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RESEARCH NOTE

Impact of early diagenesis and bulk particle grain size distribution on estimates of relative geomagnetic palaeointensity variations in sediments from Lama Lake, northern Central Siberia

Norbert R. Nowaczyk,[1] Stefanie Harwart[2] and Martin Melles[2]

[1] *GeoForschungsZentrum Potsdam, Projektbereich* 3.3 *'Sedimente und Beckenbildung'- Laboratory for Palaeo- and Rock Magnetism, Telegrafenberg,* D-14473 *Potsdam, Germany, E-mail: nowa@gfz-potsdam.de*
[2] *Alfred-Wegener-Institute for Polar and Marine Research, Research Unit Potsdam,Telegrafenberg* A43, D-14473 *Potsdam, Germany*

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SUMMARY

High-resolution analyses of rock magnetic and sedimentological parameters were conducted on an 11 m long sediment core from Lama Lake, Northern Siberia, which encompasses the late Pleistocene and the Holocene epochs. The results reveal a strong link between the median grain size of the magnetic particles, identified as magnetite, and the oxidation state of the sediment. Reducing conditions associated with a relative high total organic carbon (TOC) content of the sediment characterize the upper 7 m of the core ($\approx$Holocene), and these have led to a partial dissolution of detrital magnetite grains, and a homogenization of grain-size-related rock magnetic parameters. The anoxic sediments are characterized by significantly larger median magnetic grain sizes, as indicated, for example, by lower median destructive fields of the natural remanent magnetization (MDF_{NRM}) and lower ratios of saturation remanence to saturation magnetization (M_{SR}/M_S). Consequently, estimates of relative geomagnetic palaeointensity variations yielded large amplitude shifts associated with anoxic/oxic boundaries. Despite the partial reductive dissolution of magnetic particles within the anoxic section, and consequent minimal variations in magnetic concentration and grain size, palaeointensity estimates for this part of the core were still lithologically distorted by the effects of particle size (and subsidiary TOC) variations. Anomalously high values coincide with an interval of significantly more fine-grained sediment, which is also associated with a decrease in TOC content, which may thus imply a decreased level of magnetite dissolution in this interval. Calculation of relative palaeointensity estimates therefore seems to be compromised by a combined effect of shifts in the particle size distribution of the bulk sediment and by partial magnetite dissolution varying in association with the TOC content of the sediment.

Key words: early diagenesis, lake sediments, magnetostratigraphy, palaeointensity, Quaternary, rock magnetism.

INTRODUCTION

Sediments from both lacustrine and marine environments are frequently investigated for directional and relative palaeointensity variations of the geomagnetic field. In principle, they can provide continuous records of geomagnetic field behaviour, such as secular variation, excursions, and major reversals. For a classical palaeomagnetic investigation, that is, analysis of directional field behaviour only, the most important criteria for selecting a material to be analysed are: (1) sufficient amount of stable magnetic carrier minerals present throughout the whole sediment sequence; (2) preferably, a continuous record of deposition; (3) an intact sedimentary fabric, that is, absence of disturbances due either to syn- or post-depositional processes or to sampling; (4) a stable sediment matrix, e.g. lacking horizons of unconsolidated sand; (5) preservation of the primary magnetization direction; and (6) a good age control. For the reconstruction of relative palaeointensity variations additional criteria are required (e.g. Tauxe 1993): minimum variation in (7) magnetomineralogy; (8) magnetic concentration; and (9) grain size of the magnetic components.

Sediments affected by partial dissolution of magnetic minerals may still yield accurate information relating to the geomagnetic field directions at the time of their deposition, but the amplitudes of the recorded relative palaeointensity variations would be suppressed, since the concentration of magnetic particles will be depleted, particularly at the fine-grained end of the magnetic grain-size spectrum, because their grains have a higher surface area-to-volume ratio than larger grains. Sediments where new, authigenic or bioauthigenic magnetic minerals have formed, involving acquisition of a post-depositional, chemical remanent magnetization (CRM) are not useful for reconstructions of geomagnetic field behaviour, since the time of CRM formation is mostly unknown. In this paper we discuss the influence of early diagenetic, partial reductive dissolution of magnetite in anoxic sediments on their bulk rock magnetic properties and the consequences for estimation of relative palaeointensity variations. In addition, we investigate a possible link between changes in the particle-size distribution of the bulk sediment and apparently related variations in estimates of relative palaeointensity.

