

Rock magnetic studies on sediments from Erlongwan maar lake, Long Gang Volcanic Field, Jilin province, NE China

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Accepted 2006 August 4. Received 2006 August 3; in original form 2005 August 30

SUMMARY

Detailed rock magnetic investigations were carried out on two 23-m-long sediment cores from Erlongwan maar lake, NE China. The completely laminated sediment sequence of the lake is interrupted by 410 graded layers with thicknesses between 0.1 and 150 cm. Magnetite of PSD-size was identified as the main magnetic carrier mineral by temperature-dependent measurements of the saturation magnetization and determination of hysteresis parameters. The minerogenic components in the laminated sediments and the graded layers are nearly identical, and their rock magnetic characteristics reflect the prevailing conditions, anoxic or oxic, during deposition. The most reliable criteria for estimating the availability of oxygen is whether an increase in minerogenic influx is linked to a shift in the magnetic grain size spectrum to coarser (oxic) or finer (anoxic) grains. Comparison of different rock magnetic parameters indicative for magnetic grain size and coercitivity revealed, that the *S*-ratio which is known to reflect the presence of high coercive minerals, is grain size indicative in sediments with a monomineralic magnetic composition.

Key words: graded layers, laminated sediments, Late Quaternary, NE China, rock magnetism.

INTRODUCTION

Laminated sediments have a high potential for accurate dating, either due to an annual lamination that can be counted and/or to an undisturbed succession of different types of sediment where hiatuses, turbidity layers and so on could easily be identified. Therefore, laminated sediments are an ideal subject for magnetostratigraphic investigations, yielding the potential for the crucial construction of a reliable depth/age model. However, there is not much knowledge about how and to what extent the lamination influences the recording of the geomagnetic signal. Investigations performed on clastic varved sediments have shown, that in this case the occurrence of lamination has no influence on the recorded geomagnetic signal (Ojala & Saarinen 2002; Snowball & Sandgren 2002, 2004). Further investigations, especially those concerning sediments with a succession of organic to minerogenic sediment are still missing. This might be due to the observation, that sediments comprising laminae of organic material are often not suitable for palaeomagnetic studies. These sediments are deposited under anoxic conditions and the resulting dissolution of Fe-bearing minerals partly destroys the geomagnetic information stored (Passier *et al.* 1996; Nowaczyk *et al.* 2000, 2001; Frank *et al.* 2002). Additionally ferromagnetic Fe-sulphides like greigite can be formed post-sedimentary (Hilton 1990; Roberts *et al.* 1999; Snowball & Torii 1999), carrying a chemical remanent magnetization that contributes to the total remanence of the sediment (Frank *et al.* 2005), and masks the primary magnetic signal. In order to obtain information about basic

rock magnetic characteristics of different types of sediment lamina, for example, of organic to minerogenic composition, a pilot study was started, combining the results of rock magnetic, sedimentological and geochemical analysis on a laminae scale. The laminated sediments chosen for this study were recovered from the small maar lake Erlongwan (ERL) in NE China. In the following text the basic rock magnetic information on the two sediment cores investigated are presented, the results of a detailed rock magnetic analysis of single lamina will follow in a separate paper. Additional information on the two cores from Erlongwan maar lake obtained by the magnetostratigraphic investigations will be presented elsewhere (Frank 2005).

SITE LOCATION AND MATERIAL

The maar lake Erlongwan is a part of the Long Gang Volcanic Field (LGVF) in the Jilin Province, NE China (Fig. 1). The LGVF is situated at the northeastern margin of the North China craton near the northeast–southwest trending Fushun–Mishan fracture zone. Alkali-basaltic rocks of Quaternary age cover around 1700 km² of the plateau-like upper Archaean basement. Today there are 148 volcanic cones and eight water-filled maar and crater lakes in the LGVF, with water depths between 15 and 127 m (Mingram *et al.* 2004). The last volcanic activity occurred around 1.6 ka ago, forming the large Jinlongdingzi scoria cone (Fan *et al.* 2000). The ERL maar lake (42°18'N, 126°22'E) lies 724 m above sea level, it has a water

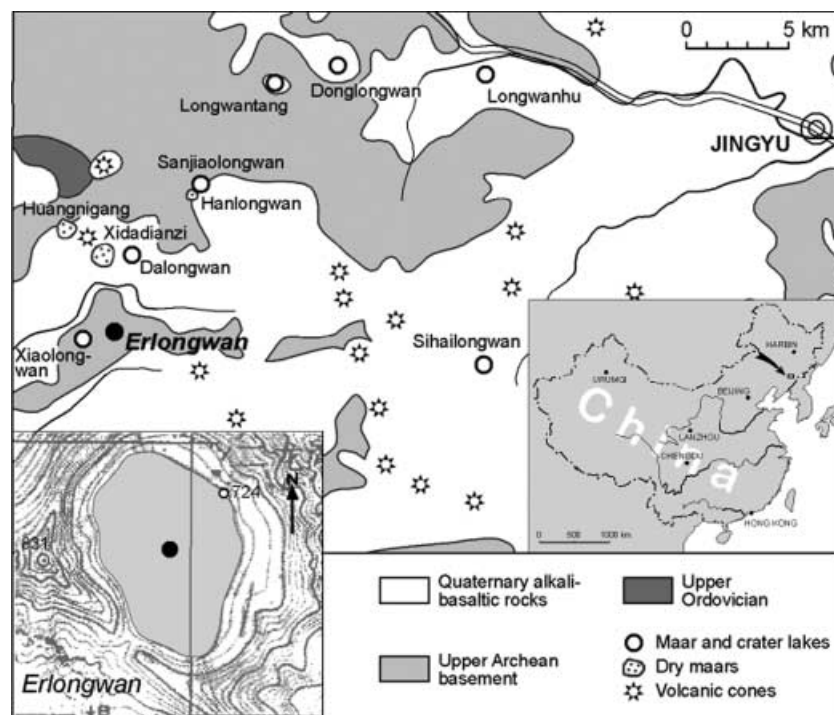


Figure 1. Geographical position and simplified geological map of the Long Gang Volcanic Field (LGVF). The coring location in Erlongwan maar lake is marked by a dot on the topographical map.

depth of 36 m, a surface area of 0.3 km² and a catchment area of 0.4 km². The lake is situated in the eastern part of the LGVF within the Archaean basement (Fig. 1). The rocks in the catchment area of the lake consist of gneisses, amphibolites and magnetite-bearing quartzites from the Anshan Migmatite group (Geological Survey of Jilin 1994). The fine laminated sediments of the lake are composed of detrital muds with varying amounts of organic material. The sediment sequence is interrupted by 410 graded layers with thicknesses between 0.1 and 150 cm. There is no difference between the minerogenic composition of the graded layers and the composition of the minerogenic layers within the laminated parts as was revealed from the microscopically analysis of thin sections.

METHODS

Field work and subsampling

During a drilling campaign in 2001, within the frame of the Asian Lake Drilling Project (ALDP), two 23-m-long sediment cores were recovered from the centre of ERL maar lake (Fig. 1). The coring sites are only some metres apart. Both cores were taken using a raft-operated Usinger piston corer (a modified Livingston piston corer). The individual core sections are 2 m long with a diameter of 80 mm down to 16 m (ERL-A) and 15 m depth (ERL-B), respectively. Below this depth the diameter of the cores is 55 mm. The lowermost core section from the profile ERL-A has a diameter of 40 mm and was not available for subsampling. In the laboratory the cores were cut into 1 m segments and split into halves. They were then sealed in polythene and stored at 4°C.

Subsampling was performed continuously with cubic plastic boxes (20 × 20 × 15.5 mm) that were pushed into the sediment surface in intervals of 20 mm. A filled sample was carefully removed

before the next sample was pushed into the sediment. In the more minerogenic and, therefore, harder parts of the sediment profile, the contours of the samples had to be cut into the sediment surface with a blade before pushing the box into it. This was done in order to avoid greater damages of the cores. The coarse-grained parts of the cores, for example, the lowermost part of thick graded layers, are not suitable for any kind of magnetic investigations. Moreover, it was not possible to sample this parts accurately, thus only a thick graded layer intercalated into the sediment sequence between 60 and 210 cm depth was sampled completely, for rock magnetic purposes only. A total of 942 and 945 samples were obtained from cores ERL-A and ERL-B, respectively. All samples were weighted in order to get initial information about the variations in the composition of the sediment.

Rock magnetic investigations

Continuous high-resolution logs of the magnetic susceptibility (κ_{LF}) were measured with a Bartington MS2E spot reading sensor in steps of 1 mm on the split halves of the cores. The sensor is integrated in an automated core logging system designed at the Laboratory for Palaeo- and Rock Magnetism in Potsdam. All 1987 samples were subjected to standard palaeomagnetic and rock magnetic analysis. A complete list of the rock magnetic investigations that were carried out is given in Table 1. *S*-ratios were calculated following Bloemendal *et al.* (1992): $S\text{-ratio} = 0.5 \times (1 - \text{IRM}_{-0.3T} / \text{SIRM}_{1.5T})$.

