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Magnetic susceptibility in sediment records of Lake Ådran, eastern Sweden: correlation among cores and interpretation

Per Sandgren[1], Jan Risberg[2] & Roy Thompson[3]
[1] *Department of Quaternary Geology, Tornavägen 13, S-223 63 Lund, Sweden,* [2] *Department of Quaternary Research, Odengatan 63, S-113 22, Stockholm, Sweden,* [3] *Department of Geophysics, University of Edinburgh, Edinburgh EH9 3JZ, Scotland*

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Abstract

Magnetic susceptibility was used to test the representativity of the lithostratigraphy of a master sediment sequence from Lake Ådran, eastern Sweden. Five further sediment cores from the same lake were correlated and compared with the master sequence using magnetic susceptibility records. Mineral magnetic correlations are generally based on matching prominent susceptibility features but may be significantly improved by using slot sequence analyses. The result of these analyses show that the sediment in the Lake Ådran master sequence can be considered representative for the basin. The variations in the magnetic susceptibility in relation to pollen and diatom analyses also seem to reflect water level changes and shore displacement in the Baltic between 9900 ^{14}C years B.P. and the isolation at 5900 ^{14}C years B.P. The first emergence of scattered non-vegetated islands is characterised by high susceptibility values. Along with a continuous water lowering and the development of the vegetation during the Ancylus fresh water stage, susceptibility values gradually decrease. A rapid phase of the Ancylus regression between 9200 and 9000 ^{14}C years B.P. is seen as an increase in magnetic susceptibility. During the following Baltic brackish water stage, the Litorina stage, susceptibility values are at their lowest, followed by higher values at the isolation from the Baltic with a maximum around 5000 ^{14}C years B.P.

Shore displacement between 9900 and 5900 ^{14}C years B.P. is discussed based on the magnetic susceptibility measurements and their relationship to the pollen and diatom analyses.

Introduction

Lake Ådran is situated c. 20 km south of Stockholm (59° 10′ N, 18° 01′ E, Fig. 1). The basin is situated in a fissure valley landscape with major fault lines trending northeast to southwest. Relative height differences are in the order of 50 m. Geologically the surroundings consist of bedrock outcrops (gneiss and granite) partially covered with a thin till layer and minor areas of clay and fine sand. Rare finds of artefacts indicate that human impact in the area can be neglected. This, in combination with the relatively large lake area (0.4 km^2), makes Lake Ådran a most suitable reference site for Holocene vegetational studies (Risberg & Karlsson, 1989). Since deglaciation, with a water level of more than + 120 m, the basin has experienced several stages of the

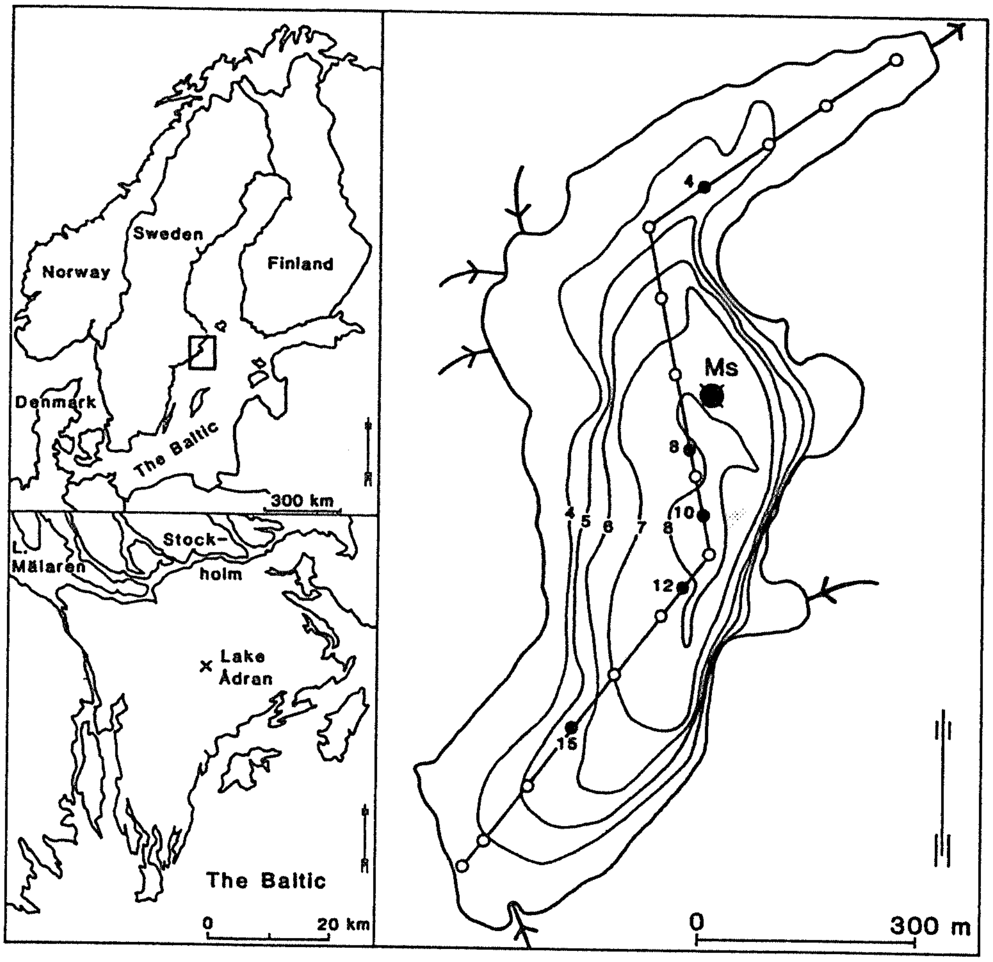


Fig. 1. Investigation area (upper left) and location of Lake Ådran c. 20 km south of Stockholm (lower left). The right figure shows the position of the master section (MS) and the five analysed sections (filled circles) of the lake transect (Risberg & Karlsson, 1989). Water depth given in metres below water level.