MATERIALS AND METHODS

The clastic sediment components in the lacustrine deposits in Lama Lake (69.5°N, 90.2°E) originate predominantly from the thick Permian flood basalts in the Puturan Plateau that covers large areas in Central Siberia (Fig. 1). The recovered 11.1 m long sediment sequence from Site PG1111 consists of five separate but overlapping gravity and piston core segments with a maximum length of 3 m (Fig. 2). A detailed description of the coring technique is given by Melles *et al.* (1994). Correlation of the individual core segments, and creation of a composite profile, could be achieved by analyses of whole-core physical and geochemical properties of overlapping sediment horizons (Harwart *et al.* 1999). Age control is provided by a palynologic record (Fig. 2), indicating that the recovered sediments encompasses the Holocene and late Pleistocene epochs, extending back to about 17 kyr BP (before present).

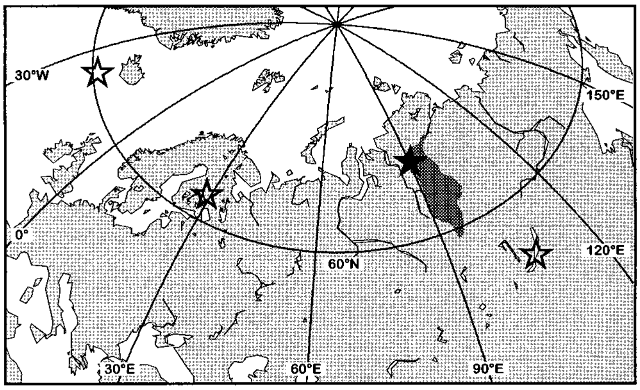

Figure 1. Location map of coring site PG1111 (black star) in Lama Lake, northern Central Siberia. The dark area indicates the occurrence of Permian flood basalts, the Putoran Plateau. Included also are sites (open stars) with palaeointensity records used for comparison: North Atlantic, ODP Site 983 (Channell *et al.* 1997), Finland (Saarinen 1998) and Lake Baikal (Peck *et al.* 1996).

Sediments in core PG1111 partly consist of laminated silty clays. The lowermost section (1112–735 cm) is characterized by an olive brown colour and TOC (total organic carbon) contents of 0.1 per cent or less (Fig. 2). Between 735 and 20 cm, sediments are dark greyish and black with TOC contents of up to 0.9 per cent and abundant FeS_2, indicating anoxic conditions. In the upper 20 cm TOC contents also range between 0.7 and 0.9 per cent, but the brownish colours here indicate (still) oxic conditions, that is, the lower boundary of interstitially down-migrating O_2 from the overlying water column (see also Harwart *et al.* 1999; Nowaczyk *et al.* 2000).

Core PG1111 was split along the central axis and subsampled for palaeo- and rock magnetic analyses with cubic plastic boxes of 6.2 cm^3. The natural remanent magnetization (NRM) of each of the 504 specimens obtained was subjected to incremental alternating field demagnetization in 10 steps of up to 100 mT, and subsequent principal component analysis (Kirschvink 1980). As a first estimation for relative magnetic grain-size variations the median destructive field (MDF_{NRM}) was calculated. Rock magnetic analysis for all samples included measurement of low-field magnetic volume susceptibility (κ_{LF}), acquisition of anhysteretic remanent magnetization (ARM), and saturation isothermal remanent magnetization (SIRM) with determination of the *S*-ratio ($S_{-0.3\,T} = 0.5 \times [1 - IRM(-0.3\,T)/SIRM]$, after Bloemendal *et al.* 1992). Complete IRM acquisition curves and determination of hysteresis parameters were performed on selected samples concentrating on the anoxic/oxic boundaries (Fig. 2). A more detailed description of the applied methods is given in Nowaczyk *et al.* (2000). In order to estimate relative palaeointensity variations, ratios of NRM intensities after demagnetization with 20 mT relative to low-field magnetic susceptibility (J_{NRM} 20 mT/κ_{LF}), SIRM (J_{NRM} 20 mT/J_{SIRM}) and ARM, also demagnetized with 20 mT (J_{NRM} 20 mT/J_{ARM} 20 mT) were calculated. Then each curve was normalized to its average.

RESULTS AND DISCUSSION

Intensities of the NRM in core PG1111 are relatively high, ranging from 138 to 1394 mA m^{-1}. All palaeomagnetic samples are characterized by a more or less (see below) stable, mainly single component magnetization, with steep inclinations between 55° and 85° (Fig. 2). Small viscous overprints were generally removed in fields of 20 mT (Fig. 3). The core mean inclination is 75°, which is only 4° lower than the theoretical dipole inclination of 79°. In general, a similar inclination pattern is also recorded by the more recent Lama Lake sediment core PG1341, taken from a site near that of core PG1111, which includes the distinct minima in inclination values seen in core PG1111 (work in progress). Therefore, the inclination pattern recorded by core PG1111 can be interpreted as a late Pleistocene and Holocene record of geomagnetic secular variation in northern Central Siberia.