For calculation of the dry density (DD) every second rock magnetic sample of core ERL-B was freeze dried and weighted, before it was powdered in a mortar. The powdered samples were used for geochemical analysis as well as for the hysteresis and temperature-dependent measurements, since using material taken from the same horizons for all magnetic and geochemical/sedimentological

Table 1. Rock magnetic investigations carried out on the sediments from cores ERL-A and ERL-B, Long Gang Volcanic Field, NE China.

Investigation	Instrument	Remarks	Number of samples
Measurement of the anisotropy of the magnetic susceptibility	AGICO Kappabridge KLY-3S	Operating frequency 875 Hz	All samples
Measurement of low and high field magnetic susceptibility	Bartington MSB2-sensor	Operating frequency 460 Hz	All samples
Imprinting of an anhysteretic remanent magnetization (ARM)	2G Enterprises 600 single-axis Demagnetizer including an ARM-coil (max. static field 1 mT)	Produced along positive z-axis Static field: 0.5 mT, AF amplitude: 100 mT	All samples
measurement of ARM	2G Enterprises cryogenic magnetometer (2G-755-SRM)		All samples
demagnetization of ARM	In-line tri-axial alternating field demagnetizer of the 2G-755-SRM	7 steps up to 80 mT	All samples
imprinting of complete IRM-acquisition curves	Princeton Measurement Corp. 'Alternating Gradient Force Magnetometer' (MicroMag; max. amplitude 2.2 T)	35 steps up to 2 T	75 samples from ERL-B
Imprinting of a saturation isothermal remanent magnetization (SIRM)	2G Enterprises 660 pulsemagnetizer (max. amplitude 2.7 T)	Produced along positive z-axis peak field of 1.5 T	All samples
Measurement of SIRM	Molyneux Minispin Fluxgate magnetometer (Minispin)		All samples
Measurement of the hysteresis parameter M_S , M_{SR} , B_C and B_{CR}	MicroMag	Max. field 500 mT	75 samples from ERL-B
Temperature-dependent measurement of the saturation magnetization	Vibrating Field Transition Balance (VFTB) build by N. Petersen, Munich	Max. temperature 650–700°C Saturation field: 340 mT, in argon atmosphere	60 samples from ERL-B
temperature-dependent measurement of the magnetic susceptibility	AGICO Kappabridge KLY-3S	Max. temperature 700°C in Argon atmosphere	8 samples from ERL-B

analyses, is the best method to obtain a consistent interpretation of the results.

Total carbon was measured by standard LECO combustion at 1350°C. Total inorganic carbon (TIC) was analysed by coulometry, based on the amount of CO₂ produced after treatment of the samples with 85% phosphoric acid. Total organic carbon (TOC) was calculated by subtraction of TIC from total carbon.

Correlation and chronology

The correlation between the two cores from Erlongwan maar lake is based on the identification of the 410 graded layers. Additionally, the high-resolution logs of the magnetic susceptibility were used (Fig. 2) and a peak to peak correlation was possible for a greater part of the profile. Only the thick graded layers (>50 cm) show no comparable internal susceptibility variations in both cores. In order to get a continuous sedimentary record a composite profile was created based on macroscopic inspection of the cores (J. Mingram, personal communication, 2003) which was later improved by the results of the core correlation. The core depths of ERL-A and ERL-B were transformed into composite depth which will be referred to throughout the whole text.

The chronology of the ERL profile is based on the results of radio-carbon dating of 15 bulk sediment samples taken from fine laminated sediment section (Fig. 3), (Frank 2005). The AMS ¹⁴C ages were calibrated with the calibration programs IntCal04 (Reimer *et al.* 2004) for ages younger than 22 ka and CalPal (<http://www.calpal-online.de>) for ¹⁴C ages older than 22 ka. All graded layers, interpreted as event layers, were excluded from the data set before calculation of the age model was performed.

RESULTS

Sedimentology

The ERL profile consists of organic to minerogenic sediments with an macroscopically visible lamination based on either seasonally changes in the content of organic material (Holocene) or grain size variations of the minerogenic components (Glacial; Fig. 4). Graded layers with thicknesses from 0.1 up to 150 cm are intercalated into the sedimentary sequence, especially in the uppermost 940 cm and below 1712 cm depth. Visual inspection of the cores revealed a subdivision in five lithozones (A–E) as presented in Fig. 4. This is confirmed by the results of the rock magnetic, sedimentological and geochemical investigations. The organic carbon content has the highest values (15–20 wt %) in the uppermost 63 cm of the profile (lithozone A), consisting of organic sediments. Accordingly the dry density is low (<0.2 g cm⁻³). The higher DD values between 10 and 30 cm depth are related to a graded layer, a phenomenon which can be observed throughout the whole profile (Fig. 4). However, the difference between the mean DD value within a lithozone and the peak values of the imbedded graded layers is decreasing with increasing minerogenic content of the bulk sediment. Analysis of the thin sections taken from both cores revealed, that there is no difference in the mineral composition of the graded layers and the surrounding minerogenic sediments, only the grain size and the amount of plant remains differs. The only exception comprises the depth interval between 575 and 615 cm, where a reworked volcanic ash layer is part of a disturbed sediment sequence (Fig. 4). This depth interval nearly marks the end of lithozone B (63–632 cm depth). Within lithozone B the total organic carbon content decreases from values around

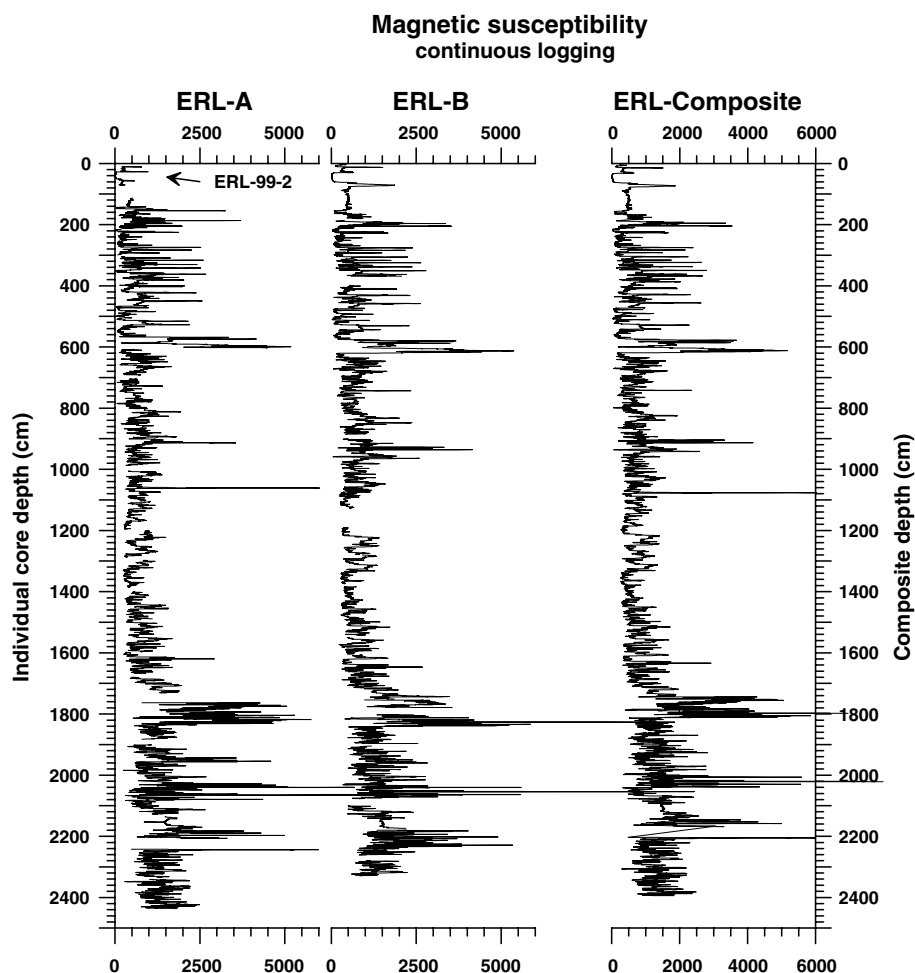


Figure 2. High-resolution logs of magnetic susceptibility measured on the surface on the splitted core halves for the individual cores ERL-A and ERL-B (left) and the ERL-composite (right).

15 wt % down to 5 wt % whereas the DD varies less, that is, between 0.3 and 0.4 g cm^{-3} , reaching up to 0.8 g cm^{-3} in the more minerogenic layers. Below 632 cm depth, within a short sequence build up by minerogenic–organic sediments (lithozone C), the DD increases up to 0.7 to 1 g cm^{-3} with less variability than in the sequences above (Fig. 4). The magnetic susceptibility shows variations similar to DD and is anticorrelated with TOC. Between 815 cm and 1712 cm depth (lithozone D) the DD (TOC) record shows only minor variability with values slowly increasing (decreasing) from 0.8 to 1.1 g cm^{-3} (4 to $3 \text{ wt } \%$; Fig. 4). The graded layers are less frequent and most of them are only a few centimetres thick. Below 1712 cm , in the coarse-grained minerogenic sediments of lithozone E, there is again a quick succession of graded layers with thicknesses of up to 120 cm (Fig. 4). This change in sedimentation pattern is mainly reflected in the magnetic susceptibility with the highest mean values in lithozone E, whereas the DD slightly decreases to around 1 g cm^{-3} . The most interesting observation here is a minor increase in TOC which is due to an increased transport of terrestrial plant remains from the catchment area into the lake as a part of the graded layers. The occurrence of the graded layers probably reflects periods with a higher precipitation rate or snow melting events in the region (Mingram *et al.* 2004). Their formation is supported by the topography with only a small flat area between the crater rim and the lake

shore (Fig. 1). Therefore, nearly all eroded material is transported into the lake.