Baltic Sea. The altitude of the lake (+45 m) is most critical for determination of the shore displacement of the transition between the fresh water stage of the Ancylus Lake and the brackish water stage of the Litorina Sea.

The Lake Ådran basin has been chosen as a reference site within the IGCP 158b project 'Palaeohydrological changes in the temperate zone in the last 15000 years (Ralska-Jasiewiczowa (ed.) 1986; Miller, 1987) and is also included in the research project 'Eastern Svealand: Development of the Holocene landscape' (Brunnberg, Miller & Risberg, 1985; Miller & Hedin, 1988).

Previous analyses (Risberg, 1988; 1989; Risberg & Karlsson, 1989) all have been performed on samples from a master sequence (MS), situated close to the deepest part of the lake (Fig. 1). In order to examine the lateral distribution and uniformity of the stratigraphic units and to determine to what degree the sediment succession of the master sequence can be considered representative for the whole basin, 18 sequences were cored along a north northeast to south southwest transect (Fig. 1). Magnetic susceptibility measurements on six of the cores (including the master sequence) have been studied to assess the correlation of sediment successions from various parts of the basin and in particular to determine whether or not the stratigraphy of the master sequence can be considered representative of the lake. The master sequence was cored in 1984 and the transect cores collected in 1987.

The lithostratigraphy of the transect showed that the main stratigraphic units can be traced laterally across the lake (Risberg & Karlsson, 1989, Fig. 8). This does not, however, exclude the possibility of hiatuses in the stratigraphic records within laterally traceable units or at the upper or lower boundaries of the sedimentological units.

A rapid and non-destructive method for detailed intercore comparisons is the measurement of magnetic susceptibility (Dearing, 1983; Dearing *et al.*, 1981). Magnetic susceptibility is a measure of the concentration of ferrimagnetic minerals (mainly magnetite) in a sample. Concentrations as low as ten parts per million can be measured accurately. Analyses can be carried out either on individual subsamples or even whole cores. Single sample susceptibility measurements as the basis for detailed lake core correlations from Antrim Bay in Lough Neagh in Ireland were first used by Thompson (1973). Despite its apparent advantages over other core correlation techniques, magnetic susceptibility has only been employed to a limited extent in studies of Swedish lake sediments (Dearing, 1983; Sandgren, 1986).

Susceptibility records lend themself to analysis by statistical correlation techniques. The results of the visual correlation of susceptibility profiles can thus be significantly improved through formalized core matching algorithms. The quality of match of the stratigraphic sections can also be formally assessed using the correlation algorithms.

We have evaluated variations in the magnetic susceptibility records in relation to diatom (Risberg, 1988) and pollen analyses (Risberg & Karlsson, 1989) in terms of changing conditions in the environment connected with erosion and with water level changes.

Methods

Sampling

All the sections were cored with a Russian peat sampler (Jowsey, 1966) operated from ice in the winter months. Subsampling for the magnetic susceptibility analyses of the master sequence was carried out in the laboratory while the other cores (core 4, 8, 10, 12, 15) were subsampled in the field. Subsamples were taken at every 5 cm. The material was dried at 30 °C, put into pre-weighed non-magnetic polystyrene boxes, and the weight of the dry sediment found. The boxes were packed with foam to prevent the dried sediment from moving.