Due to the outcrops of Permian flood basalts surrounding Lama Lake (Fig. 1) magnetic susceptibilities in core PG1111 are relatively high, mainly ranging from 500 to 3500×10^{-6}. However, close to the position of the Pleistocene/Holocene boundary in the core, a steep increase of the mean level from about 1070×10^{-6} below 730 cm, to 2460×10^{-6} above 730 cm, is present (Figs 2 and 4). A more pronounced and even sharper boundary can be observed at 745 cm, where median destructive fields of the NRM (MDF_{NRM}) drop from >35 mT down to

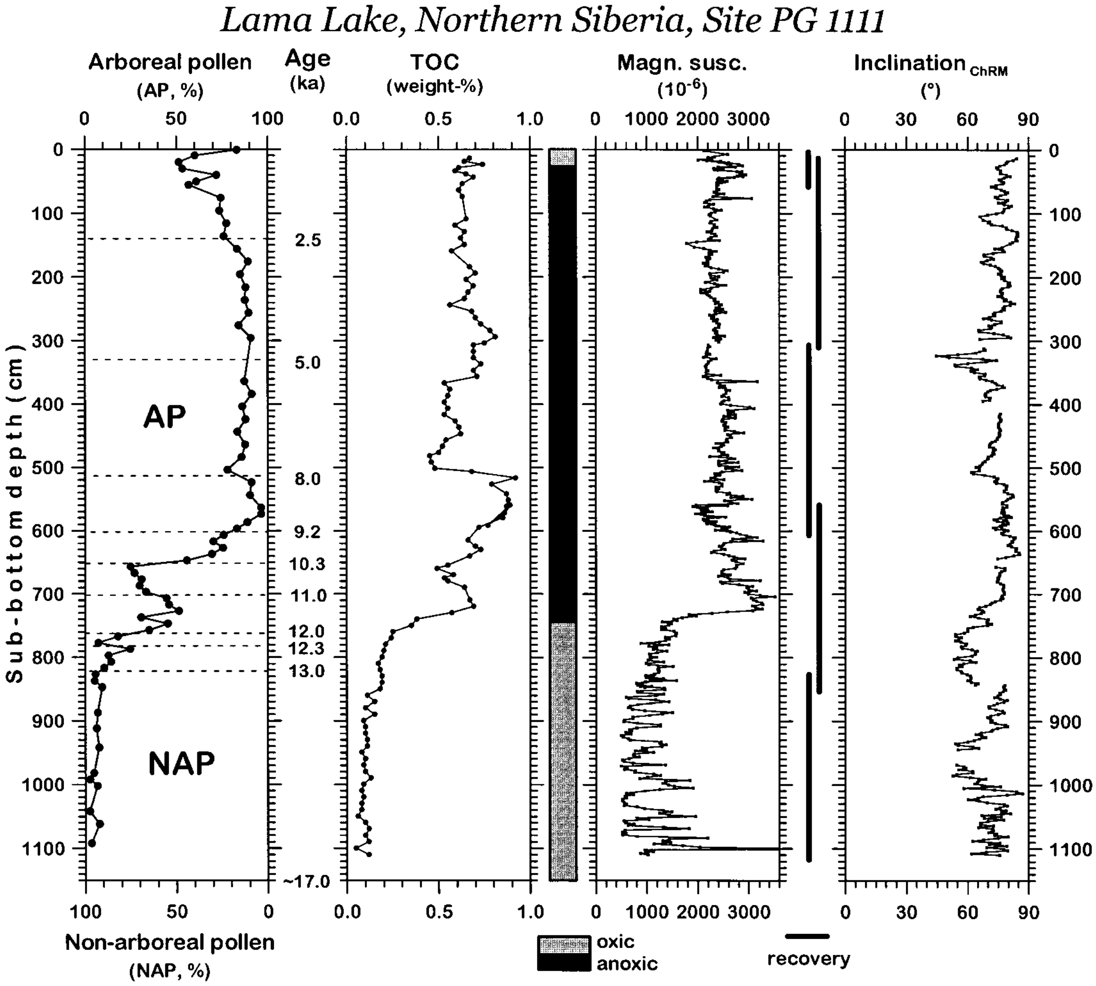

Figure 2. Basic stratigraphic profiles of core PG1111 from Lama Lake: ratio of arboreal to non-arboreal pollen, TOC, magnetic susceptibility and inclination of characteristic remanent magnetization (ChRM), smoothed with a weighted three-point running average. Dashed lines and ages in the pollen stratigraphy mark major pollen zone boundaries (Hahne & Melles 1997). The black rectangle in the middle represents an interval of anoxic sediments. The whole sequence was recovered with one gravity and four overlapping piston cores as indicated by thick vertical lines in the right section.

