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# Bacterial magnetite in Swedish varved lake-sediments: a potential bio-marker of environmental change

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**Abstract**

Detailed mineral magnetic measurements were carried out on three varved lake-sediment sequences in Sweden, which extend to ca. 7000 BC. The comparison of the magnetic properties of the organic rich varved lake-sediments with their respective catchment materials indicates that the magnetic properties of the sediments are dominated by relatively high concentrations of single-domain magnetite magnetosomes produced by magnetotactic bacteria. The dimictic nature of the lakes, which help form and preserve the varves due to the weakly oxic or suboxic environment, also appear to be suitable for a high degree of magnetosome preservation. The concentration of the magnetosomes in two of the sequences, as determined by mass specific magnetic measurements, exhibits a positive linear relationship with the total organic carbon content and suggests that magnetic remanence measurements reflect lake productivity, via processes of organic matter accumulation and decomposition. Further research should focus on the potential to use the fossil magnetosomes as proxy-climate/environmental change indicators and as recorders of geomagnetic field variations and behaviour. © 2002 Elsevier Science Ltd and INQUA. All rights reserved.

## 1. Introduction

Previous work conducted on organic rich lake-sediments in Northern Sweden demonstrated that their bulk magnetic properties were dominated by high concentrations of magnetite formed intracellularly by bacteria (Snowball, 1994). Such bacteria (e.g. *Magnetospirillum magnetotacticum*) are common in freshwater and marine environments and Hesse and Stolz (1999) reviewed their provenance, ecology and relevance to studies of Quaternary climates. The ferrimagnetic magnetite grains produced by magnetotactic bacteria (referred to as magnetosomes or fossil magnetosomes) are of a narrow and specific grain-size distribution (ca. 0.03–0.05 μm) and their presence in natural magnetic assemblages can be identified by the careful application of mineral magnetic measurements (reviewed by Hesse and Stolz, 1999). Downcore magnetic measurements conducted on a varved lake-sediment sequence in Northern Sweden by Snowball et al. (1999) showed that a positive linear relationship existed between the concentration of magnetosomes (as determined by magnetic analyses) and the percentage of total organic carbon (TOC). Oldfield and Wu (2000) also demonstrated that magnetosomes made a significant contribution to the magnetic properties of recent sediments in a eutrophic lake in England. Recent results obtained from mountain sites in the UK also indicate that organic productivity in lakes may, over long timescales, be driven by temperature, related to the length of ice cover and the number of ice-free days during the summer months (Barber et al., 1999). The observed relationship between the concentration of magnetosomes and TOC in the varved lake-sediment sequence studied by Snowball et al. (1999) suggests that stratigraphic variations in the concentration of fossil magnetosomes in lake-sediments, where magnetosomes are well preserved, may reflect temporal variations in climate. This paper focuses on the magnetic properties of three varved lake-sediment sequences in Northern and Central Sweden and the degree to which these properties are dominated by magnetosomes. Suggestions for further research are also outlined.

## 2. Site descriptions

### 2.1. Sarsjön and Frängsjön

Sarsjön (64°02′N, 19°36′E, altitude 177 m a.s.l.) and Frängsjön (64°01′N, 19°42′E, altitude 163 m a.s.l.) are

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situated in the boreal forest region of Northern Sweden, ca. 60 km northwest of the city of Umeå. The geographical setting of Sarsjön was described by Snowball et al. (1999). Sarsjön (area 10 ha) has a maximum water depth of 7.3 m, three inlets, one outlet and a catchment area of 350 ha. Frängsjön (area 7 ha) has a maximum water depth of 7.1 m, one inlet, one outlet and a catchment area of 120 ha. Frängsjön is situated approximately 15 km NW of Sarsjön and the soils within both drainage basins are dominated by fine-grained clay that accumulated in the ancient Ancylus Lake. The two freshwater lakes were formed at approximately 7000 BC due to isostatic uplift (Renberg and Segerström, 1981). At the points of maximum water depth Sarsjön had, at the time of fieldwork, a post-isolation sediment thickness of 4.3 m; that of Frängsjön had 4.5 m. Significant regional human influence, in the form of forest clearance, began as late AD 1700 (Segerström, 1990). Spruce, pine and birch dominate the present catchment vegetation around both the lakes.