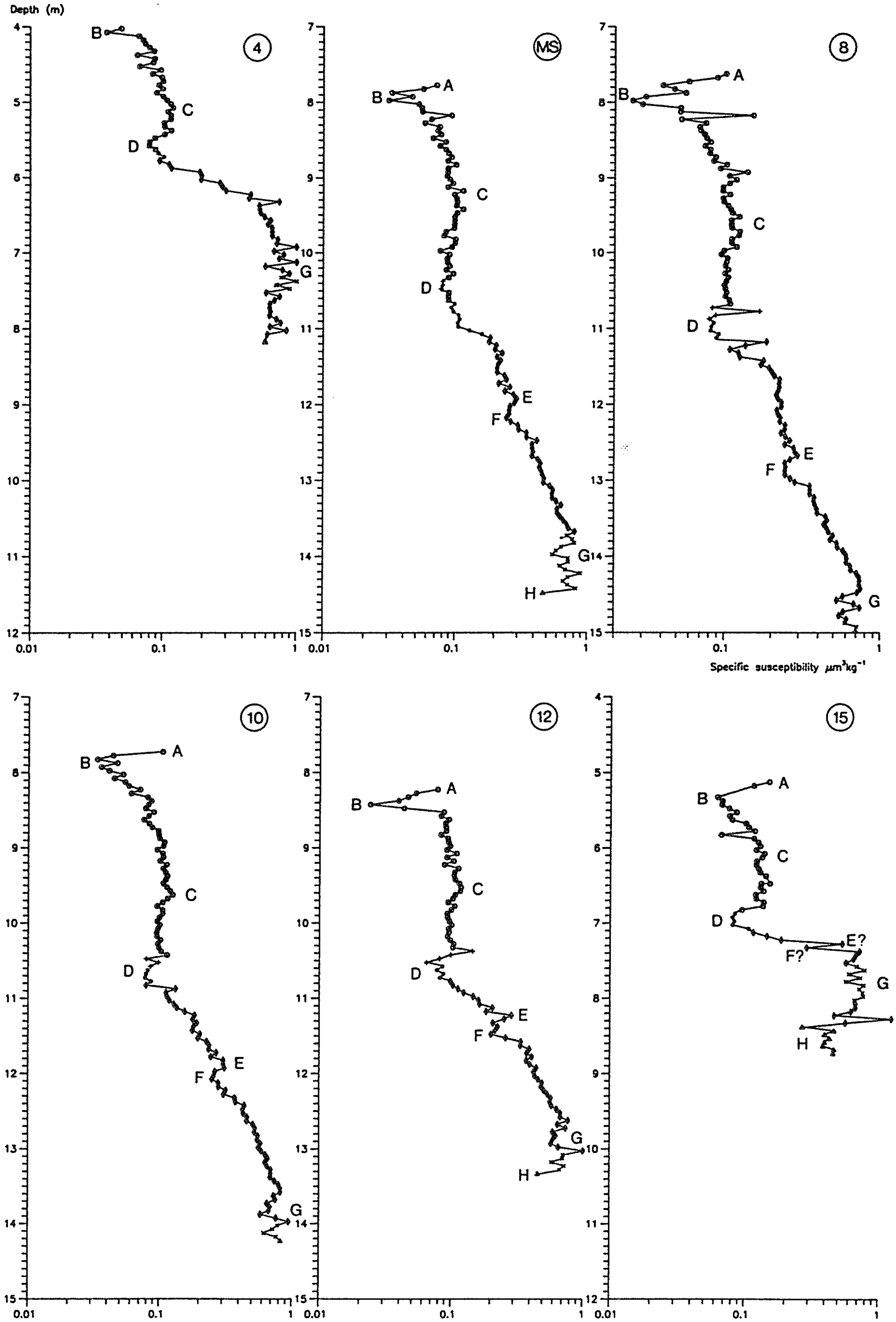
Instrumentation

Magnetic susceptibility has been measured using an air-cored susceptibility bridge (Bartington susceptibility bridge) in a peak alternating field of 0.1 m Tesla. Each susceptibility measurement took roughly a few seconds. Altogether 675 samples were measured. The organic carbon content was determined using an Eltra Metalyt 80 W (ignited at 550 °C).

Statistical analyses

Sequence slotting provides a statistical approach to analyzing and assessing core correlations (Gordon, 1973; Thompson & Clark, 1989). The general idea of sequence slotting is to combine two ordered sequences (e.g. core records) into one joint sequence in such a way as to minimize the difference between the two original sequences, while retaining the stratigraphic ordering of the individual sequences. In effect the best joint sequence is achieved by placing similar measurements as close to one another as possible.

At first sight it would appear to be prohibitively time consuming to assess all possible slottings and hence to find the best correlation. However, this problem of assessing a large number of slottings can be surmounted elegantly by use of



Depth (m)
4
MS
8
10
12
15
Specific susceptibility μm^3kg^{-1}
A
B
C
D
E
F
G
H
E?
F?

Bellman's optimality principle (Delcoigne & Hansen, 1975). The whole slotting exercise is formulated as a highly structured cascade of subproblems such that the optimal slotting can be discovered directly.

In analysing the Lake Ådran susceptibility sequence, we chose to follow Thompson & Clark (1989) by minimizing the combined path length of the Euclidean distances between the logarithms of the susceptibility values. As in Thompson & Clark (1989), we found it necessary to include a constraint that limited the relative deposition rates between sequences to within a factor of four. Inclusion of this type of stratigraphic constraint has been found to be a way of overcoming the blocking or clumping problem which has previously hindered application of the original slotting procedure of Gordon (1973) to practical problems.

Results

Magnetic susceptibility

The magnetic susceptibility records of the six measured cores (Fig. 2) have visually correlatable susceptibility features that are labeled A to H, from the sediment surface. The lithostratigraphy (Table 1) of the six cores, as determined in the field, is shown by different symbols on the susceptibility plots.

Unit 1

The susceptibility of the lowermost stratigraphical unit found in section 15 (Fig. 2) is fairly constant at around 0.4 $\mu m^3\ kg^{-1}$ (peak H). According to the lithostratigraphy the lowermost sediment in the other sections is considered to be from the same unit. Based on the susceptibility, however, the varved clay is penetrated only in section 12 and in the master sequence, where it is represented by a low magnetic susceptibility.

Table 1. Lithostratigraphic units of the sediment succession in the master section of Lake Ådran, unit 1 being the oldest.

Unit	Sediment
8	Fine detritus gyttja
7	Laminated gyttja
6	Clay gyttja
5	Gyttja clay
4	Non varved clay
3	Silty clay
2	Fine sand
1	Varved clay

Unit 2 to 4

The varved clay is overlain by a sequence of non varved clay, which in the lower part contains silt and coarser particles. Susceptibility in this lower part of the non-varved clay displays a pattern of minor peaks of between 0.5 and 0.9 $\mu m^3\ kg^{-1}$. The variations in magnetic susceptibility suggest somewhat unstable environmental conditions but uniform deposition across the lake. The upper part of the non varved clay displays decreasing susceptibility values with one distinct fluctuation (feature E–F, Fig. 2).

Unit 5 to 8

Organic matter gradually increases in the sediment above the non-varved clay (Fig. 3). Compared to the susceptibility values of units 5, 6, and 7, there are minor discrepancies compared to the lithostratigraphic records. In all sections, susceptibility has low values of about 0.08 $\mu m^3\ kg^{-1}$ (minimum D, Fig. 2). At or somewhat above the transition to the gyttja of unit 8 susceptibility rises slightly. The susceptibility of the fine detritus gyttja of unit 8 displays a long amplitude peak with low values of about 0.1 $\mu m^3\ kg^{-1}$ followed by a marked minimum B. Immediately below the surface there is a distinct increase, seen in all the sections.