Magnetic carrier minerals

High-temperature runs of the saturation magnetization revealed that magnetite is the main carrier of the magnetic remanence in the sediments from ERL maar lake (Fig. 5). The magnetite originates from the Archaen rocks in the catchment area which have been described as gneisses, amphibolites and magnetite-bearing quartzites (Geological Survey of Jilin 1994). The heating/cooling curve of an archaic rock sample from a cliff on the NE crater rim of ERL maar lake show similar results to those obtained from the majority of the sediment samples (Fig. 5), indicating that the Archaen rocks supply most of the minerogenic sediment components. This assumption is corroborated by a the preliminary analysis of thin sections taken from the core halves. The mineral composition is dominated by quartz, plagioclase and mica. Volcanic products, originating from the Late Quaternary volcanic activity in the LGVF (Fan & Sui 2002; Liu 1988), were also found, but mostly as clasts and glass shards within the graded layers. Only three tephra layers could be identified (Fig. 4). The quaternary volcanoclastic products are either alkalibasalts or basanites (Chen *et al.* 2003; Fan

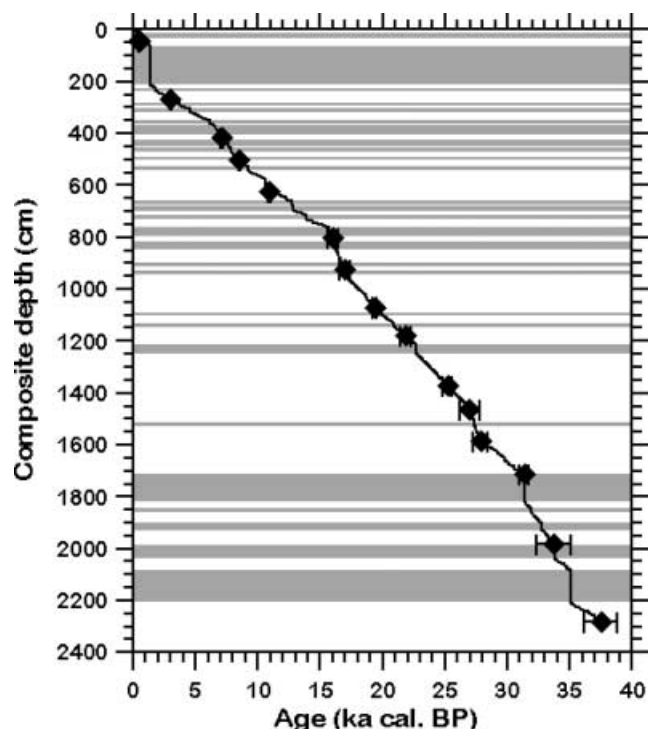


Figure 3. Depth/age model for Erlongwan maar lake based on 15 calibrated AMS ^{14}C -ages (black diamonds). Some of the error bars for the radiocarbon dates are smaller than the size of the symbol. The grey shaded areas denote graded layers thicker than 10 cm.

et al. 2000). The results of the high-temperature measurement on a tephra layer found within the sediment sequence is shown in Fig. 5 as well. The shape of the heating and the cooling curves differs significantly from those obtained from the sediment samples, except for the sample taken from a depth of 596 cm, being part of the sediment interval build up by a reworked volcanic ash layer (Fig. 5). Although the measurements were performed under argon atmosphere, there was still some oxygen left in the pulverized samples and magnetite has formed during heating above 420 to 480 °C (Fig. 5). This is mainly caused by high-temperature oxidation of non-magnetic iron-bearing minerals and, probably, also due to an unmixing of maghemite–magnetite intergrown. The presence of maghemite, formed during weathering of the exposed alkalibasaltic volcanic products and soil formation within the crater rim, could also be deduced from the heating curve obtained from the soil sample with a pronounced inversion point of around 400 °C (Dunlop & Özdemir 1997; Gendler *et al.* 2005) (Fig. 5). Maghemite is thought to contribute to the mineral magnetic fraction in small but varying amounts together with hematite and/or minor portions of iron oxyhydroxides, probably the weathering product goethite. The macroscopic analysis of the cores by eye and the rock magnetic investigations revealed that there are no Fe-sulphites, greigite and pyrite, in the sediments from ERL maar lake.

Concentration variations

The content of magnetic minerals in the ERL sediments is generally high and remains nearly constant, except for the uppermost 632 cm of the profile, indicating a fairly steady background sedimentation during long periods of time. This interpretation is supported by the depth/age model, showing relative constant sedimentation rates in

the time interval 17 to 27 ka cal. BP (0–750 cm), as well as between 0 and 15 ka (950–1450 cm; Fig. 3).

The variations in the concentration of the magnetic particles in the ERL sediments are controlled by two main factors, the composition of the sediment, for example, the content of minerogenic material in general, and the occurrence of graded layers. As was already described above, the magnetic susceptibility shows variations similar to those in the dry density record. The same is true for the concentration depend parameters intensity of the saturation isothermal remanent magnetization (J_{SIRM}) and of the anhysteretic remanent magnetization (J_{ARM}), with their highest variability in the organic to minerogenic–organic sediments down to 632 cm (lithozones A and B; Figs 6a and b). This is due to the greater contrast between the amount of minerogenic material in a graded layer compared to the rest of the organic to organic–minerogenic sediment. Below 632 cm, in the fine- to coarse-grained minerogenic sediments (lithozones C, D and E) the occurrence of graded layers does not have such an effect on the concentration variability. This is due to the similar mineralogy as was confirmed by high-temperature measurements of saturation magnetization (Fig. 5).

Magnetic grain size and coercivity

The high-frequency variations in magnetic grain size and coercivity are also linked to the occurrence of graded layers, that is, a coarsening (fining) of the grain size fraction occurs within the bottom (top) part of these layers (Figs 6a and b). This is best reflected in the ratio $J_{\text{ARM}}/J_{\text{SIRM}}$ in Figs 7(a) and (b), showing an enlarged view of lithozone B and D in core ERL-B, respectively. The variations in the MDF_{ARM} follow those in $J_{\text{ARM}}/J_{\text{SIRM}}$, smaller grains have slightly higher coercivities than coarser grains. The concentration variations, here presented by J_{ARM} follow the trend in the grain size indicative parameters, however, the detailed picture in Figs 7(a) and (b) shows that there is a complex relationship between minerogenic influx and magnetic grain size. The grain size depends on the thickness of the graded layer and/or laminated sediment interval in general, and on the presence of Quaternary volcanoclastics in particular. The latter have rock magnetic characteristics that differ clearly from the Archaean basement rocks as it is shown in Figs 5, 6(a) and (b). A peak in the ratio of $J_{\text{SIRM}}/\kappa_{\text{LF}}$ at 210 cm depth is linked to basaltic volcanic material imbedded in the sediment (Figs 6a and b). According to the age model presented, this volcanic material can probably be attributed to the volcanic activity about 1.6 ka ago, forming the Jinlongdingzi scoria cone (Fan & Sui 2002). Two further peaks at 910 cm (Fig. 6a) and 1078 cm depth (Fig. 6b), respectively, are caused by volcanic ash layers. Except for this ash layers, the variations in the ratio $J_{\text{SIRM}}/\kappa_{\text{LF}}$, which is a grain size indicative parameter, are similar to those in MDF_{ARM} and $J_{\text{ARM}}/J_{\text{SIRM}}$ but with lower amplitudes (Figs 7a and b). The last parameter presented is the S -ratio which is commonly used to estimate the amount of high-coercive minerals like hematite or goethite in sediments (Bloemendal *et al.* 1992). However, it was shown by Kruiver & Passier (2001) that the S -ratio also reflects coercivity variations within mixtures of magnetites originating either from magnetosomes or aeolian dust, thus reflecting different grain sizes. S -ratios are highest when the coercivity dispersion is small, that is saturation is more quickly achieved in fine-grained magnetite with a narrow grain size contribution than in assemblages with higher amounts of coarser-grained magnetites. In the sediments from ERL maar lake the magnetic remanence is carried by magnetite and the S -ratio parallels the ratio $J_{\text{SIRM}}/\kappa_{\text{LF}}$ (Figs 7a and b.) thus