### 2.2. Furskogstjärnet

Furskogstjärnet (50°23′N, 12°05′E, altitude 137 m a.s.l.) is situated in the middle boreal forest region, near the town of Årjäng in Southern-Central Sweden. The lake (area 33 ha) has a maximum water depth of 14.2 m. The catchment (800 ha) is dominated by clays and clayey/silty tills. A varve chronology (Zillén, unpublished data) indicates that the sedimentary basin, which forms the present day freshwater lake, was isolated from the Ancylus Lake at ca. 7500 BC. The thickness of the post-isolation sediments in the deepest part of the lake was, at the time of fieldwork in 1999, 3.75 m. Spruce, pine, birch and alder dominate the present day catchment vegetation, although the pattern is mosaic. Information about the initiation of human impact in the region is scarce, although archaeological excavations indicate the presence of a human population since ca. 4000–3000 BC. The positions of the three sites are shown in Fig. 1.

## 3. Methods

### 3.1. Sediment core collection

Sediment cores were collected from the ice-covered lakes during late spring (between AD 1997 and 2000). A Russian peat corer (Jowsey, 1966) was used to recover undisturbed "D" shaped sediment cores, 1 m long and 7 cm in diameter. At least two parallel, overlapping, Russian core sequences were obtained from the deepest part of each lake. The uppermost, unconsolidated lake-sediments were recovered using a freeze-corer.

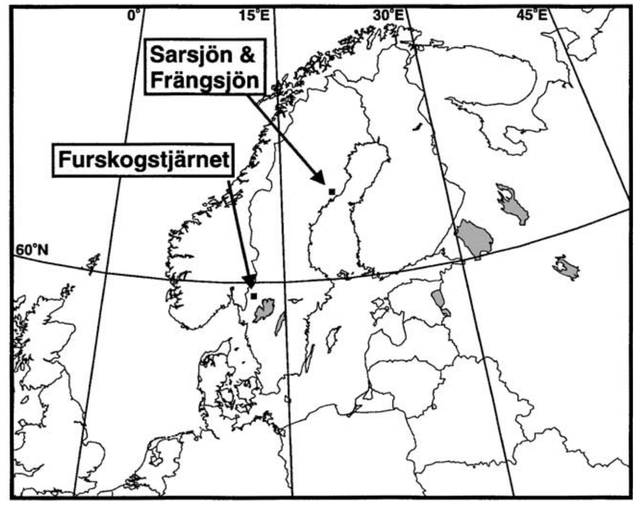


Fig. 1. Map of Northern Europe showing the approximate positions of the three varved lake-sediment sequences.

### 3.2. Surface scanning initial magnetic susceptibility

Prior to subsampling, the initial magnetic susceptibility of two Russian core sequences from each lake was measured. These measurements were undertaken at 4 mm intervals using a Bartington Instruments Ltd. MS2E1 surface scanning probe, coupled to a TAMISCAN-TS1 automatic stage (manufactured at Lund University). The cores were prepared with a fine metal blade to provide an even surface, which was covered with a thin plastic film ($>0.1$ mm thick) during measurement. These measurements were used as a complement to core matching based on the visual correlation of marker varves.

### 3.3. Subsampling

The sediment sequences were subsampled into contiguous $2\times2\times2$ cm plastic cubes commonly used for the palaeomagnetic analysis of soft sediments. These were used for magnetic analysis (in a moist condition). See Snowball et al. (1999) for details.

### 3.4. Sediment embedding

Sediment embedding was primarily undertaken to provide consolidated samples suitable for magnetic hysteresis analyses. The sediment sequence collected from Sarsjön was embedded in epoxy resin, as described by Snowball et al. (1999). The sediment sequence from Frängsjön was treated in an identical fashion, which provided 12 cm long, 1 cm wide and 0.5 cm thick sections of sediment for further thin section analyses and detailed high-resolution magnetic hysteresis measurements (to be reported in a future publication). Two similar sections of sediment were also embedded from

Furskogstjärnet for magnetic hysteresis measurements (the remainder of the sequence will be embedded at a later date). Single samples (ca. 20 mg) were cut from the side of each embedded section at 2 mm intervals.