Fig. 2. Log specific susceptibility versus depth (beneath the ice) of six analysed sections along the transect. Correlated features labeled A-H. For comparisons between susceptibility and litostratigraphy the lithostratigraphical units (after Risberg & Karlsson 1989) are as follows ○ = gyttja, + = laminated gyttja, □ = clay gyttja, $*$ = gyttja clay, ◇ = non varved clay, × = silty clay, △ = varved clay.

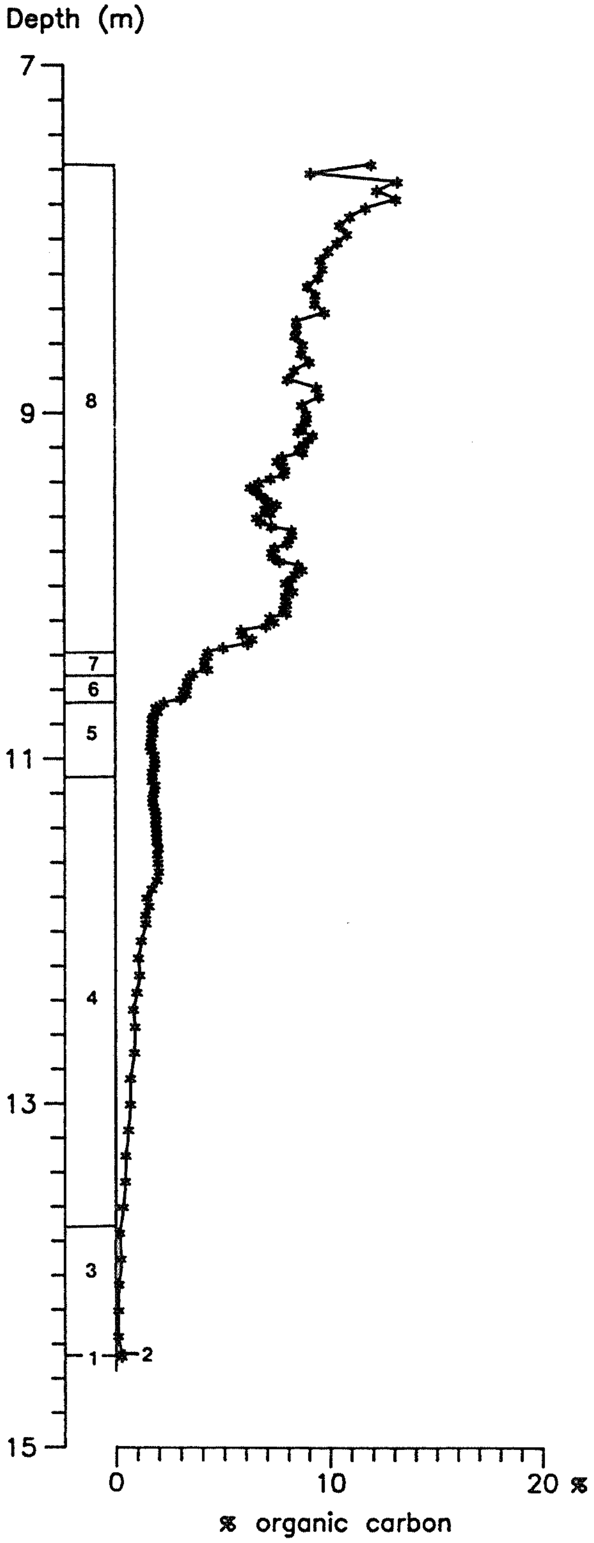


Fig. 3. Percent organic carbon calculated per dry weight versus depth for the master section. Lithostratigraphical units are shown in the left column.

Sequence slotting results

In order to determine if the sediment in the master section could be considered representative of the sediment succession of the whole lake basin, the susceptibility records from three cores (core 8, 10 and 12) in the central parts of the basin were compared statistically with each other and with the master sequence. Both section 8 and 10 reveal throughout the entire sequence a very close match with the master section (Fig. 4). There are however minor discrepancies between the lithostratigraphic field correlations and those of slot sequence calculations based on magnetic susceptibility.

The Lake Ådran core correlations derived from the sequence slotting approach are of high quality. Three quantitative methods have been used to assess the quality of the Lake Ådran slottings. First, the statistic delta (Gordon, 1982; Clark, 1985) can be used as a guide to the overall quality of match. Delta can vary between 0, for identical sequences, and 1 (strictly slightly over 1) for sequences with completely mismatch. Delta values of less than about 0.5 are good for geological data, while deltas values of over about 0.7 are poor. The delta value of 0.325 (Table 2) for the match between the Lake Ådran master sequence (MS) and sequence 10 is extremely good.

Second, the optimal fit of the slotting procedure can be used to produce a correlation coefficient (range − 1 to 1) through an interpolation proce-

Table 2. Sequence slotting statistics.

Sequence A	Sequence B	Delta	Standard error on delta in partition tests
MS	10	0.325	-
MS	8	0.365	-
MS	12	0.554	-
8	10	0.369	-
MS split*	MS remainder*	0.348	+ 0.009
10 split	10 remainder	0.347	+ 0.009
MS split*	10 split*	0.337	+ 0.008

* A subset of the full master sequence (MS) was used in the partition tests for computational convenience.

