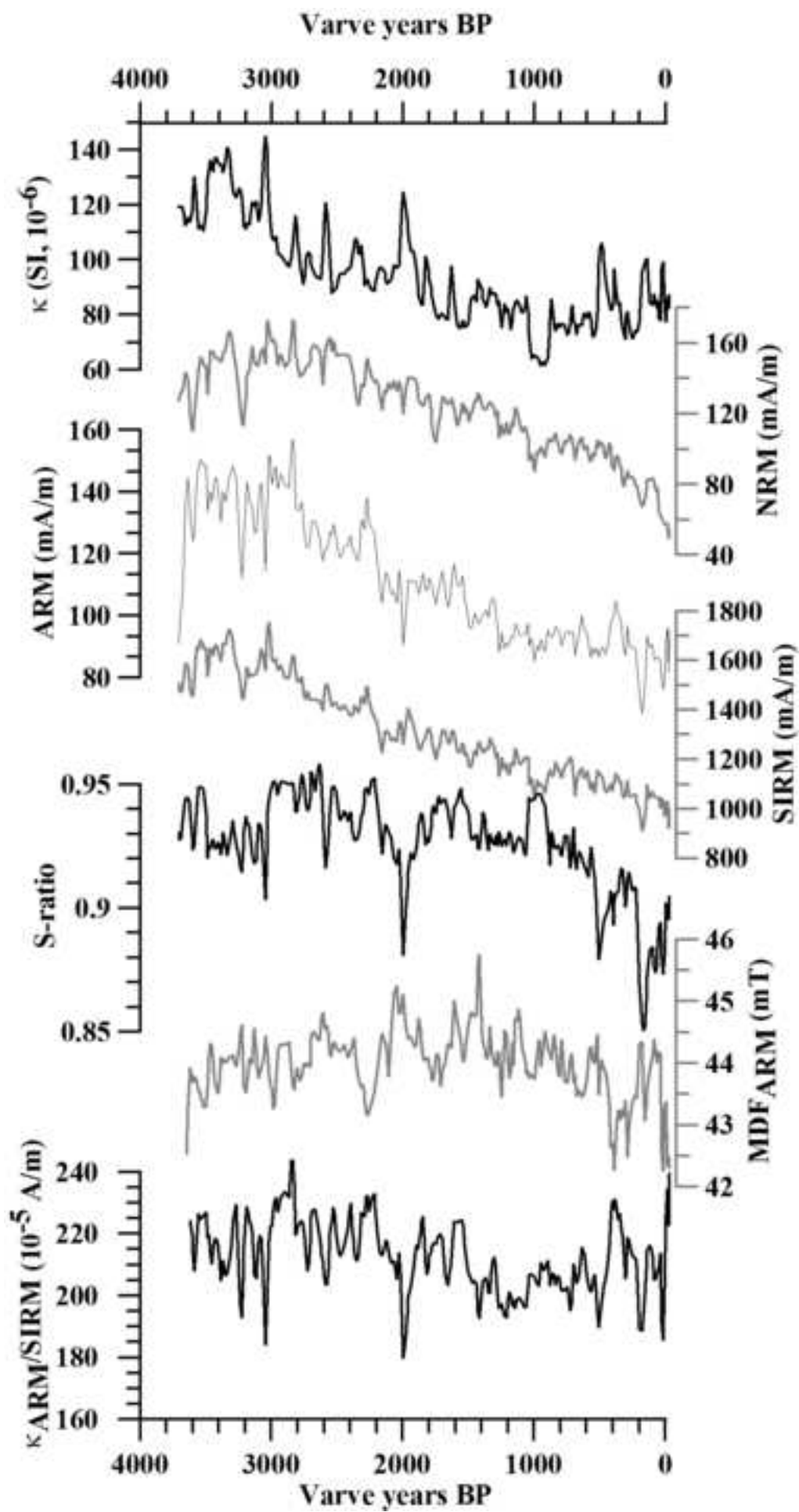
Figure 6. Moving cross correlation of relative mean x-ray density and the three relative palaeointensity estimates for Lehmilampi (filled grey line) and Kortejärvi (black line). Investigated time window is 200 years and increment 20 years. CC = correlation coefficient.