### 3.5. Catchment sampling

Catchment materials (soils, tills and stream bank samples) were collected from the drainage basins of each lake during the summer after sediment core collection. The catchment samples were oven-dried at 40°C overnight. In addition, duplicates of the catchment soils were wet-sieved to provide samples of the $<63\,\mu m$ fraction for magnetic analyses. The $<63\,\mu m$ fraction was considered to be representative of the average grain size of the minerogenic fraction of the lake sediments (as determined from preliminary petrological inspection of thin sections).

### 3.6. Mass specific magnetic measurements

All magnetic measurements of the lake-sediments were carried out while the samples were in a fresh, moist condition. Initial magnetic susceptibility ($\chi$) was determined using a Geofysica Brno (now AGICO) KLY 2 susceptibility bridge. Attempts to measure the frequency dependency of susceptibility ($\chi_{FD}$) with a Bartington MS2C bridge were hampered by a low signal/noise ratio. Susceptibility of anhysteretic remanent magnetisation ($\chi_{ARM}$) was induced in a Molspin AF demagnetiser in a bias field of 0.1 mT imposed upon a peak-alternating field of 100 mT. Saturation isothermal remanent magnetisation (SIRM) was induced in a field of 1 T using a Redcliff BSM-700 pulse magnetiser. $\chi_{ARM}$ and SIRM were measured with a Molspin Minispin magnetometer, or alternatively a 2G-Enterprises 755R SQUID magnetometer. The two magnetometers were inter-calibrated using a standard magnetic tape. The dry mass of the samples was determined after oven-drying at 40°C and used to calculate mass specific SI units. Magnetic hysteresis measurements were carried out on the embedded sediments according to the method of Snowball et al. (1999). The embedding in epoxy resin does not have adverse effects on the magnetic properties of lake-sediments (Snowball, 1997). Magnetic hysteresis measurements were conducted at room temperature with a Princeton Measurements Corporation alternating gradient magnetometer (model M-2900). All measurements were carried out at Lund University.

### 3.7. Organic carbon analysis

The percentage of organic carbon in alternate subsamples taken from the sediment sequences of Sarsjön and Frängsjön was measured with a LECO RC412 multiphase carbon determinator according to the method described by Snowball et al. (1999).

## 4. Results

### 4.1. Comparison of the magnetic properties of catchment materials and lake-sediments: evidence for bacterial magnetite

Table 1 demonstrates that the average ferrimagnetic concentrations of the post-isolation lake-sediments, as determined by $\chi_{ARM}$ and SIRM, are considerably higher than their respective catchment materials.

The average magnetic concentration values are remarkably similar for all of the post-isolation lake-sediments, particularly the $\chi_{ARM}$ values, which lie between 16.0 and $17.8 \times 10^{-6}\,m^3\,kg^{-1}$. The inter-parametric ratios, SIRM/$\chi$ and $\chi_{ARM}$/SIRM, are also considerably higher in the post-isolation lake-sediments than the respective pre-isolation sediments and catchment materials (for which the data are more scattered). Higher values of these two ratios are generally acknowledged to indicate a finer grain size distribution of magnetite when there is no significant superparamagnetic (SP) contribution (Maher, 1988). Biplots of $\chi_{ARM}$/SIRM vs. $\chi/\chi_{ARM}$ and SIRM/$\chi$ vs. $\chi/\chi_{ARM}$ are shown in Fig. 2(a) and (b). These plots clearly demonstrate the division between the source catchment materials and the post-isolation lake-sediments. Also plotted in Fig. 2 are the values for the uppermost lake sediments in Pajep Njakajaure (Northern Sweden), where TEM evidence and magnetic measurements (Snowball, 1994) identified the presence of magnetosomes. Fig. 2 shows that, despite scattered values of the catchment materials, the post-isolation sediments form a distinct cluster. The magnetic hysteresis loops presented in Fig. 3, which are representative of the post-isolation lake-sediments in each lake-basin are almost identical. According to the magneto-granulometric developed by Day et al. (1977), the values of the inter-parametric ratios $(B_O)_{CR}/(B_O)_C$ and $M_{RS}/M_S$ exhibited by the post-isolation lake-sediments indicate a stable-single-domain grain size. There is no evidence for constricted loops, which could be caused by SP grains (Fukama and Torii, 1998). According to data obtained from well-characterised synthetic magnetites of known grain size (Maher, 1988), the sedimentary values of $\chi_{ARM}$/SIRM presented here (ca. $140 \times 10^{-5}\,A\,m^{-1}$) indicate magnetite grains with a diameter between ca. 0.03 and $0.05\,\mu m$. This grain size is typical of single-domain magnetite produced by magnetotactic bacteria for navigation purposes (Snowball, 1994; Maher et al., 1999).