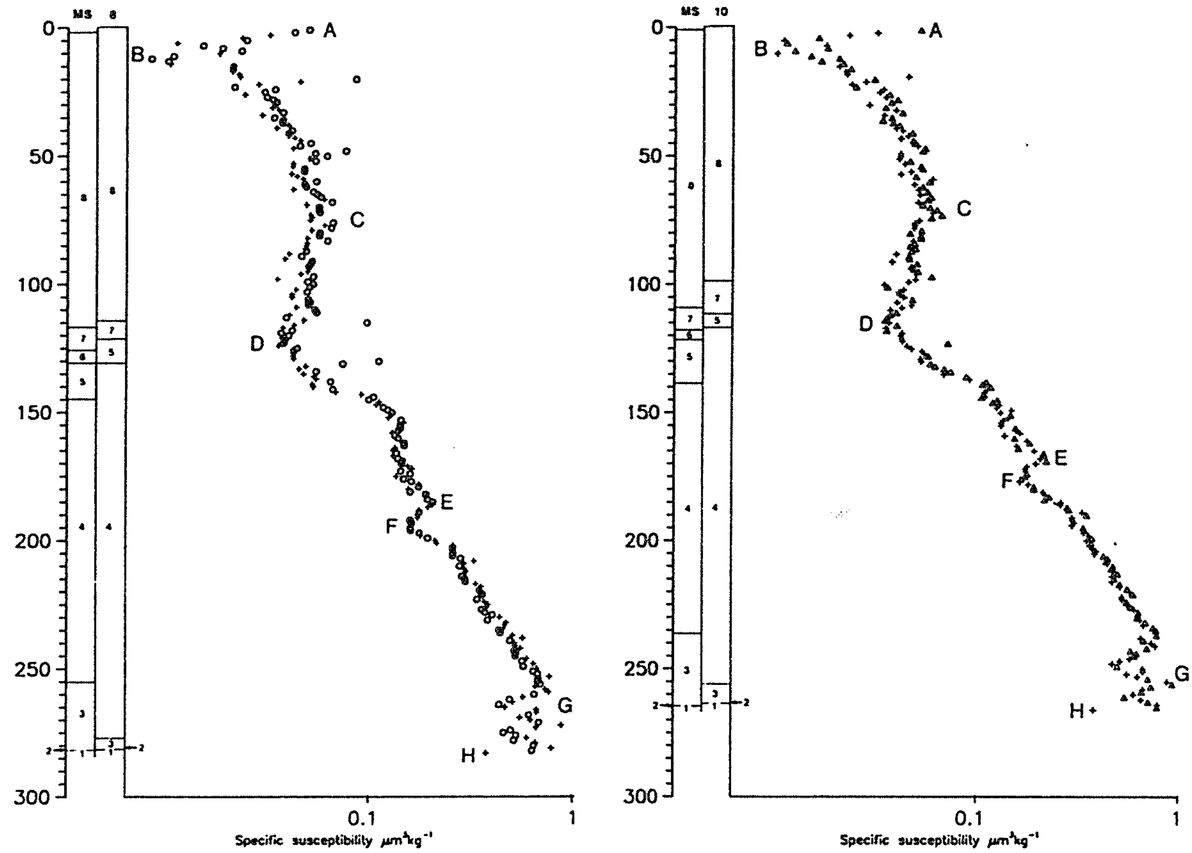


Fig. 4. Correlation of the log specific susceptibility of the master section (crosses) and section 8 (open circles) and section 10 (open triangles) based on the slot sequence calculations. Numbers on the Y-axis refers to slotting numbers. Lithostratigraphic units of the two sections respectively are denoted along the susceptibility logs (MS = main section, 8 = section 8, 10 = section 10). The susceptibility features of Fig. 2 are also labeled.

dure. The interpolated correlation coefficient for the master sequence (MS) to sequence 10 of 0.991 is again excellent.

Third, Clark (1985) suggests a series of tests based around slotting randomly produced partitions, or splits, of the data. Slotting of the Lake Ådran master sequence and core 10 partitions led to indistinguishable delta values (Table 2). Other tests on these partition slottings further indicate that there is no statistical evidence of any systematic difference between the sequences.

For every measurement horizon in core 10, an equivalent horizon has been calculated in the master sequence (Fig. 5). Tie lines connecting all those horizons were drawn between the two sequences and plotted (Fig. 5). The results of some of the other slottings are also presented with susceptibility plotted against joint slotting positions (Fig. 4). On these diagrams one can judge by eye the high quality of match expressed quantitatively by the delta values of Table 2.

In contrast with the good slottings found for cores 8 and 10 (Table 2), core 12 yielded a poor delta value of 0.554 when matched to the master sequence. Core 12 appears to have a slower deposition rate than the master sequence (Fig. 2). However, the delta value of the fit between MS and 12 indicates a rather poor match, which cannot just be ascribed to deposition rate differences. Further slotting analyses of short sections from core 12 have demonstrated that the origin of the poor delta value must lie in hiatuses in core 12.

In summary, the master sequence can be correlated extremely well with several other cores in the basin and is an excellent master sequence for use in palaeoenvironmental studies.