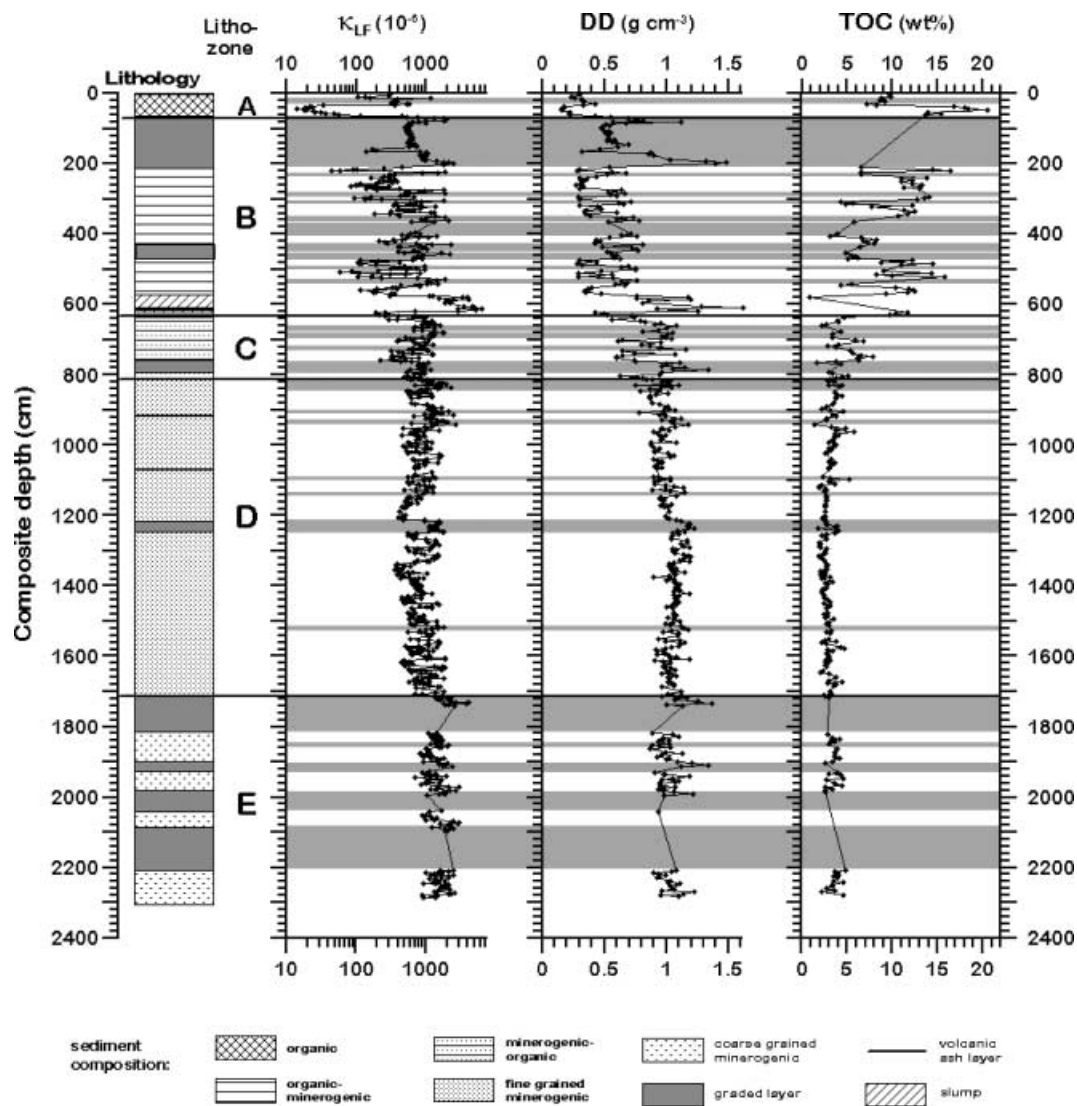


Figure 4. Lithology, low field magnetic susceptibility (κ_{LF}), dry density (DD) and total organic carbon content (TOC) measured for the samples from core ERL-B versus composite depth. The capital letters denote the five lithozones. The Pleistocene/Holocene boundary corresponds to the change from minerogenic–organic to organic–minerogenic sediments at 632 cm depth (lithozones C/B). Graded layers ≥ 10 cm thickness are marked by grey shaded areas.

indicating, that the S -ratio could be interpreted as a grain size indicative parameter with high values corresponding to fine-grained minerals. This interpretation corresponds to findings based on rock magnetic investigation of Dead Sea sediments: the IRM acquisition curves of magnetic assemblages dominated by greigite have a small coercivity dispersion and the S -ratio is near 1 (Frank *et al.* 2005).

There are also low frequent variations in the magnetic grain size and coercivity parameters obtained from the ERL-sediment cores. These could be detected after removing all samples containing graded layers > 1 cm of the rock magnetic records (Figs 8a and b). The laminated sediments in lithozones A and B are characterized by a distinct increase in the coercivity, expressed by high (low) values of MDF_{ARM} (S -ratio), which is apparently caused by an enrichment of high-coercive minerals as a result of dilution and dissolution of magnetite in the highly organic sediments. The ratio of J_{ARM}/J_{SIRM} is also high with values $> 60 \times 10^{-3}$, indicating the presence of fine-grained magnetite. Below 210 cm depth down to the end of Lithozones B the MDF_{ARM} is nearly constant between 20 and 26 mT and the grain size indicative parameters show only minor variability. Below 632 cm (lithozones C) an increase in the MDF_{ARM} values goes along

with an increase in J_{ARM}/J_{SIRM} , reflecting a shift in the grain size fraction towards finer magnetite grains. In lithozones D (890–1710 cm) the magnetic coercivity and grain size indicative parameters show similar low frequent variations, suggesting a high variability within the magnetic grain size fraction. For lithozones E there are too few samples left after cleaning the records for the graded layers to give any explanation for the scattering of the data. The variations in the S -ratio and the ratio of J_{SIRM}/κ_{LF} stays are nearly identical throughout the whole profile and correspond to those known from MDF_{ARM} and J_{ARM}/J_{SIRM} (Figs 8a and b). The observed variability in the sediments of lithozones C, D and E seems to reflect changes in the minerogenic influx since the TOC content of the sediments below 500 cm depth is nearly constant at 3 wt % (Fig. 4). Therefore, changes in the dissolution rate of the ferromagnetic minerals, assuming that the ERL sediments were deposited under anoxic conditions, cannot account for changes in the magnetic grain sizes. Additionally the variations in magnetic concentration parallels those in the grain size and coercivity indicative parameters, with an decrease in magnetic grain size during periods of increased concentration. So during periods with increased minerogenic influx less fine-grained