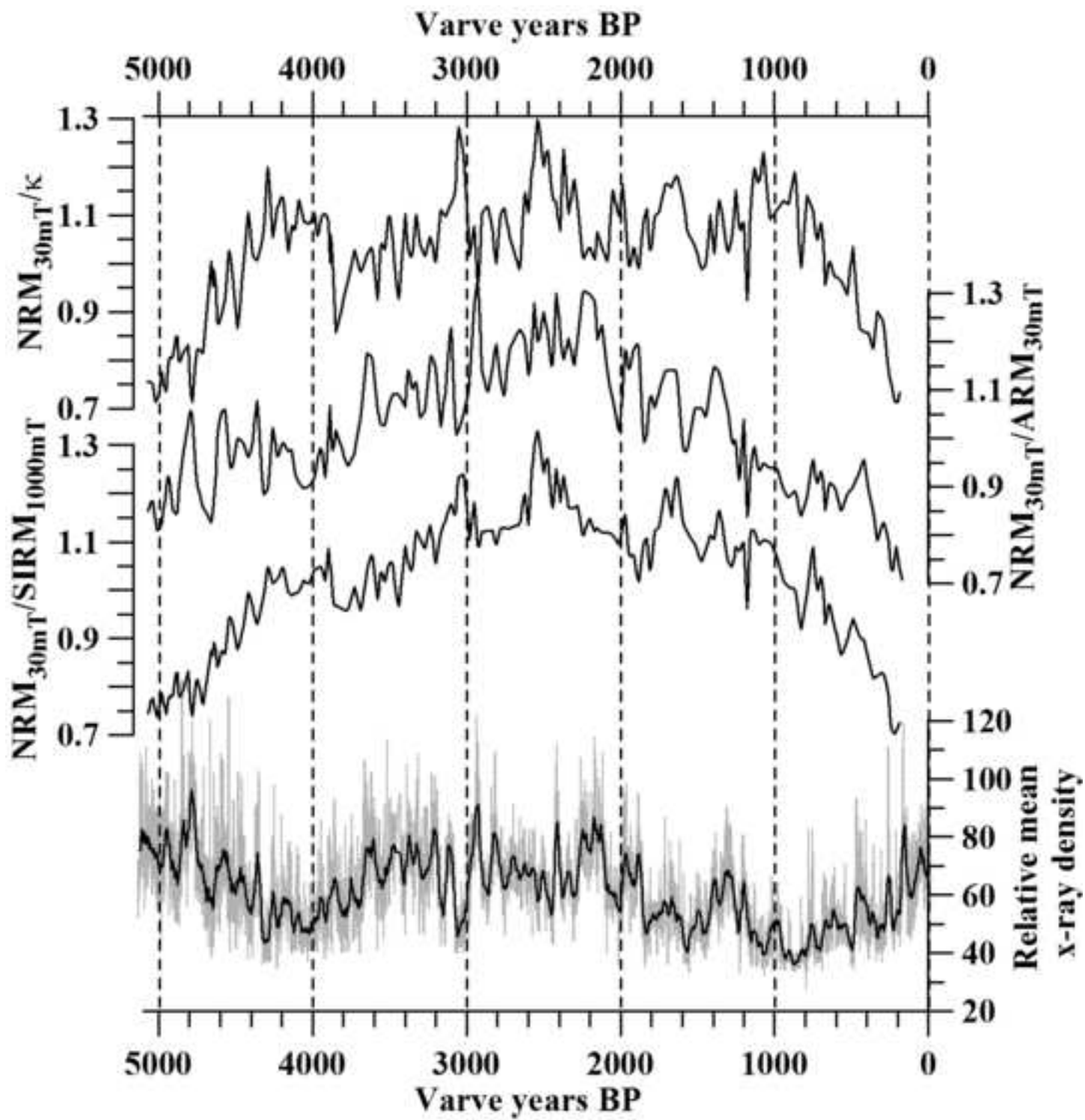
Figure 7. Coherence between RPI estimates and normalisers in Lehmilampi (a, b, and c) and Kortejärvi (d, e, and f). The dashed lines indicate the 95% confidence limit. None of the calculated RPI estimates is free from environmental bias, but the coherence is significantly reduced when using $SIRM_{1000mT}$ in Lehmilampi (c).