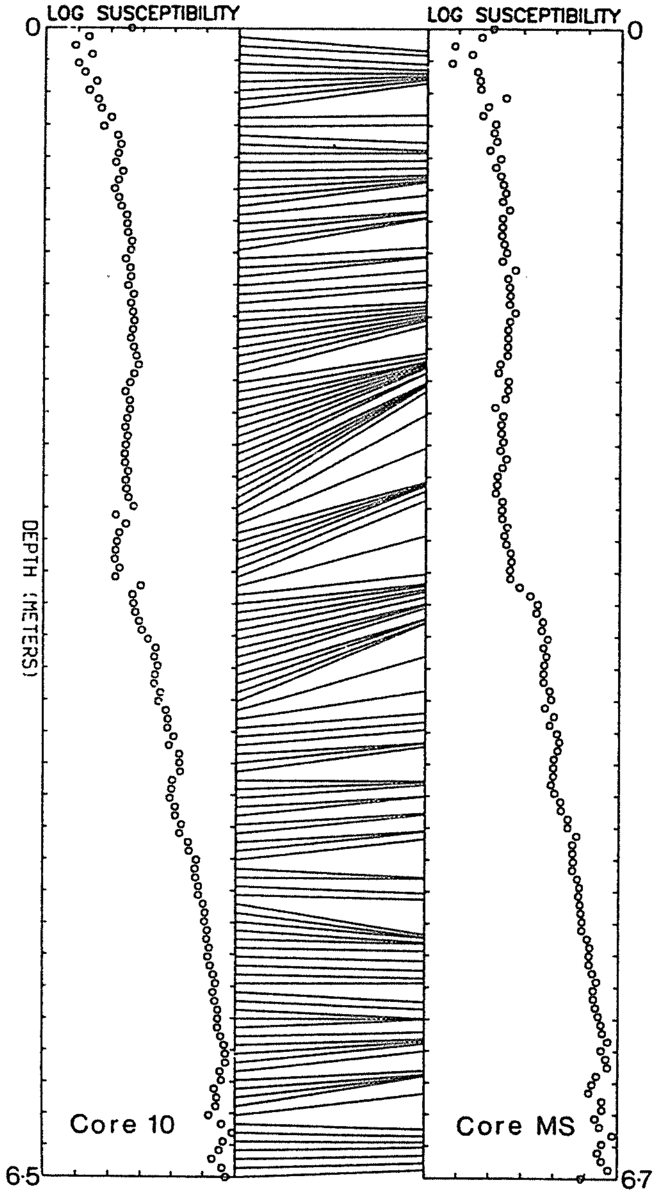


Fig. 5. Sequence slotting of core 10 to the master section (MS). The tie lines in the center of the figure join the positions of the core 10 subsamples at the left hand side with their slotted positions in the master sequence at the right hand side. Constrained sequence slotting performed with maximum block lengths of 4 in either sequence and by iterative scaling of the log susceptibility values using a simplex optimization algorithm with two free parameters.

Chronology

The sampled sediments of Lake Ådran span approximately 9900 ^{14}C years. This chronology is based on radiocarbon dates from five levels in the master sequence and one radiocarbon-dated level in core 10 (Risberg & Karlsson, 1989). The dated level of core 10 has been transferred to the master section using the slot sequence calculations.

The age of the level at the transition from the varved clay to the non varved clay has been estimated at 10450 ± 200 varve years B.P. (Brunnberg, pers. comm.). According to Björck *et al.* (1987) 10450 varve years B.P. correspond approximately to 9900 ^{14}C years B.P.

By assuming a decreasing sedimentation rate for the non varved clay, as is supported by the decrease in minerogenic content (Fig. 3), some additional levels of the non-varved clay can be dated indirectly. These additional ages have been incorporated with the ^{14}C data to yield the time depth curve shown in Fig. 6.

Basin history

During the last 9900 ^{14}C years, the Lake Ådran basin has experienced dramatic water level changes as well as having been influenced both by the fresh water during the Ancylus stage and the saline water during the Litorina stage (Risberg, 1988). The diatoms indicate no evidence for saline water during the Yoldia stage (Risberg, 1988) ending about 9500 ^{14}C years B.P. (Fromm, 1976; Florin, 1977; Hyvärinen, 1988; Svensson, 1989). The highest water level in the vicinity, + 150 m, was recorded in the hilly Kolmården area bout 100 km southwest of Lake Ådran (Persson & Svantesson, 1972). When the Lake Ådran area was deglaciated, about 10450 varve years B.P. (c. 9900 ^{14}C years B.P.), the drainage at Mt Billingen had already occurred (cf. Björck & Digerfeldt, 1986), allowing the first small islands to appear above water level. Successively the emerging islands formed a denser and denser archipelago. The continuous water level lowering resulted in the basin becoming progressively more sheltered.

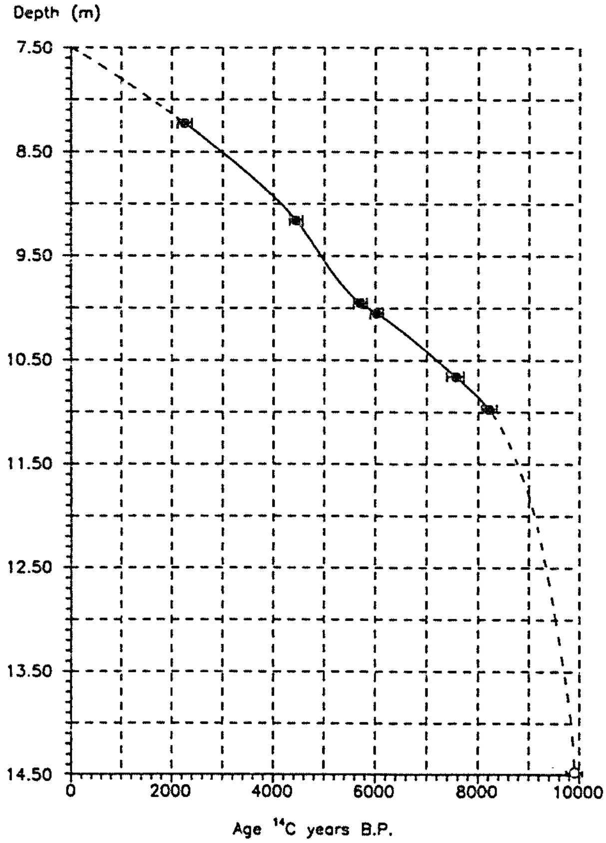


Fig. 6. Time depth curve based on six radiocarbon dated levels (solid dots) and a resumed age of 9900 ^{14}C years B.P. of the transition between unit 1 and 2.