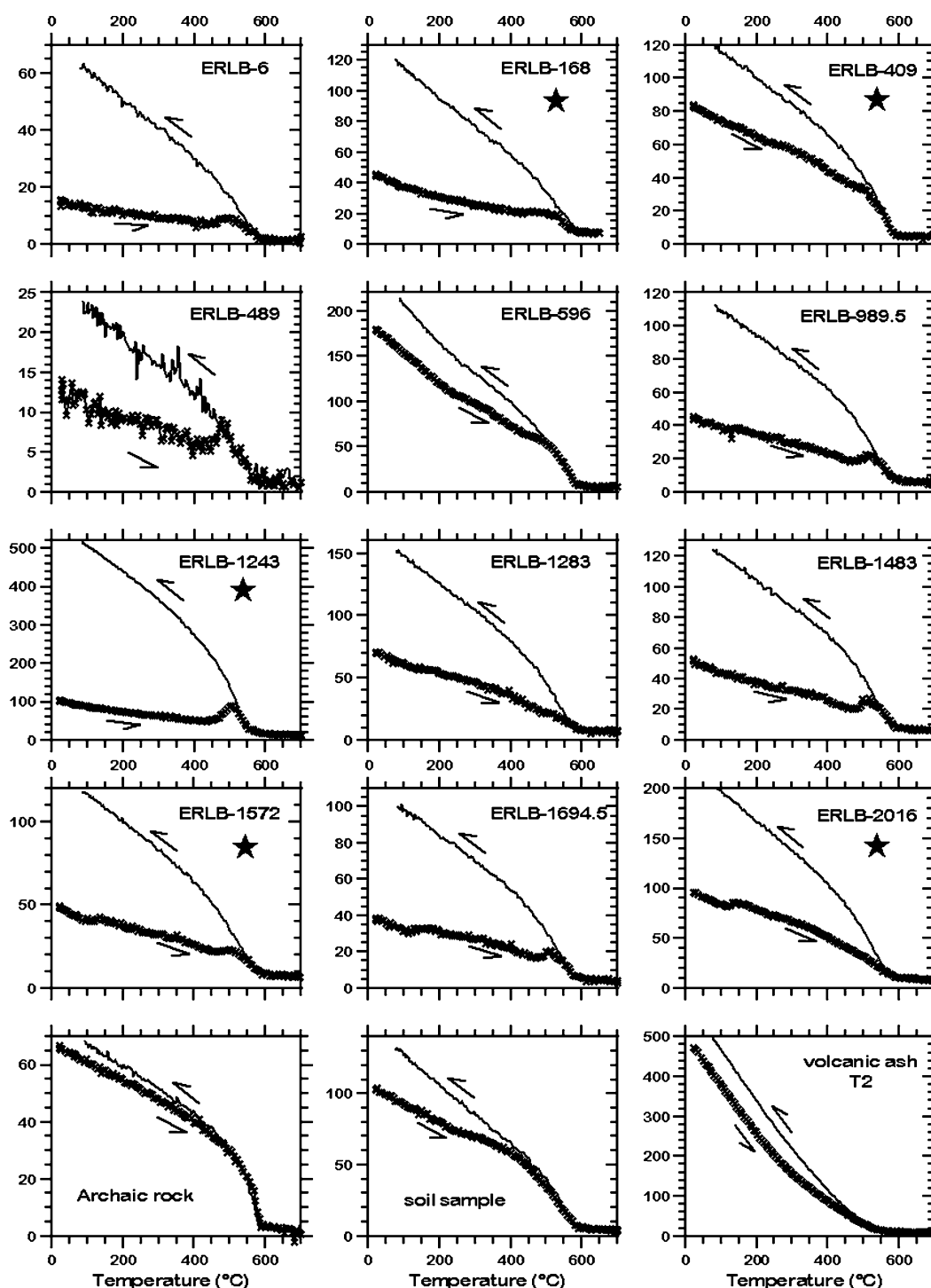


Figure 5. Temperature-dependent measurements of the saturation magnetization of sediment samples from core ERL-B. Curves obtained from an archaic rock and a soil sample from the catchment area as well as from a volcanic ash layer found within the sediment sequence are presented for comparison. The stars within the individual figures denote samples from graded layers. Heating curves are marked by crosses, cooling curves by black lines.

magnetites are probably affected by dissolution processes in the laminated sediments.

More information on the grain size of the magnetites were obtained from the measurement of the hysteresis parameter. They were determined after correcting the hysteresis loops for the paramagnetic trends. M_{SR}/M_S - and B_{CR}/B_C -ratios were calculated for a total of 75 samples from the ERL profile (Fig. 9). More than 65 per cent of the samples on the diagram are representing graded layers.

This is an effect of a 'taking every 20th sample' routine because roughly the half of the sediment profile is build up by graded layers. The origin of the samples, however, has only little influence on the distribution in the Day-plot, because there is no differentiation between samples from the different lithozones in the diagram. The laminated sediments are less scattered indicating a more homogenous composition (Fig. 9). The majority of the samples plots in the PSD field of the Day-plot, following the hyperbolic trend of

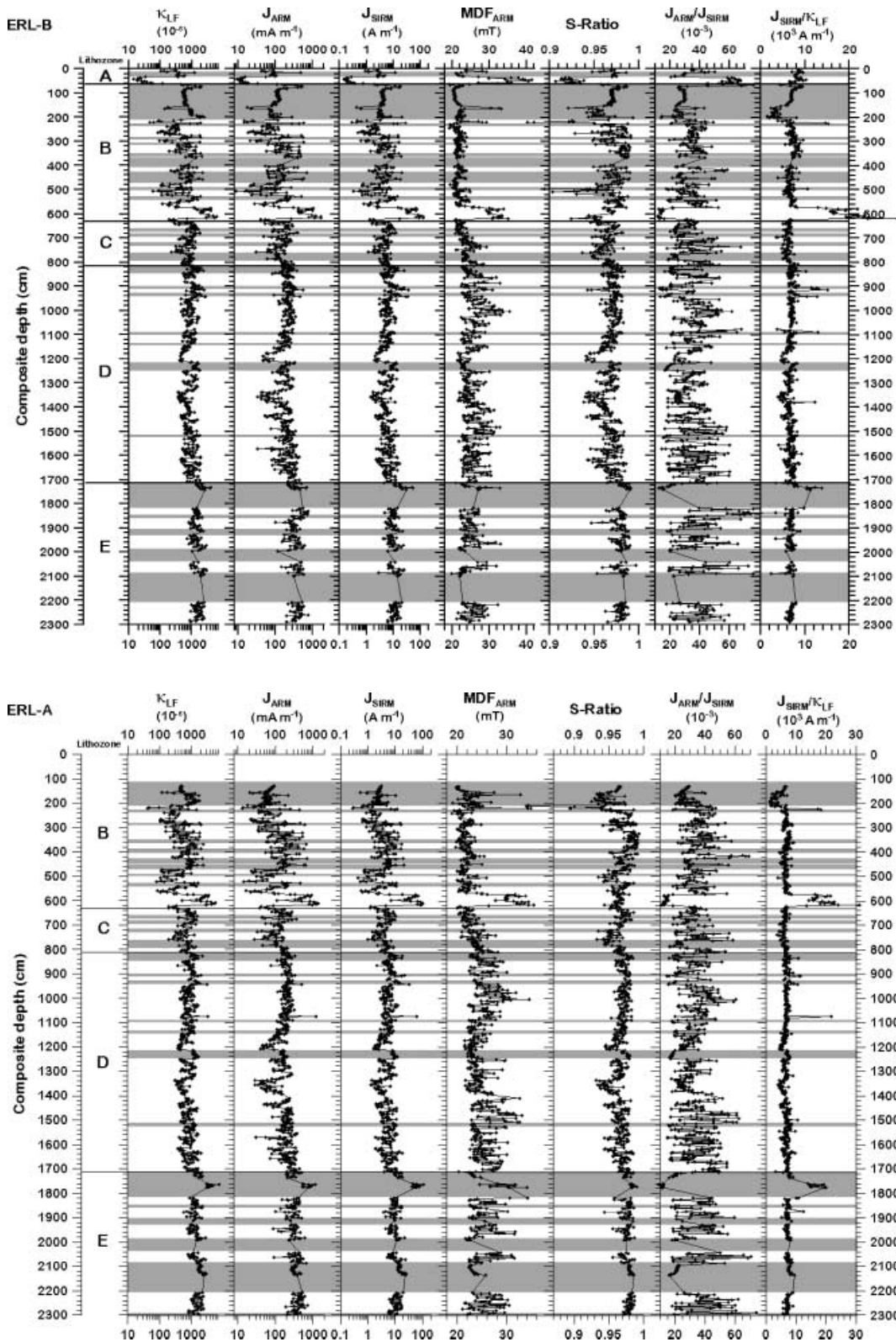


Figure 6. Lithozones, records of the concentration-dependent parameters intensity of the anhysteretic remanent magnetization (J_{ARM}), low field magnetic susceptibility (κ_{LF}), and intensity of the saturation isothermal remanent magnetization (J_{SIRM}), and records of parameters indicative for magnetic grain size and coercivity: median destructive field of the ARM (MDF_{ARM}), S -ratio, J_{ARM}/J_{SIRM} and J_{SIRM}/κ_{LF} , for a) core ERL-B, and b) core ERL-A versus composite depth. S -ratio = $0.5 \times (1 - IRM_{-0.3T}/IRM_{1.5T})$. Graded layers ≥ 10 cm thickness are marked by grey shaded areas.