≈26 mT, with only minor variation between 30 and 745 cm. This interval coincides with the anoxic section in core PG1111 (Fig. 4), characterized by TOC contents from 0.7 to 0.9 per cent, whereas in the underlying oxic sediments, TOC content does not exceed 0.1 per cent. Near the upper anoxic/oxic boundary (the active oxidation front), at about 20 cm, MDF_{NRM} values rise again clearly above 30 mT. The observed downcore trends in MDF_{NRM} are strong indicators of significant variations in magnetic grain size at the two anoxic/oxic boundaries. Because of this result, measurements of complete IRM acquisition curves were concentrated on sediments close to these magnetomineralogic as well as geochemical boundaries. All of the 96 samples investigated reached saturation between 250 and 500 mT, indicating that magnetite is the only remanence carrier. This result was verified by thermomagnetic measurements on 85 samples (Nowaczyk *et al.* 2000). The change from fine-grained (higher MDF_{NRM} values) to coarse-grained (lower MDF_{NRM} values) magnetite, with the transition from oxic to anoxic sediments, is also revealed in the downcore plot of the median acquisition field of the IRM (MAF_{IRM}, Fig. 4, middle) with higher (lower) values in the oxic (anoxic) section. Nowaczyk *et al.* (2000) pointed out that in this case the result of the *S*-ratio calculation (Fig. 4) is strongly influenced by grain-size changes of magnetite, rather than by the presence of a high-coercivity mineral. Results from the determination of hysteresis parameters of the 120 samples investigated all cluster in the pseudo-single domain (PSD) field of the Day plot (Day *et al.* 1977). The division of the sediment profile of core PG1111 into three sections of different magnetic properties can be seen most clearly in the plot of M_{SR}/M_S ratio versus depth (Fig. 4). All four coercivity and/or grain-size-related parameters in Fig. 4 point to a drastic shift in the average magnetic grain size towards coarser PSD magnetites within the anoxic section. Its lower boundary coincides with the end of the transition from the last glaciation into the Holocene and is a sedimentological as well as a geochemical boundary as indicated by the increase in TOC content (Fig. 2) and coarsening of bulk sediment particle size (Fig. 5) above this boundary. The observed shift from finer to coarser PSD magnetite therefore could be the result of a major change in sedimentology, indicating a change in the scource or relative flux-density of detrital input from different scources to the site of deposition. However, rock magnetic properties exhibit a much sharper transition than environmental indicators (pollen and TOC, Fig. 2). Moreover, the sharp upper geochemical and rock magnetic boundary near 25 cm does not coincide with a major climatic event. The