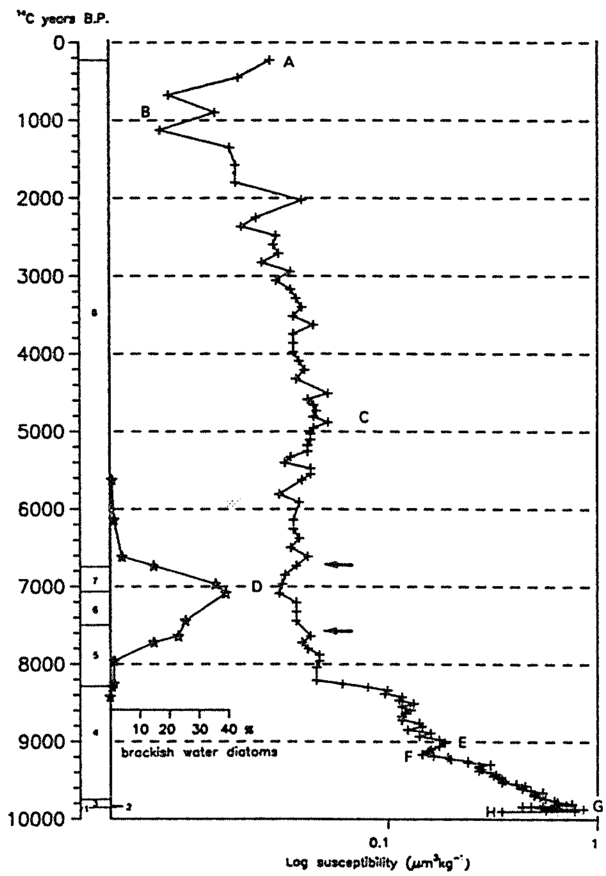


Fig. 7. Susceptibility on log scale of the master section related to radiocarbon years B.P. based on the time depth curve in Fig. 6. Solid line denotes the occurrence of brackish (marine) diatoms according to Risberg (1988). Stratigraphic units are shown in the left column. Arrows indicate the position of the two susceptibility peaks discussed in the text.

Well before the final isolation, the last remaining narrow straights were cut off and for a long time a bay situation with a very narrow outlet existed (Risberg & Karlsson, 1989, Figs. 13–20). When the water level dropped below +45 m, corresponding to the isolation threshold (Annerberg & Risberg, 1984), the basin was topographically cut off from the sea. Based on the diatom flora Risberg (1988) inferred that the isolation occurred at about 5900 ^{14}C yr. B.P.

Interpretation of magnetic data

Only one point exists in the varved clay, but an increase in the magnetic susceptibility is visible at the transition from unit 1 to unit 2–3 (Fig. 7, peak H). The relatively low susceptibility values of the varved clay can be explained in terms of very fine (clay) particles settling in deep water (Björck *et al.* 1982).

The silty lower parts of the non-varved clay (unit 3) and accompanying higher susceptibility values, recorded in all the cores (Fig. 2, peak G), are believed to indicate that several islands emerged above the water level. Coarser sediment, in combination with the rapid regression during the end of the Yoldia stage (Björck, 1987), could then be washed out from non-vegetated or sparsely vegetated islands and from newly emerged littoral zones. Pollen spectra from these levels reveal a vegetation consisting of pioneer plants such as *Artemisia*, *Hippophaë*, and Poaceae. The abundance of *Pinus* and *Betula* pollen grains at these levels may reflect long-distance transport (Risberg & Karlsson, 1989) from areas further west situated above the highest cost line. Water level must have been about + 100 m when the first islands appeared in the area south of Stockholm. The diatom flora of unit 3 is dominated by *Melosira islandica*, with abundances of up to 90% of the total flora, indicating deep water conditions (Risberg, 1988). Changing conditions in the sedimentation are reflected in the varying susceptibility values of these sediments. Because the oscillating lower and higher susceptibility values correlate quite well between sections (Fig. 4) we have concluded that these changes are of regional significance rather than just local events effecting isolated parts of the basin.

Deposition of the non-varved clay (unit 4) took place between c. 9700 and c. 8300 ^{14}C years B.P. The susceptibility records (Fig. 2) indirectly distinguish the differences in particle size in this homogenous unit. The susceptibility of this material shows gradually decreasing values. During this period the water level decreased continuously as indicated by the diatom flora (Risberg, 1988). According to the pollen records (Risberg & Karlsson, 1989), *Pinus*, *Betula*, *Corylus* and *Alnus* immigrated first to be followed by the decidious trees *Ulmus* and *Querqus* and finally by *Tilia* at about 7400 ^{14}C years B.P. The gradually lower magnetic susceptibility values of the non varved clay is probably the result of a slower regression during the Ancylus stage (c. 9400 to c. 8200 yr B.P.) in combination with a gradually denser vegetation causing more stable soil conditions. The ongoing regression must also have caused the basin to become even more sheltered, so reducing the wind fetch and thus leading to sedimentation of finer particles. An interesting feature, that can be noted, is the rapid oscillation in the susceptibility values around 9150 ^{14}C years B.P. followed by gradually increasing values during the following 200 ^{14}C years. This increase could be related to a local event but as these two features are clearly visible in all the sections (features E and F in Fig. 2) and as Lake Ådran was not isolated at this time, it more likely reflects a regional change in water level of the Ancylus Lake.