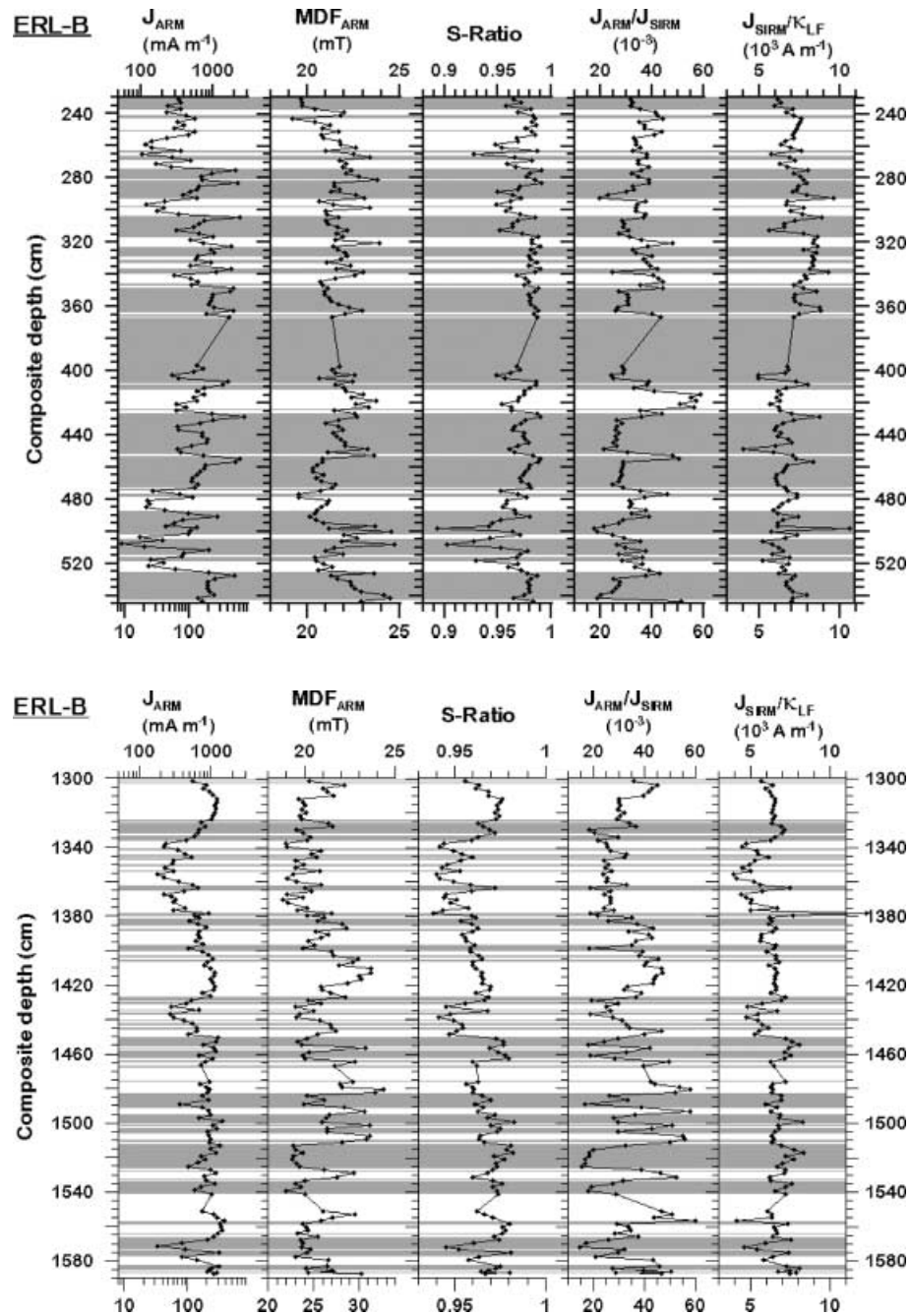


Figure 7. Records of the concentration-dependent parameter J_{ARM} , and the coercivity and grain size indicative parameters MDF_{ARM} , $S\text{-Ratio}$, $J_{\text{ARM}}/J_{\text{SIRM}}$ and $J_{\text{SIRM}}/K_{\text{LF}}$ from ERL-B versus composite depth. (a) Lithozone B, 230–545 cm depth, (b) Lithozone D, 1300–1590 cm depth. The graded layers are marked by grey lines and areas.

the SD–MD mixing lines by Parry (1982, 1980) and Dunlop (2002). Most of the samples fall slightly above mixing curve 3 with one cluster at $M_{\text{SR}}/M_{\text{S}} = 0.2$ and $B_{\text{CR}}/B_{\text{C}} = 2.5$. These values nearly correspond to a MD contribution of 60% (Fig. 9). The samples close to the MD area of the diagram are either from the coarse-grained part of graded layers or have a very low saturation magnetization. Additionally, the hysteresis parameters determined on some soil samples from the lake shore, two volcanic ash layers and archaic rock samples are shown for comparison. The latter show MD behaviour and comprise the end member of the SD–MD mixing line (Fig. 9). It is

more interesting to look at the soil samples which follow the trend of the mixing lines but lay above most of all samples. The shift towards higher $B_{\text{CR}}/B_{\text{C}}$ ratios can probably be explained by higher amounts of goethite and/or hematite in this samples (Roberts *et al.* 1995) which were exposed to weathering. However, none of these minerals was identified in the thermomagnetic curves for sure (Fig. 5). The samples from the volcanic ash layers plot on the SD–SP mixing line indicating the presence of SP grains. The existence of the latter would explain for the high (low) values of J_{SIRM}/K ($J_{\text{ARM}}/J_{\text{SIRM}}$) obtained for the volcanic ash layers, magnetite grains at the SD–SP

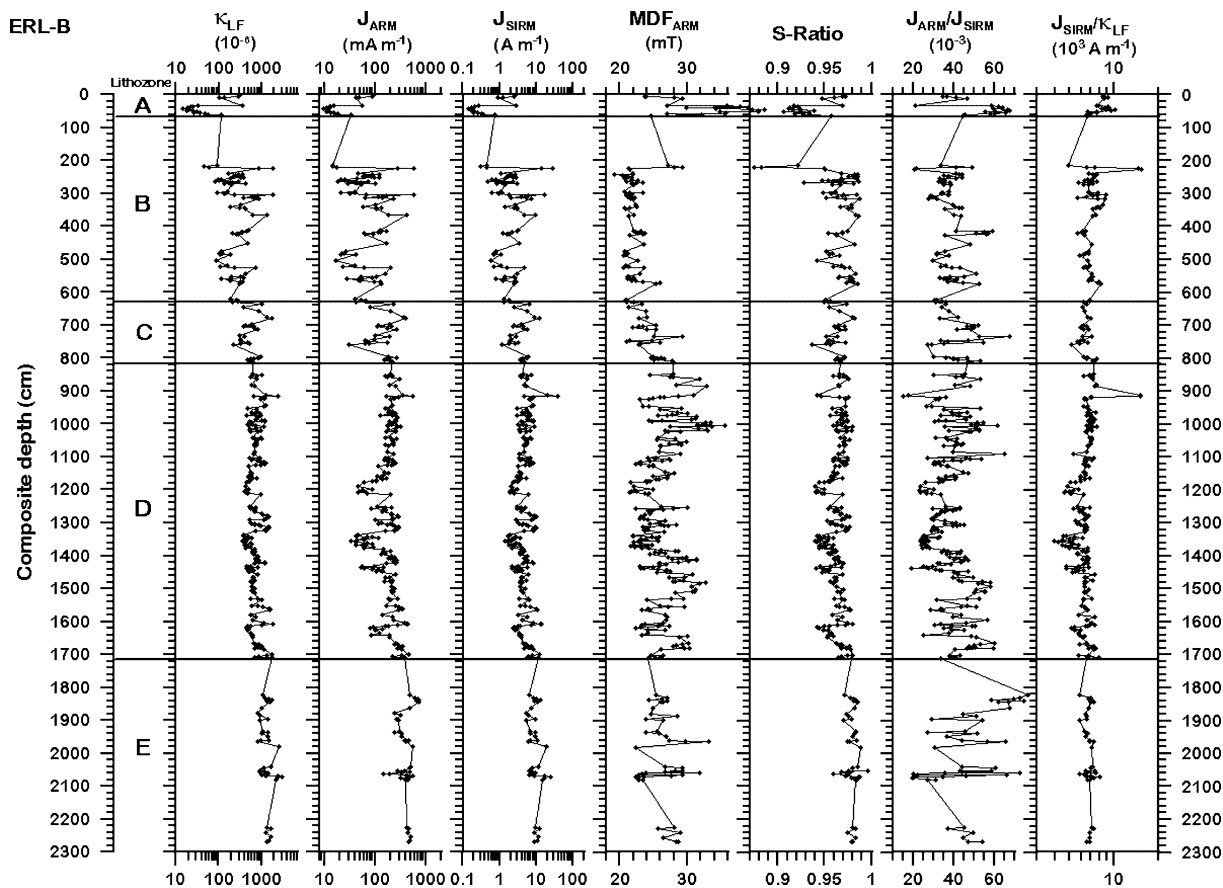


Figure 8. Lithozones, records of the concentration-dependent parameters: κ_{LF} , J_{ARM} , and J_{SIRM} , and records of parameters indicative for magnetic grain size and coercivity: MDF_{ARM} , S -ratio, J_{ARM}/J_{SIRM} and J_{SIRM}/κ_{LF} , for (a) core ERL-B, and (b) core ERL-A versus composite depth. Presented are samples from laminated sediment sections only.

boundary have an extremely high saturation remanence (Thompson & Oldfield 1986).

DISCUSSION

Considering the parameters presented the question arises, if there is any diagenetic overprint that has altered the primary mineral magnetic fraction in the laminated sediment sections and if so, to what extent. Since the typical diagenetically formed minerals like greigite and/or pyrite are missing in ERL, other parameters must be evaluated for fingerprints of diagenesis. As was shown by the rock magnetic investigations on sediments from Lake Lama, Siberia, a TOC content of around 0.5 wt % is enough to alter considerably the rock magnetic signal of a sediment (Frank *et al.* 2002; Nowaczyk *et al.* 2000). In this Siberian lake anoxic conditions in the sediments have led to a distinct coarsening of the magnetic grain size fraction, which is reflected in all grain size and coercivity indicative parameters. The TOC content in the ERL sediments is 3 wt % or higher (Fig. 4). The development of a at least seasonal lake bottom anoxia in temperate fresh water lakes is a main presumption for the preservation of seasonally laminated sediments, like those found in the Holocene part of the ERL profile (lithozones A and B). In ERL maar lake geochemical investigations of the water body revealed a thermal stratification during summer (Mingram *et al.* 2004), allowing for the existence of anoxic bottom water. All these hints point to the occurrence of

dissolution processes which affected the fine-grained ferromagnetic minerals after deposition. However the values of J_{ARM}/J_{SIRM} ($30\text{--}40 \times 10^{-3}$) in the uppermost 800 cm of the ERL sediment profile are comparable to those measured for oxic sediment samples from core PG1341 (Lake Lama, Siberia Frank *et al.* 2002). They also correspond to values measured for samples from the highly organic sediments of Lago di Mezzano, Italy (Frank *et al.* 2000). These sediments were deposited under anoxic conditions and their magnetic fraction suffered from a dissolution of the fine-grained minerals as well as the coarser-grained minerals (Frank 1999). Detailed rock magnetic investigations of the Siberian and Italian sediments revealed (Ti-) magnetite as the dominant magnetic carrier mineral, as in ERL. The sediments from the three lakes also have in common, that the sedimentation in the discussed sections was interrupted by event layers interpreted as turbidites (Lago di Mezzano) or described as graded layers (ERL) and periodically inwash of material from the catchment area (Lake Lama). Therefore, it can be assumed that an increased transportation of minerogenic material into the lake has led to a temporary change from anoxic to oxic conditions at the lake bottom and the sediment/water interface. As a result the dissolution process is interrupted and more fine-grained magnetites are preserved. The graded layers themselves are characterized by a higher content of coarse-grained magnetic minerals when compared to the laminated sediment sections (Figs 7a and b), a result of enhanced transport capacity and energy.