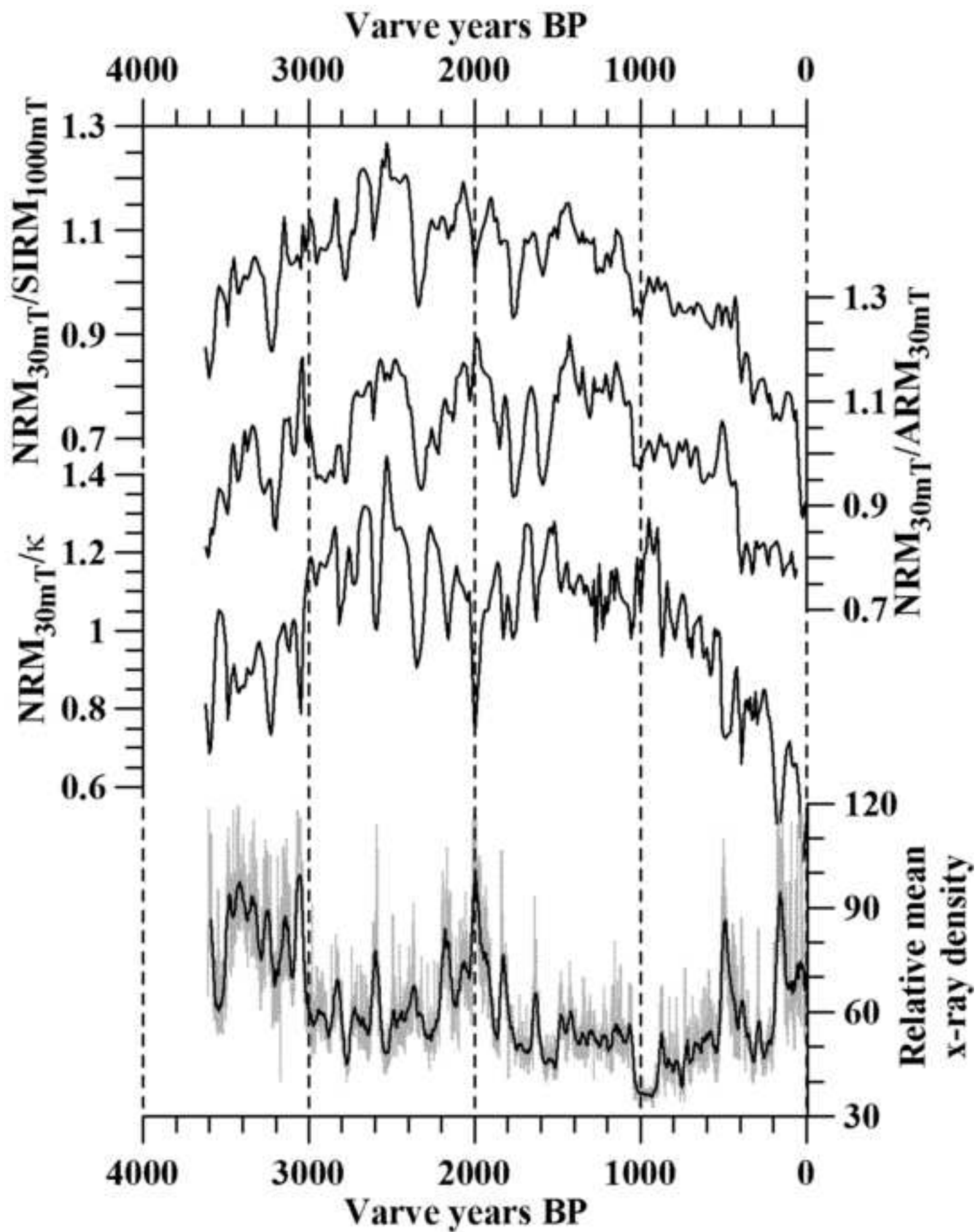
Figure 8. Relative and absolute palaeointensity estimates from Europe. For references for the data presented in a-c and e-g, see the text. For Lake Pohjajärvi, Lake Nautajärvi, and Bulgarian archaeomagnetic data, original data is plotted with grey line and the black line denotes a 5-point running average. The grey line in Lehmilampi represents the original data and the black line denotes a 150-year running average. The associated 95% confidence limits are included with FENNORPIS. The associated error in the archaeomagnetic data from Finland are shown as well.