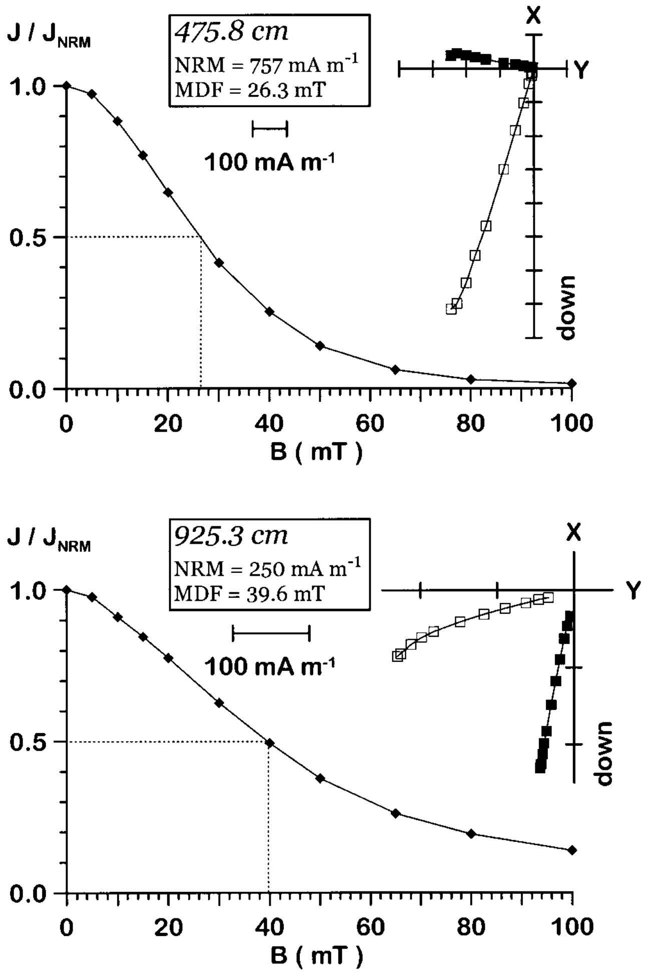

Figure 3. Demagnetization curves and Zijderveld diagrams (sample coordinates) of two typical samples from core PG1111. Solid (open) symbols denote the horizontal (vertical) plane.

associated transition in magnetomineralogical properties of the youngest Holocene sediments towards the values of late Pleistocene oxic sediments in terms of mean magnetic grain size is likely to be due solely to a geochemically induced diagenetic effect. The same inference can be made for the lower anoxic/oxic boundary ($\approx$745 cm). The drastic shift to a larger median magnetic grain size within the anoxic section therefore should mainly be the consequence of grain size selective, reductive dissolution of iron (Fe^{2+}) oxides, that is, dissolution of the smallest magnetite particles (Nowaczyk *et al.* 2000).

Estimates of relative palaeointensity variations also show drastic shifts associated with the anoxic/oxic boundaries (Fig. 5). Since fine-grained magnetite particles are selectively dissolved within the anoxic section, their previous contribution to the NRM intensity is now largely or totally missing. Consequently, the palaeointensity estimates for this section yield significantly lower values. Thus, variations in the intensity of reductive diagenesis associated with changes in the amount of TOC in the sediment (Fig. 5, inner left) may have influenced the results of relative palaeointensity estimates. This is indicated by a drop in TOC content at $\approx$500 cm depth in the core to about half of its value below, which coincides with an increase in relative palaeointensity by a factor of two (note that TOC is plotted inversely). This may mean that, above 500 cm, magnetite dissolution was less intense than in the sediments below 500 cm. However, the process of magnetite dissolution was sufficiently intense to homogenize the variations in grain-size-related rock magnetic parameters, since, at 500 cm, no significant change is visible (Fig. 4).

The overall match of the three different approaches to palaeointensity estimation is not very good. This could be due to the lithologically modulated variation in rock magnetic properties within the Holocene and late Pleistocene sections, respectively. Since the partial magnetite dissolution within the anoxic section yielded a clear homogenization of the magnetic grain-size spectrum (Fig. 4), the average normalization was recalculated for this section only (Fig. 5, inner right). The three different relative palaeointensity estimates now match almost perfectly, except for the interval from $\approx$500 to 420 cm. As already discussed, the lower boundary of this interval matches the level where TOC content drops by 50 per cent. However, its upper boundary does not clearly coincide with a change in TOC content. Detailed analysis of the bulk sediment particle size distribution revealed clear shifts in sediment composition associated with the apparent 'palaeointensity' maximum (Fig. 5). At 500 cm, the lower boundary of the maximum, a sudden shift to more fine-grained sediments was detected, followed by a more or less continuous shift back to higher proportions of coarser material, roughly in phase with the 'palaeointensity' amplitude. Thus, shifts in the particle grain-size spectrum of the bulk sediment are probably an additional factor which may account for the anomalous results of the relative palaeointensity estimates. Possibly, the higher content of fine-grained matrix minerals resulted in a more effective alignment and/or fixation of the magnetic particles. Hence, despite apparently 'ideal' rock magnetic properties, that is, minimum concentration and grain-size variations of the magnetic particles, the calculation of relative palaeointensities yields spurious results, probably caused by the combined effect of shifts in the particle size of the bulk sediment and partial, grain-size-selective (and variable?) dissolution of detrital magnetite grains.