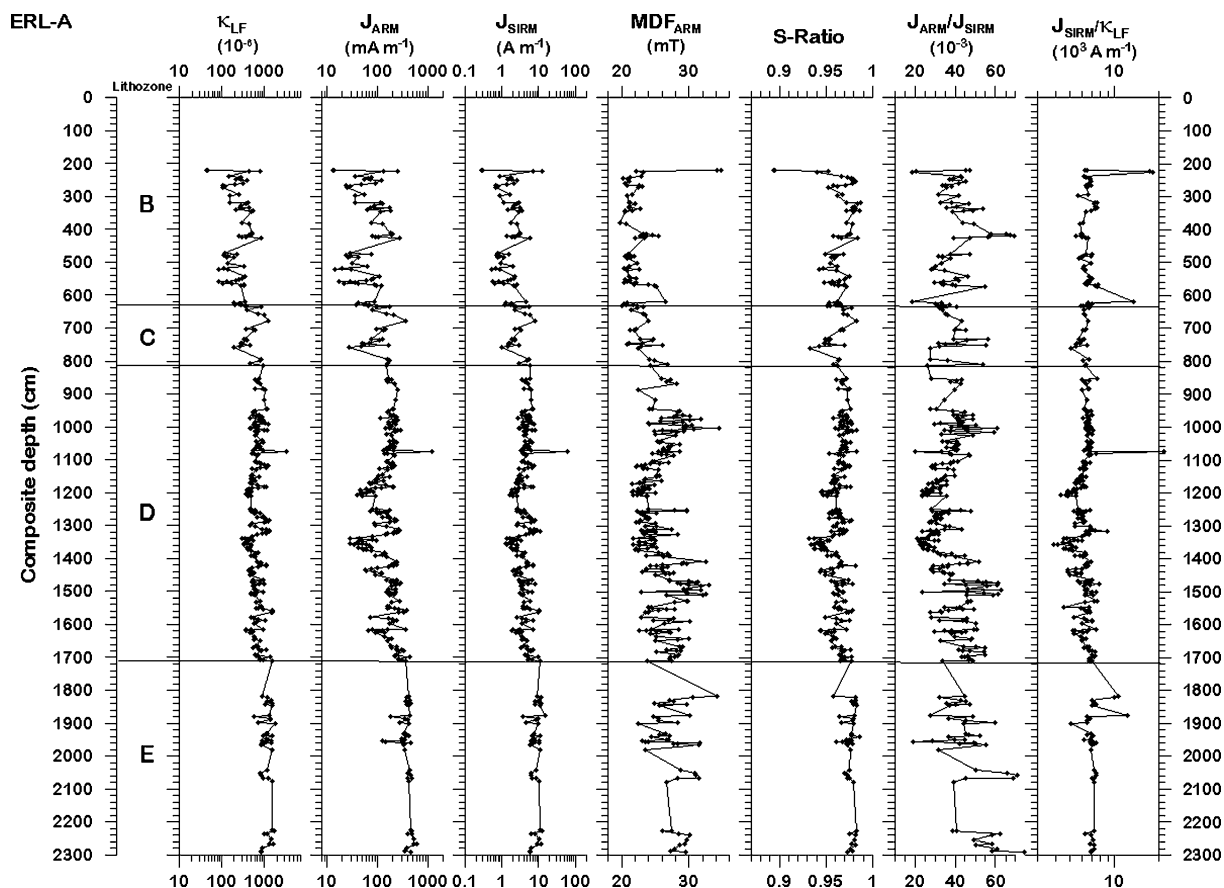


Figure 8. (Continued.)

As shown in Figs 10(a) and (b), there is no clear relation between the grain size of the magnetite in the laminated sediment sections presented by $J_{\text{ARM}}/J_{\text{SIRM}}$ and MDF_{ARM} and the TOC content which supports the interpretation made ahead. Merely the samples from lithozone C and B tend towards some linear relation between finer-grained magnetic minerals and lower TOC. Yet this cannot be interpreted in terms of reduced dissolution but rather as increased sedimentation of minerogenic material, as revealed by the scatterplots of TOC versus J_{ARM} and J_{SIRM} (Figs 10c and d). In lithozones D and E, comprising the fine to coarse-grained Pleistocene sediment sections, a constant rate of dissolution, as indicated by constant TOC values can be assumed (Figs 10a–d). The observed variability in the grain size indicative parameters within these lithozones seems, therefore, to be controlled by variations in the minerogenic input into the lake rather than by changes in the geochemical conditions at the lake bottom and topmost cm of the sediment. During periods with increased input of minerogenic material a higher amount of fine-grained magnetites was preserved within the sediments (Figs 10e and f). In lithozone E, which is the sediment interval with the most abundant graded layers and the highest mean values in the concentration-dependent parameters (Fig. 6a) the magnetite is characterized by the finest grain sizes, as reflected by high S -ratios and ratios of $J_{\text{ARM}}/J_{\text{SIRM}}$ (Figs 10e and f).

In contrast to the laminated sediments which are affected by post-sedimentary diagenetic processes, the rock magnetic results obtained from the graded layers reflect changes in geochemical conditions at the time of deposition. The increase in the minerogenic influx linked to the occurrence of graded layers and the resulting increase in the amount of coarse-grained magnetic minerals

in the sediments, are covering the effects of the magnetic mineral dissolution. The occurrence of the graded layers, which are interpreted as a result of increased precipitation or snow melting events (Mingram *et al.* 2004), is associated with a thoroughly mixing of the water column and penetration of oxygen to the sediment/water interface. As a consequence the fine-grained magnetic particles are preserved and at the same time the magnetic grain size fraction within most of the graded layers is shifted to coarser grains (Figs 11a and b). The lowest values for the grain size indicative parameter $J_{\text{ARM}}/J_{\text{SIRM}}$ are obtained from graded layer samples with high magnetic mineral concentration. These samples are also characterized by lower S -ratios, indicating that in the ERL-sediments this parameter is suitable for the estimation of grains size variations. An exception comprises lithozone A where an apparent enrichment of high coercivity minerals was observed (Figs 10b and f). Investigations on sediments from the Dead Sea also revealed that the S -ratio is highest for samples containing SD-particles like the chemically formed greigite found in these sediments (Frank *et al.* 2005). More detailed information on how the single rock magnetic parameters can be interpreted in terms of grain size variations will be gained by the results of the ongoing detailed investigations of the sediment laminae.

CONCLUSIONS

The sediments deposited in the Erlongwan maar lake during the last 37 ka can be subdivided into two groups with extremely different rock magnetic characteristics, although their minerogenic components are similar. The laminated sediments were deposited under