The TOC analyses of the Sarsjön sediments were presented by Snowball et al. (1999). The concentration of ferrimagnets, as represented by SIRM, was found to

Table 1
Average mineral magnetic properties of the catchment soils, post-isolation and pre-isolation lake-sediments

| | $\chi$ ($10^{-6}\,m^3\,kg^{-1}$) | $\chi_{ARM}$ ($10^{-6}\,m^3\,kg^{-1}$) | SIRM ($mA\,m^2\,kg^{-1}$) | SIRM/$\chi$ ($kA\,m^{-1}$) | $\chi_{ARM}$/SIRM ($10^{-5}\,A\,m^{-1}$) | *N* |
|---|---|---|---|---|---|---|
| *Sarsjön* | | | | | | |
| Soils <63 μm | 0.115 | 0.438 | 1.15 | 9.59 | 44.9 | 16 |
| Post-isolation sediments | 0.383 | 16.0 | 10.7 | 27.2 | 145 | 148 |
| Pre-isolation sediments | 0.387 | 2.76 | 4.63 | 11.6 | 52.4 | 19 |
| *Frängsjön* | | | | | | |
| Soils <63 μm | 0.139 | 0.355 | 1.01 | 6.94 | 43.8 | 10 |
| Post-isolation sediments | 0.435 | 16.7 | 12.6 | 28.9 | 132 | 248 |
| Pre-isolation sediments | 0.355 | 2.92 | 4.32 | 12.0 | 64.6 | 5 |
| *Furskogstjärnet* | | | | | | |
| Soils <63 μm | 0.264 | 0.681 | 1.66 | 4.66 | 98.2 | 22 |
| Post-isolation sediments | 0.545 | 17.8 | 17.1 | 31.1 | 142.2 | 119 |
| Pre-isolation sediments | 0.42 | 2.61 | 4.14 | 8.83 | 61.9 | 9 |