Based on the age model provided by the pollen record (Fig. 2), the Lama Lake relative palaeointensity estimate was transformed into a time-series and then compared with other sedimentary records (Fig. 6). Also shown in Fig. 6 is a new stack of archaeomagnetic data (Yang *et al.* 2000), given as virtual axial dipole moment (VADM). The four sedimentary records span roughly a west–east transect across the Northern Hemisphere (Fig. 1). The Holocene data from the most distant sites, ODP 983 (Channell *et al.* 1997) and Lake Baikal (Peck *et al.* 1996), exhibit the best similarity, a long-term increase reaching a maximum at around 2 ka. They also reflect the general trend of the Earth's dipole moment (Fig. 6). For the younger interval from 3.2 ka to the present the match between the Baikal and the Finland records (Saarinen 1998) is best. Their low-frequency component also matches the archaeomagnetic stack, which gives only averages for 500 yr intervals in this period. Variance in the Lama Lake record seems to have a similar low-frequency component to that of the North Atlantic record, but no clear correlation with any of the other curves is seen. In particular, the pronounced maximum around 7 ka is not present in any other records. This is further evidence that the concentration-normalized NRM intensity record from Lama Lake should be treated with caution when interpreted as a record of geomagnetic field intensity variations.

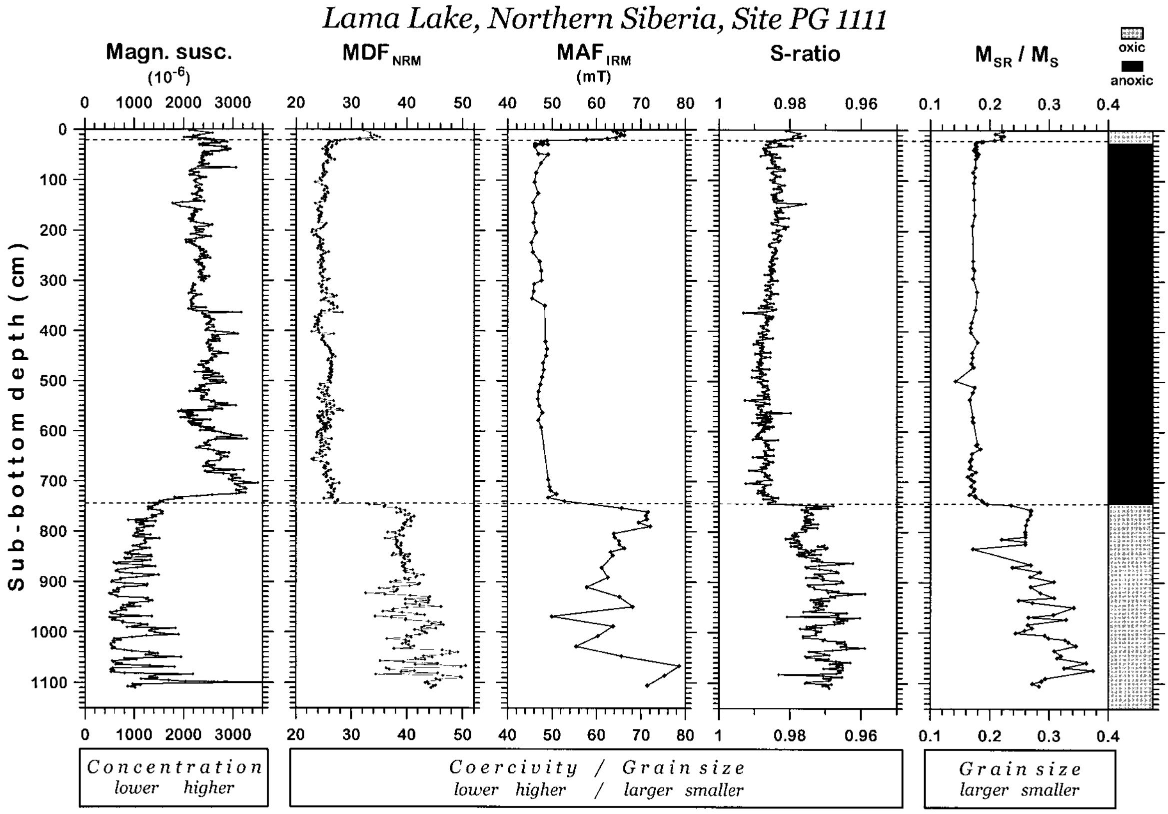

Figure 4. Selected rock magnetic parameters of core PG1111: magnetic susceptibility, median destructive field of MDF_{NRM}, MAF_{IRM}, *S*-ratio (see text) and ratio of M_{SR} to M_S as derived from hysteresis measurements. The black rectangle at the outer right and the dashed lines indicate the interval of anoxic sediments.