Lake Ådran is situated very close to the 0–isobase of the Ancylus Lake as presented e.g. by Ristaniemi & Glückert (1987, Fig. 15). This fact means that if there was an Ancylus transgression at all in this area, it was small. The Baltic was dammed 10–20 m when the transgression culminated (Björck, 1987). In any case, the Ancylus transgression was followed by a rapid regression, documented from many areas in the Baltic (e.g. Berglund, 1964; Duphorn, 1979; Gudelis, 1979; Persson, 1979; Eronen & Haila, 1982; Glückert & Ristaniemi, 1982; Eronen, 1983; Kolp, 1986; Svensson, 1989). As a result of this rapid regression, non-vegetated areas must have been exposed, producing conditions favourable for erosion, and as a consequence slightly coarser particles could be brought into the basin. The increase in magnetic susceptibility documented in the Lake Ådran sediment could be related to the rapid Ancylus regression between 9200 and 9400 ^{14}C years B.P. (Glückert & Ristaniemi, 1982; Björck 1987; Svensson, 1989).

The most rapid decrease in magnetic susceptibility takes place at the transition from unit 4 to unit 5, from non varved clay to clay gyttja (Fig. 2). The onset of this decrease can be dated to about 8400 ^{14}C years B.P. The susceptibility decrease continuously to low values. In this part of the record magnetic susceptibility does not correlate well with lithostratigraphy. The rapid susceptibility decrease can, however, be correlated to the first occurrence of brackish (marine) diatoms representing the first ingression of saline water of the Litorina Sea. In Blekinge, southern Sweden, Björck (1979) correlated rapid decreases in magnetic susceptibility to isolations of lake basins from the Baltic Ice Lake. The rapid decrease in magnetic susceptibility in Lake Ådran could be connected with the dissolution of ferrimagnetic minerals in brackish-marine water (Snowball & Thompson, 1988). Dissolution in the transgression periods investigated by Snowball & Thompson (1988) led to almost complete loss of magnetic grains and susceptibility. The brackish, but not fully marine, conditions in Lake Ådran probably could explain why magnetic grains and susceptibility were not competely lost in contrast to the Snowball and Thompson example. Dissolution or partial dissolution in the Lake Ådran sediment is supported by the fact that the lowest set of susceptibility values are actually recorded during the richest occurrences of brackish (marine) diatoms slightly before 7000 ^{14}C years B.P. (Fig. 7 peak D, cf. also Fig. 2). At about 6500 ^{14}C years B.P. magnetic susceptibility values increased slightly coinciding with the almost complete disappearance of the brackish (marine) diatoms.

A feature in the susceptibility records, not seen in the master sequence, but clearly visible in section 8, and to some extent also in section 10 (Fig. 2), within the zone of low susceptibility values, are two narrow peaks of higher, clearly off set susceptibility values. These peaks must reflect very rapid events in the sediment history of the basin. The reason for why these peaks are not recorded in the master sequence probably is due to the discrete sampling interval of 5 cm. If the positions of the peaks are transferred to the master sequence (Fig. 7), based on the slot-sequence calculations in Fig. 5, then the first peak is found to occur at about 7700 ^{14}C years B.P. The second peak can be similarly dated to about 6700 ^{14}C years B.P. The positions of these peaks thus coincide with the beginning and the end of the highest occurrence of brackish (marine) diatoms, i.e. during the period of most saline conditions. Possibly these peaks could be a reflection of coarser material transported into the basin, caused by increased erosion in the catchment, during some stage of the Litorina transgression and the following regression. The datings of these peaks coincide well the culmination of the Litorina transgression in southwestern Finland (Eronen, 1974).

Magnetic susceptibility decreases continuously from a relative maximum around 5000 ^{14}C years B.P., to about 1000 ^{14}C years B.P. (Fig. 7). The documented decrease in magnetic susceptibility could be caused by dense vegetation of the surrounding landscape and low energy environments of the now isolated lake bringing only fine grained sediments into the basin.

The increasing susceptibility values (peak A, Fig. 2) in the top of all the cores are difficult to explain but could possibly be due to anthropogenic disturbances in the catchment bringing coarser particles into the lake.

Conclusions

The general conclusions are:

1. Magnetic susceptibility can be used as a more accurate tool than lithostratigraphy alone in the correlation of sediment sections from different parts of a basin.
2. Statistical analyses of the susceptibility records, based on sequence slotting, significantly improve the core correlations, compared to eye matching of prominent features of the susceptibility records.
3. Magnetic susceptibility, in combination with other parameters, is a good indicator of changes in the local environment that affected sedimentation in the Lake Ådran basin.

With respect to the history of the development of Lake Ådran, the magnetic susceptibility records in conjunction with the diatom and pollen analyses allow the following conclusions to be made:

1. The lithostratigraphy of the master section can be considered representative of the lake as a whole.
2. The susceptibility fluctuations at about 9000 ^{14}C years B.P. most likely reflect the rapid regression following the Ancylus transgression.
3. The ingression of salt water, as defined by the occurrence of brackish (marine) diatoms, resulted in a dramatic decrease in magnetic susceptibility.
4. According to the susceptibility records there are no evidence of more than one Litorina transgression.

5. The decrease in magnetic susceptibility from a relative maximum after the isolation is probably a reflection of stable conditions in the catchment.

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In the present paper Sandgren is responsible for the magnetic susceptibility analyses and correlations. Risberg for the corings, sediment descriptions and other laboratory analyses, and Thompson for the slot sequence calculations. The environmental interpretations and discussions have been carried out jointly by Sandgren and Risberg.

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