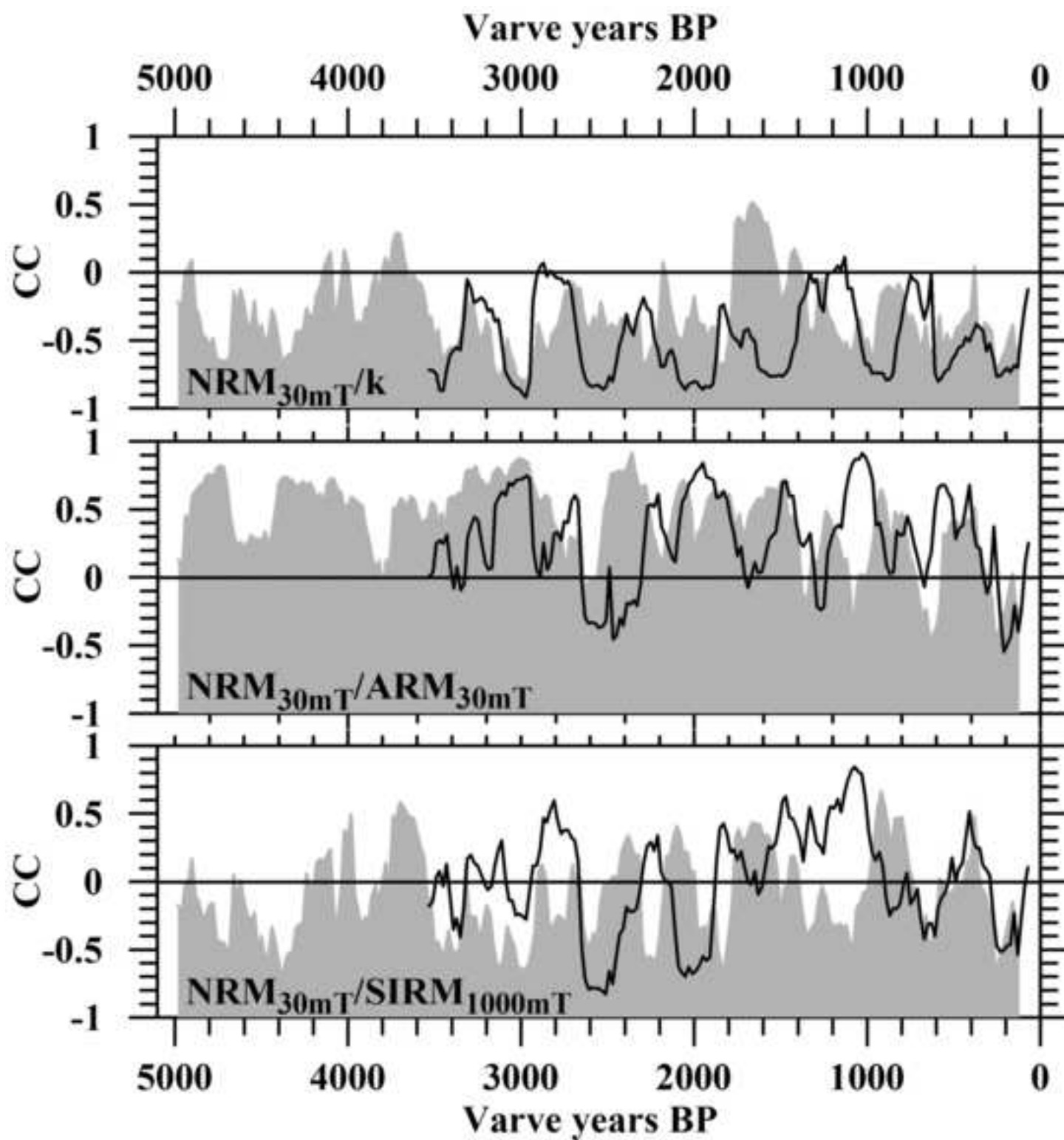






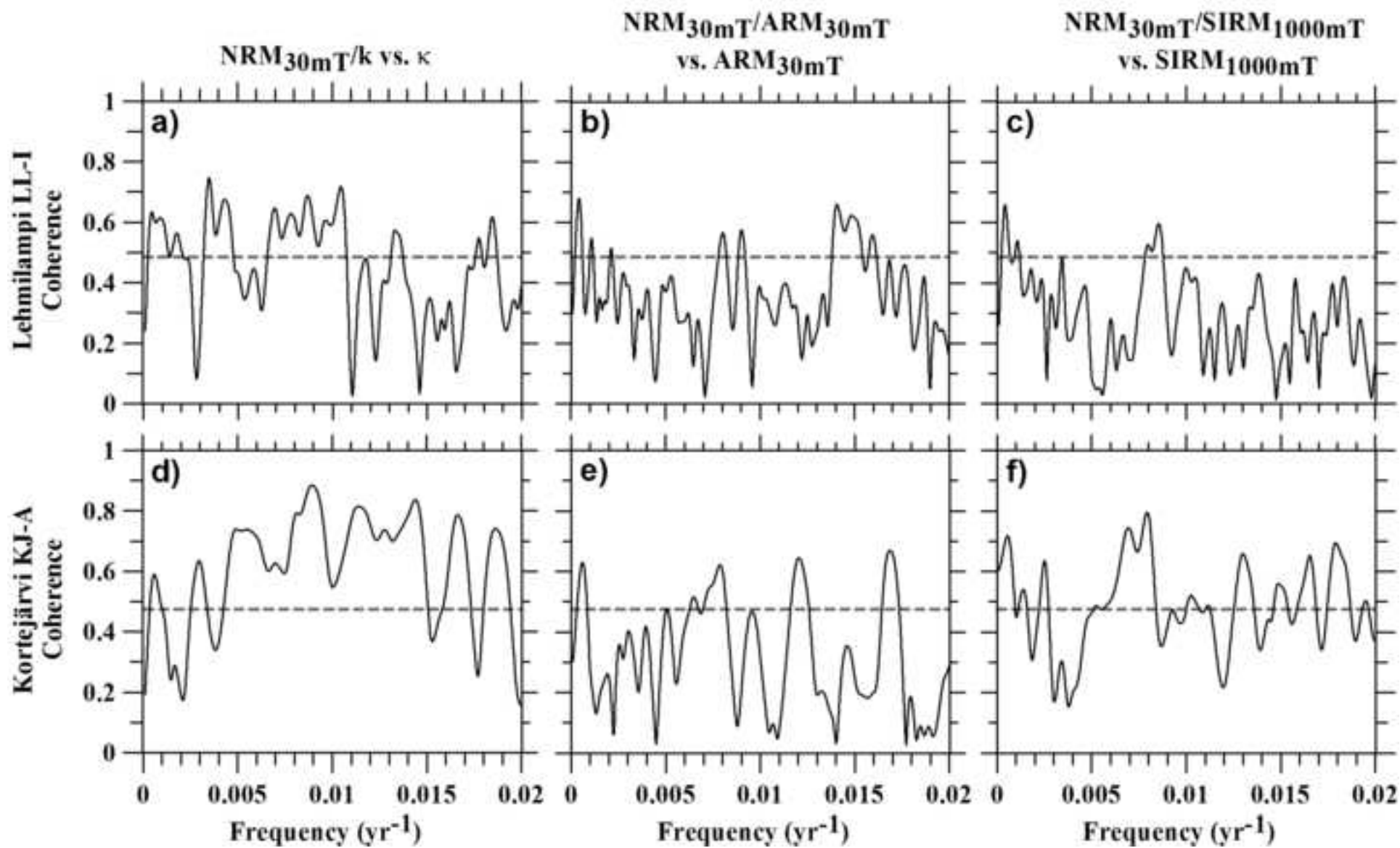


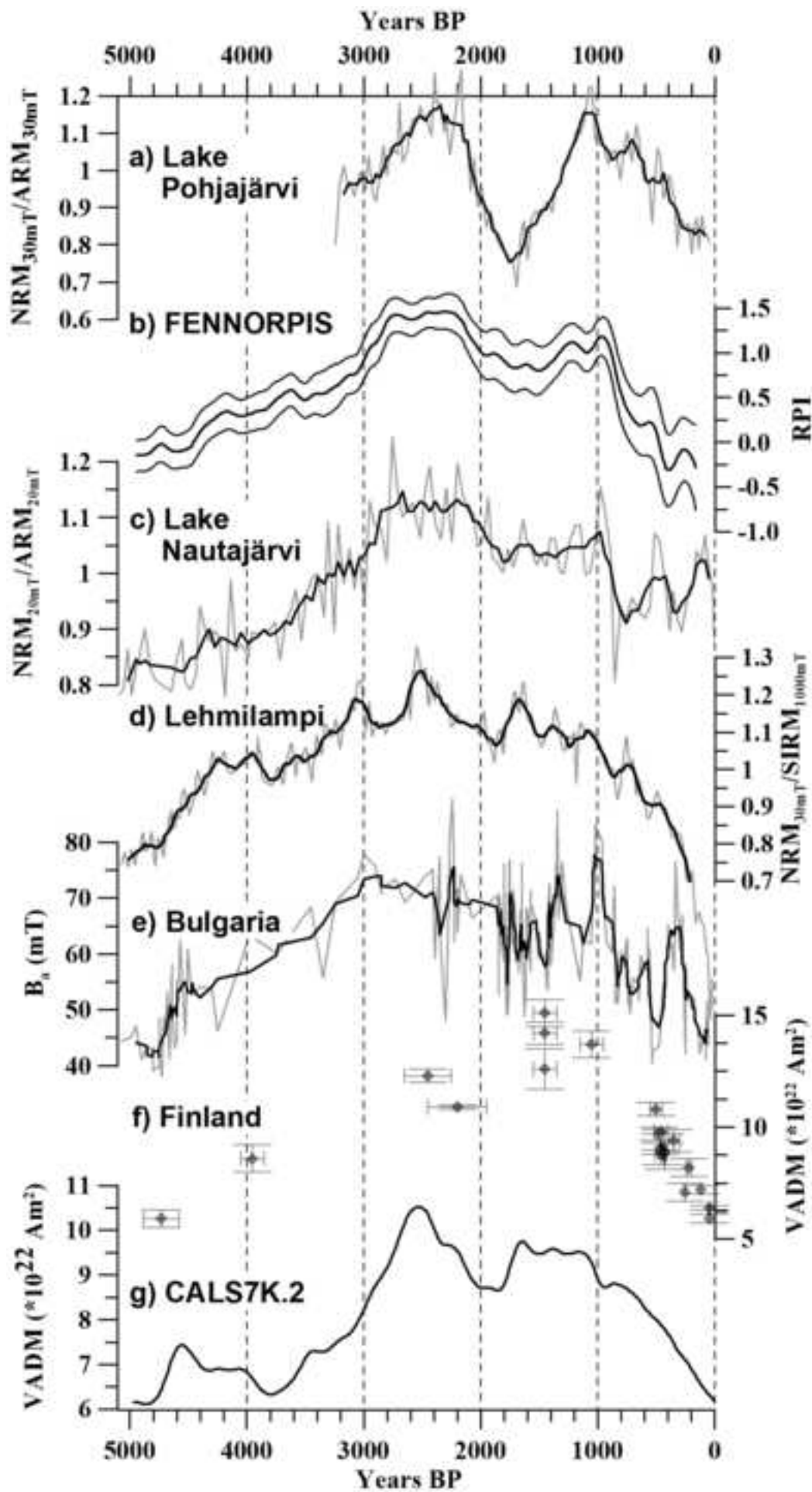




Figure(7)

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Lake	Core	Coring tool	Investigated section (cm)	Water depth (m)	Coring time	N:o of samples
Lehmilampi	LL-I	PP-corer*	0-415**	10.80	2/2006	178
Kortejärvi	KJ-A	Piston corer	0-300	12.05	4/2006	228

Measurement type	Instrument	Details
Low field magnetic susceptibility (κ)	AGICO Kappabridge KLY-3S	
Natural remanent magnetization (NRM)	2G Enterprises cryogenic magnetometer (2G 755 SRM)	
Demagnetization of NRM	In-line triaxial alternating field demagnetizer of the 2G 755 SRM	In 10 steps up to 100 mT (5, 10, 15, 20, 30, 40, 50, 65, 80, 100 mT)
Imprinting of anhysteretic remanent magnetization (ARM)	2G Enterprises 600 single-axis demagnetizer including an ARM-coil	DC field 0.05 mT, peaking AF amplitude 100 mT
Measurement of ARM	2G Enterprises cryogenic magnetometer (2G 755 SRM)	
Demagnetization of ARM	In-line triaxial alternating field demagnetizer of the 2G 755 SRM	In 5 steps to 50 mT at 10 mT intervals
Imprinting of isothermal remanent magnetization (IRM_{1000mT} ; $IRM_{0.1mT}$)	2G Enterprises 660 pulse magnetizer	
Measurement of IRMs	Molyneux Minispin fluxgate magnetometer	