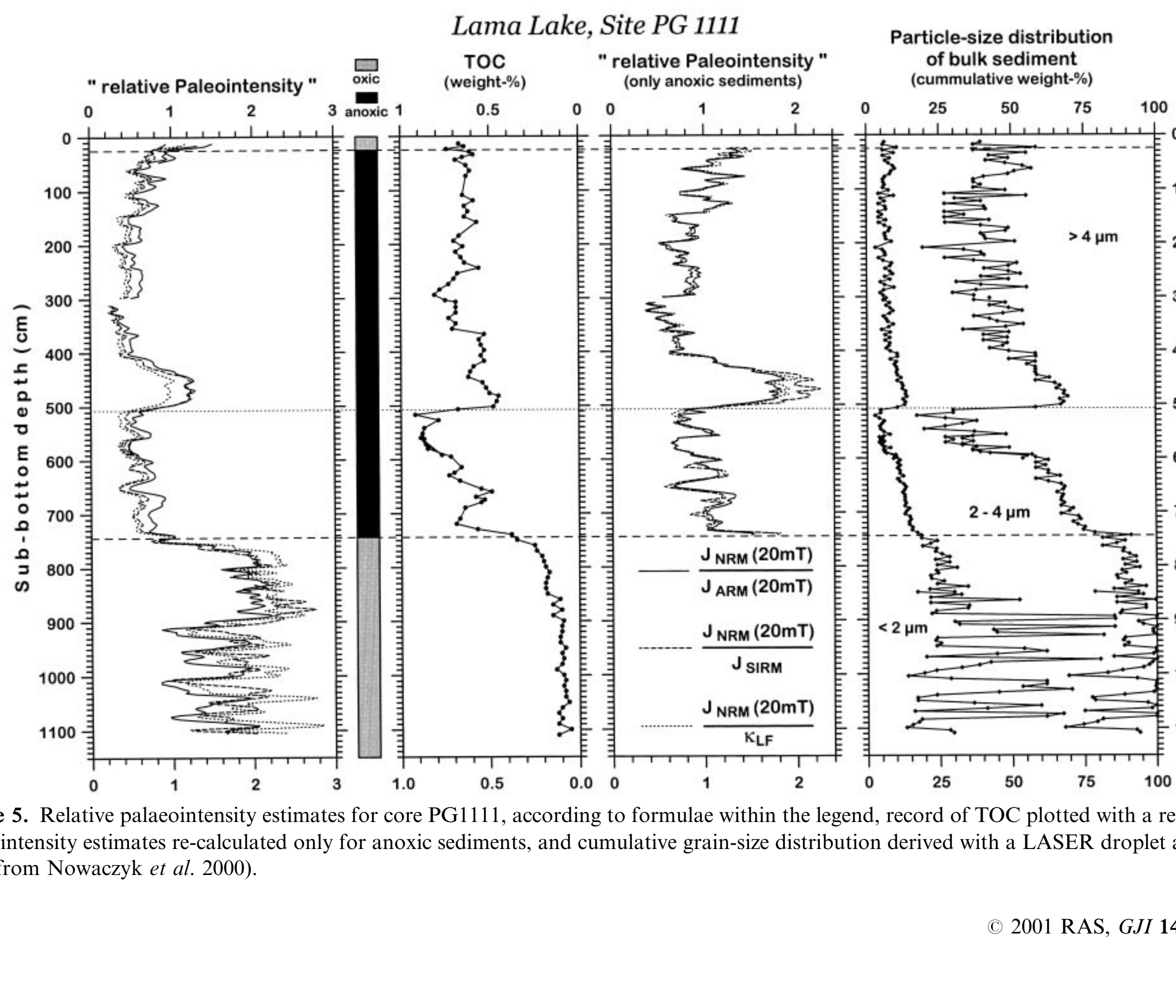

Figure 5. Relative palaeointensity estimates for core PG1111, according to formulae within the legend, record of TOC plotted with a reversed axis, palaeointensity estimates re-calculated only for anoxic sediments, and cumulative grain-size distribution derived with a LASER droplet and particle sizer (from Nowaczyk *et al.* 2000).