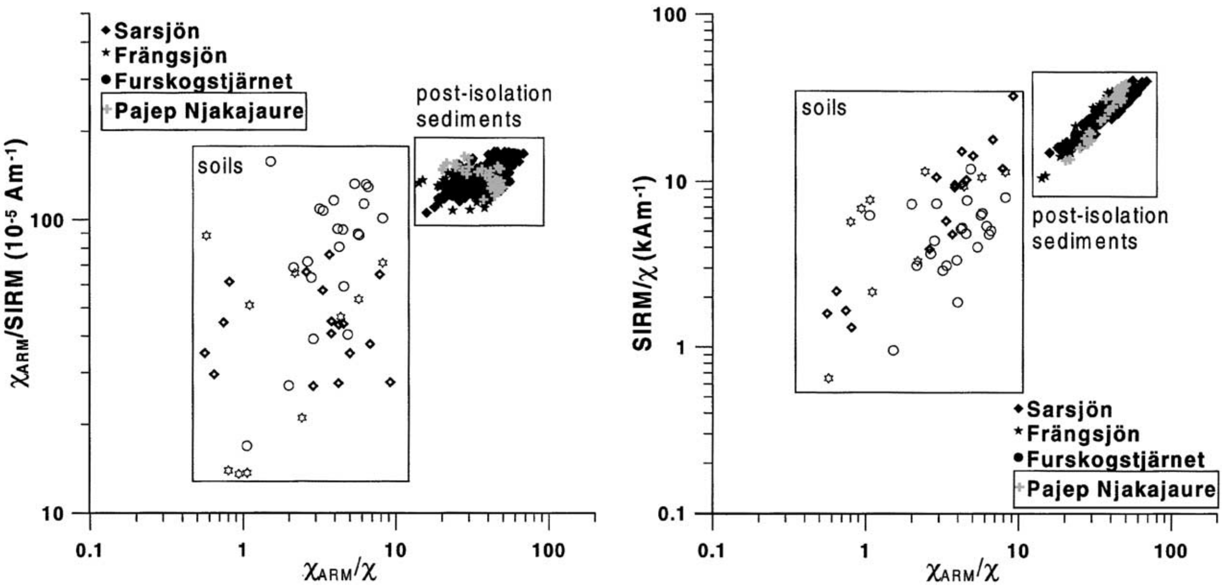


Fig. 2. Biplots of $\chi_{ARM}$/SIRM vs. $\chi/\chi_{ARM}$ and SIRM/$\chi$ vs. $\chi/\chi_{ARM}$. The post-isolation varved lake-sediments from the three localities form a distinct cluster (solid black symbols), which is clearly separated from the respective catchment materials (open symbols). Data from lake-sediment known to contain high concentrations of bacterial magnetite (Pajep Njakajaure, solid grey symbols) overlap the varved lake-sediments.

correlate positively and linearly with TOC, with a change in the slope of the relationship at ca. 1700 BC. These results are reproduced in Fig. 4(a), with the new organic carbon data obtained from Frängsjön in Fig. 4(b). Prior to 1700 BC there was also a clear positive linear relationship between TOC and the concentration of ferrimagnetic material. It is interesting to observe that this relationship is also less distinct after 1700 BC (see Section 5).

Temporal variations of the $\chi_{ARM}$/SIRM ratio in each of the varved lake-sediment sequences are shown in Fig. 5. This ratio is chosen as a representation of the concentration of bacterial magnetosomes, in relation to coarser-grained detrital magnetite originating from catchment erosion (which has lower values of the ratio, Section 5). The most notable common excursion in Sarsjön and Frängsjön occurs between ca. 6000 and 5500 BC, which was suggested by Snowball et al. (1999) to reflect a well-known Northern Hemispheric cold climatic oscillation that has become known as the 8.2 ka BP cold-event (Alley et al., 1997). The independent calendar year chronologies produced for each varved sequence permit an objective comparison of the data sets. The highest $\chi_{ARM}$/SIRM ratios in Furskogstjärnet at ca. 6000 BC occur at the same time that values are low in Sarsjön and Frängsjön. Although high-frequency

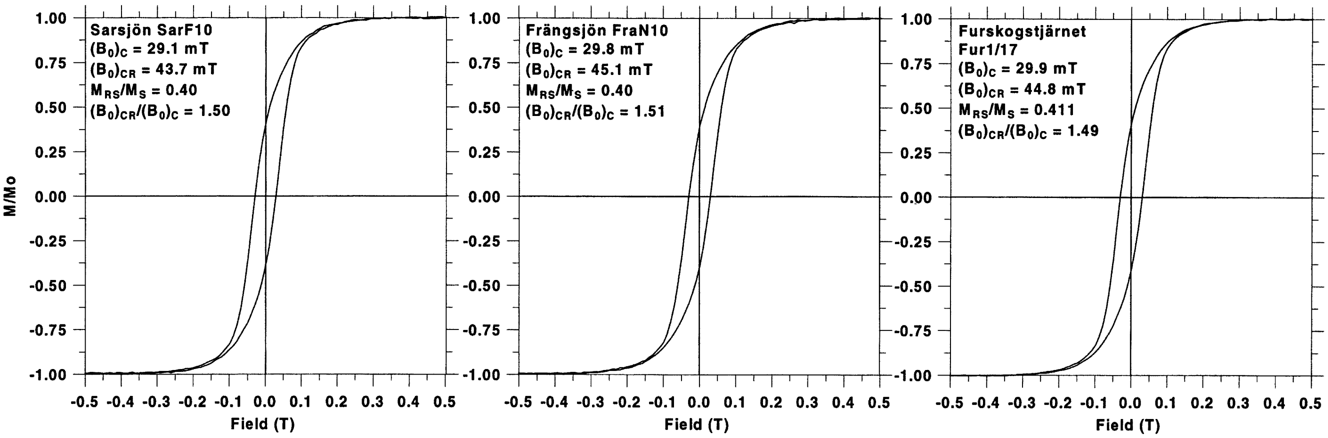


Fig. 3. Magnetic hysteresis loops of representative samples from the three varved lake-sediment sequences. The open central section and the inter-parametric ratios indicate that a single-domain ferrimagnet dominates the magnetic properties.