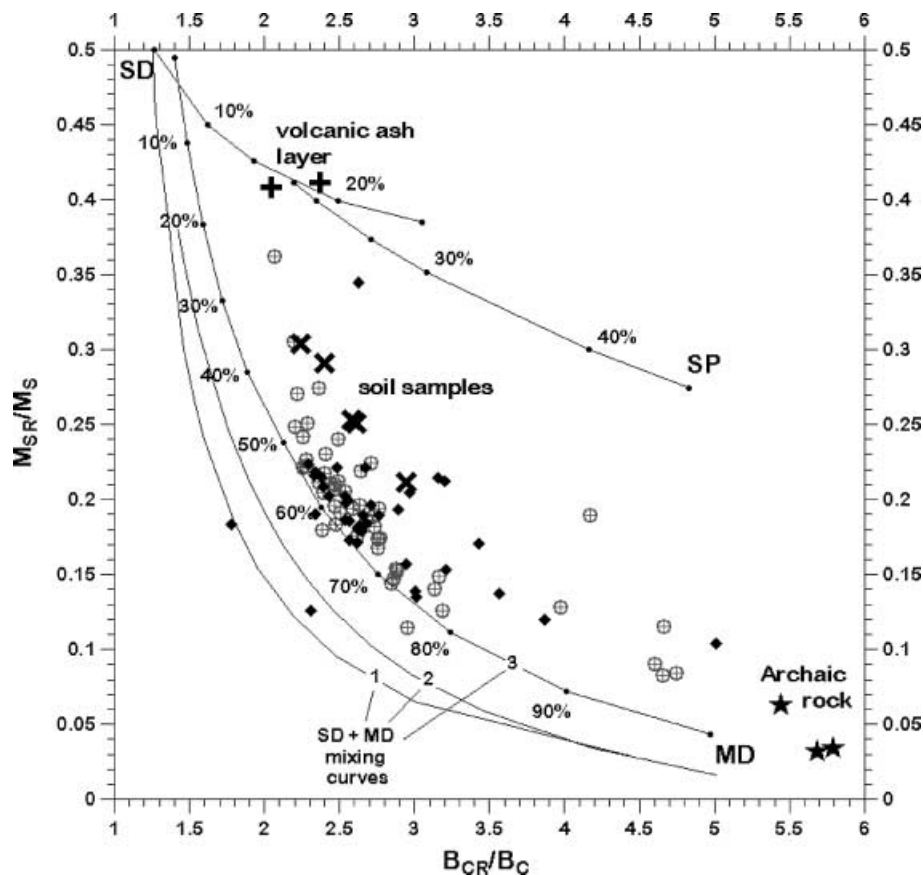


Figure 9. Results from hysteresis measurements carried out on 75 samples from core ERL-B presented in a Day plot (Day *et al.* 1977). The samples from the graded layers (laminated sections) are marked by circles (black diamonds). Additionally shown are the results obtained from the investigation of archaic rock and soil samples from the catchment area of lake Erlongwan and from volcanic ash layers intercalated into the sediment sequence. The SD–MD and SD–SP mixing lines are from Dunlop (2002).

anoxic conditions and their magnetic carrier fraction was affected by dissolution processes. This is best expressed by the enrichment of fine-grained magnetic particles during episodes with increased minerogenic input. In contrast, in the oxic sediments, an increase in the minerogenic influx has led to a coarsening of the grain size of the magnetic carrier fraction because the associated transport energy is higher and sufficient to move coarser-grained material. This process is observed in the thick graded layers where the coarse-grained bottom sections are often associated with terrestrial plant remains and volcanoclastic material from the crater rim. The graded layers which are taking up about 56 per cent of the complete sediment sequence, reflect mostly oxic conditions. The variations in the concentration, grain size and coercivity of the magnetic carrier minerals are controlled by the alternation of these two different types of sediment. Especially in the Holocene part of the profile, the contrast between the minerogenic graded layers and the organic to organic–minerogenic sediment is most conspicuous. In the Pleistocene part of the sediment profile, composed of minerogenic to organic sediments there is no such distinct contrast, although the existence of different grain size spectra is obvious in all stratigraphic and scatterplots presented.

ACKNOWLEDGMENTS

The author would like to thank J. Mingram, D. Berger, M. Köhler, D. Acksel, H. Howey and I. Heymann for coring. G. Schettler is kindly acknowledged for introducing me to the different methods of

geochemical analysis and for his essential support during measurements and data analysis. U. Kegel, C. Schmeltzer, D. Sonnabend and S. Weesemann helped during laboratory work. G. Yancheva thoroughly reviewed a former version of the manuscript. J. Mingram and G. Schettler provided the rock and soil samples, respectively. M. Torii and J. Bloemendal are acknowledged for their helpful reviews. This study was funded by the German Research Foundation (DFG), grant Fr1672/1-1.

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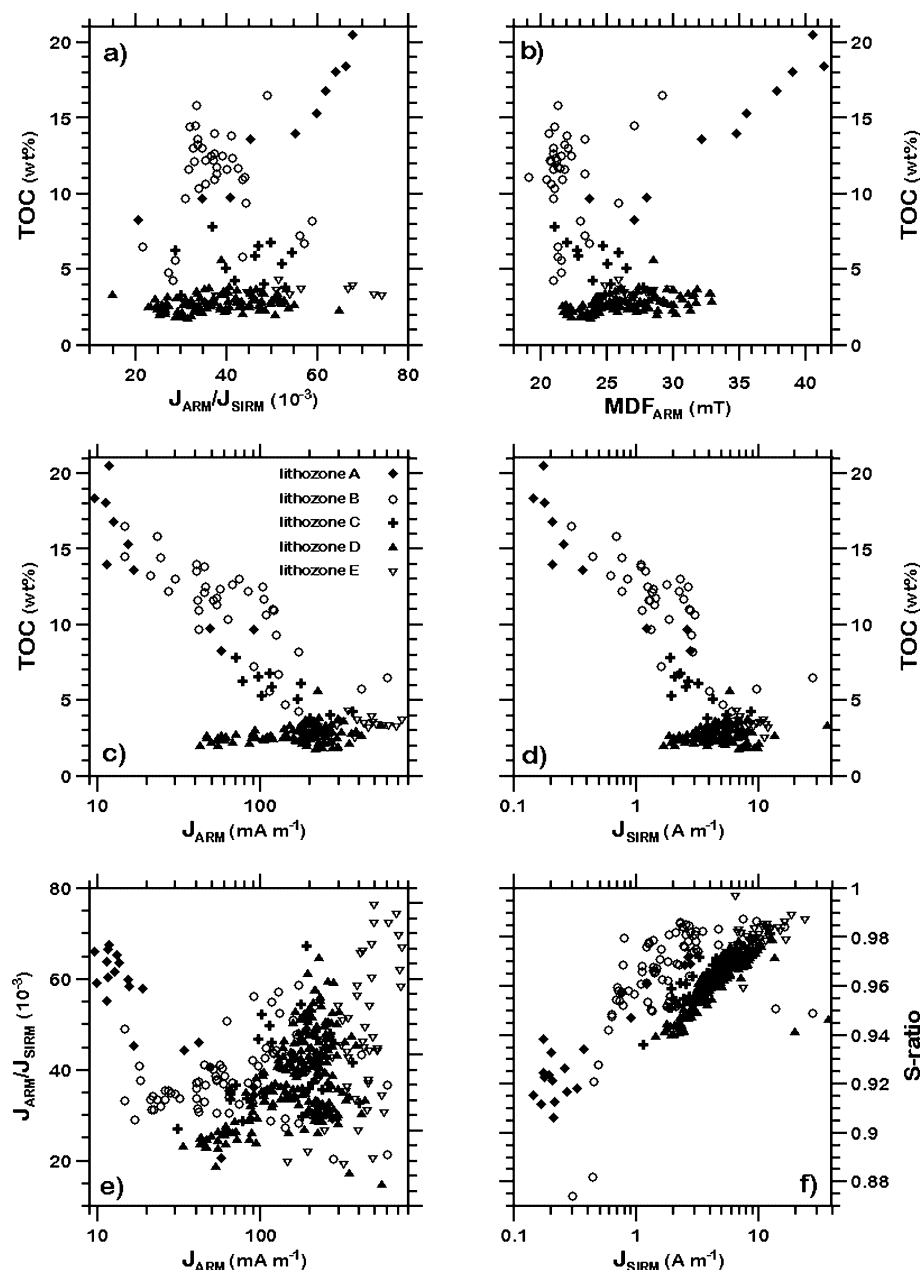


Figure 10. Scatterplots combining different rock magnetic parameters indicative for coercivity, grain size, magnetic concentration and organic carbon content (TOC) obtained for the samples from the laminated sediment sequences in core ERL-B (see Fig. 8a). The samples from the different lithozones are marked by different symbols. The legend is given in Fig. 10(c).

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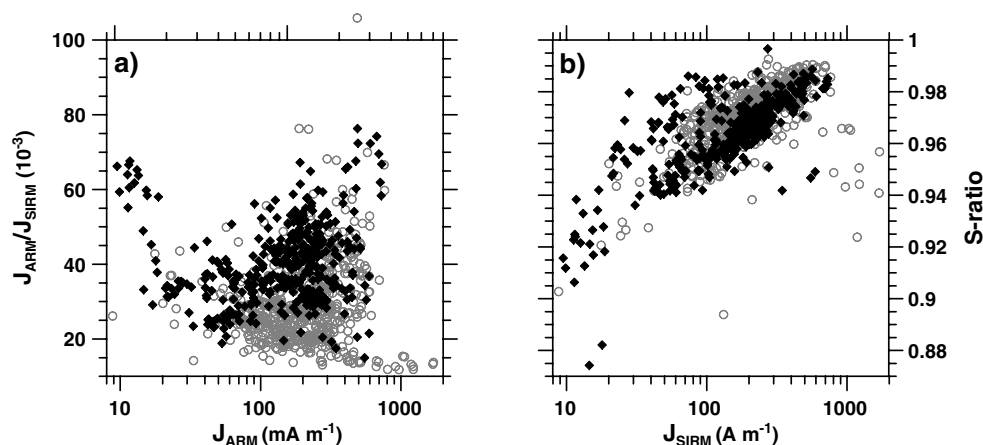


Figure 11. Scatterplots of rock magnetic parameters indicative for coercivity, grain size and magnetic concentration for all samples from core ERL-B. Black diamonds denote the samples from the laminated sections, open grey circles those from graded layers.

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