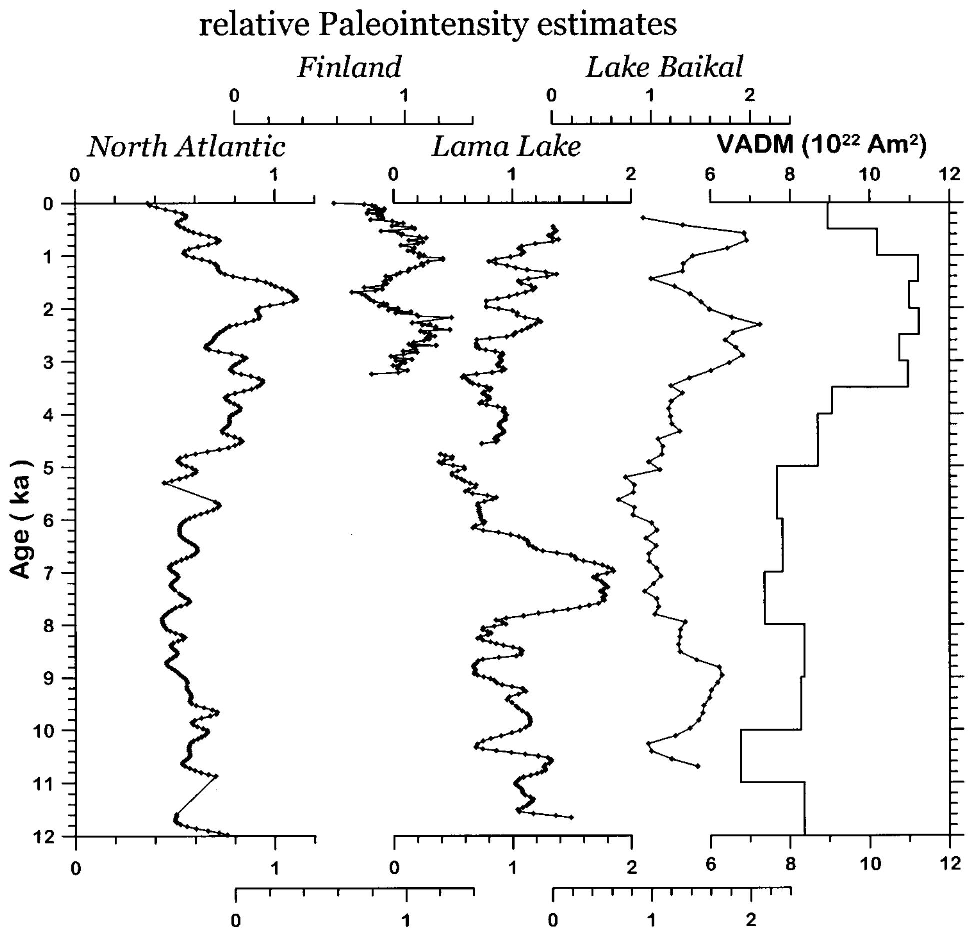

Figure 6. Relative palaeointensity estimates derived from sediments from the North Atlantic, Site ODP 983 (Channell *et al.* 1997), Finland (Saarinen 1998), Lama Lake (this study) and Lake Baikal (Peck *et al.* 1996), together with variations of the Earth's dipole moment as derived from archaeomagnetic data (Yang *et al.* 2000). For site locations of the sedimentary records see Fig. 1.

In summary, although the very homogeneous rock magnetic properties of the anoxic Holocene section in core PG1111 appeared to represent ideal conditions for estimation of relative palaeointensity variations, the results obtained are unreliable. Clearly, minimal variation in concentration and grain size of the magnetic particles is one necessary prerequisite, but not always the only criterion for an unbiased estimation of relative palaeointensity.

CONCLUSIONS

Magnetomineralogic properties of the sediments recovered from Lama Lake are strongly influenced by the oxidation state of the sediment. Although palaeoenvironmental changes since the termination of the last glacial period have led to an increased influx of magnetic material to the lake, indicated by a shift to higher magnetic susceptibilities, the contemporaneous increase in the flux of organic matter, and thus higher TOC content of the sediment, has led to the development of anoxic interstitial conditions, and thus also to partial dissolution of the finer-grained magnetite particles, resulting in generally coarser magnetic assemblages. Consequently, relative palaeointensity estimates have yielded spurious results associated with diagenetic modifications to the magnetic remanence carriers in the sediment at the anoxic/oxic boundaries. Estimating relative palaeointensity for only the anoxic interval, which should be an ideal medium because of its minimal variation in magnetic concentration and grain size, did not yield a reliable field intensity estimation. In this interval, changes in the bulk sediment's particle size characteristics, specifically, a higher proportion of finer material, together with a drop in TOC content, are linked with significantly higher 'palaeointensity' amplitudes. Since such variation in the lithological composition of sediments obviously influences the fidelity of palaeointensity estimates, detailed analysis of the sediment's matrix properties may be required to ascertain the origin of the assumed geomagnetic palaeointensity signal recorded.

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