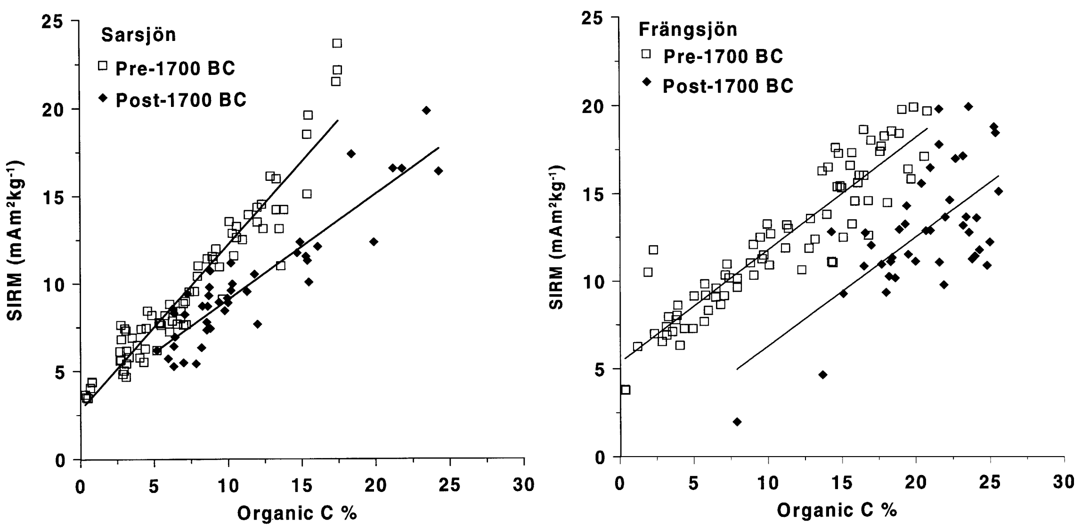


Fig. 4. Content of organic carbon vs. SIRM for Sarsjön and Frängsjön varved sediments. A positive linear relationship existed between the two parameters in both sites until ca. 1700 BC.

oscillations in the $\chi_{\mathrm{ARM}}/\mathrm{SIRM}$ ratio younger than ca. 5500 BC exist in all three sequences, it is not possible to point out direct correlations.

## 5. Discussion

The detailed mineral magnetic measurements carried out on the three varved lake-sediment sequences and their respective catchment materials indicate that the ferrimagnetic properties of the relatively organic rich lake-sediments (TOC ca. 10–20%) are dominated by the production of magnetite magnetosomes by magnetotactic bacteria. The linear relationships that exist between the organic carbon content and concentration dependent magnetic parameters in Sarsjön and Frängsjön indicate that the production of magnetosomes by the bacteria is controlled primarily by the supply of organic carbon to the lake sediments. In Sarsjön and Frängsjön, this relationship appears to be quite stable from ca. 7000 BC until 1700 BC. At this point the production of magnetosomes, in relation to the supply of organic carbon, appears to reduce (Fig. 4(a) and (b)). Further work is necessary to elucidate details of the relationship between TOC and magnetosome production in Furskogstjärnet.

As stated by Hesse and Stolz (1999), the ability to interpret past environmental changes from the concentration of fossil bacterial magnetite is heavily dependent on their degree of preservation. In the study of Pajep Njakajaure in Northern Sweden (Snowball, 1994) mineral magnetic and geochemical analyses indicated the dissolution of bacterial magnetite below a depth of ca. 70 cm. This study of varved lake-sediments indicates

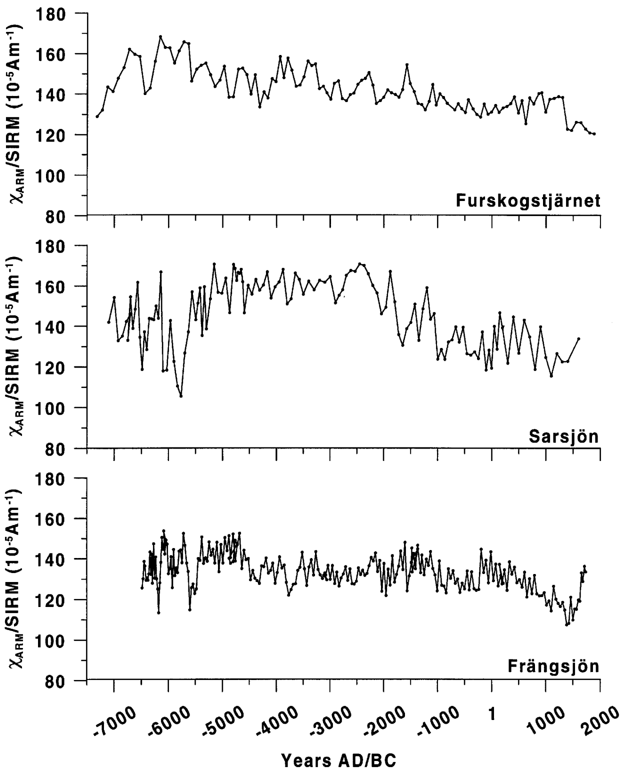


Fig. 5. Temporal variations in the $\chi_{ARM}$/SIRM ratio for the three sites studied. The continuously high values of $\chi_{ARM}$/SIRM in all three sites since isolation from the Ancylus Lake indicate that bacterial magnetosomes are well preserved. More work is required to determine whether the high-frequency variations are of direct palaeoenvironmental/climatic significance.

that fossil bacterial magnetite has been well preserved in the weakly oxic and suboxic sedimentary environments of three dimictic lakes over the past ca. 9000 yr. The dimictic nature of the lakes, which promotes bottom anoxia for part of the year and enables the formation and preservation of varves, appears to support the production and preservation of fossil bacterial magnetosomes. It can be argued that the change in the slope of the relationship between organic carbon content and SIRM at ca. 1700 BC in Sarsjön and Frängsjön points to a change in the production rate of magnetosomes, due to a change in the supply of organic carbon. However, the TOC analysis carried out as part of this study cannot distinguish between autochthonous organic carbon (e.g. carbon in the form of algal remains) and allochthonous organic carbon. In addition, the organic carbon data presented here are expressed on a concentration basis, rather than on a productivity rate (per year) basis. A major increase in mineral erosion in the Sarsjön catchment at ca. 1700 BC was observed by Snowball et al. (1999) and may have caused the transport of older, terrestrial-derived organic carbon to the lake-sediment. Such coarser-grained allochthonous organic material would not be so easily utilised (decomposed) by bacteria, which would result in the change in slope observed in Fig. 4(a) and (b). Significant long-term variations in the transport of relatively magnetically weaker catchment material may also give rise to decreases in the concentration of magnetosomes, which most likely explains the significant reduction of the $\chi_{ARM}$/SIRM ratio between 6000 and 5500 BC in Sarsjön and Frängsjön.

Due to the complicated interactions between climate, the supply of nutrients to a lake and subsequent organic production, there is unlikely to be a simple relationship between magnetosome concentration and single climate parameters. However, the state of the relationship between TOC and SIRM in Sarsjön and Frängsjön changed significantly at ca. 1700 BC, which marks the onset of a different climate regime in Sweden. This climatic shift has been observed in other palaeoclimate records, primarily in records of neo-glaciation (Karlén, 1976; Snowball, 1996) and tree-limit variation studies (Karlén, 1976). Studies of carbon/nitrogen ratios and the isotopic composition of the sedimentary organic matter will help to determine the origin of the bacterial signal observed in the varved lake-sediments. Of direct palaeoclimatic interest are the recent results obtained by Mandernack et al. (1999), which suggest that O-isotope values obtained from bacterial magnetosomes may provide information about their temperature of formation (or the isotopic value of past lake waters), via known temperature–fractionation curves. The potential exists to construct a calendar year palaeotemperature curve based on the isotopic signal carried by bacterial magnetite formed and preserved in varved lake-sediments. However, effort is required to concentrate bacterial magnetosomes to form samples of sufficient mass and purity (i.e. without contamination by detrital magnetite) for such analyses.

Previous results (Snowball, 1994) and ongoing research (Snowball and Sandgren, unpublished data) also indicate that the bacterial magnetosomes carry a stable natural remanent magnetisation (NRM) and hence a high-resolution record of variations in the direction and intensity of the Earth's geomagnetic field. These observations, plus those presented within this article, demonstrate the wide variety of palaeoenvironmental information that can be unearthed by detailed studies of fossil records of microbial activity.

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