Palaeomagnetic secular variations in the varved sediments of Lake Gosciaz, Poland: testing the stability of the natural remanent magnetization and validity of relative palaeointensity estimates

Andreas Nilsson

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Abstract: The pseudo-Thellier technique was applied to recover relative palaeointensity (PT-RPI) estimates from four core sections, each 2 m in length, obtained from Lake Gościąż, Poland. The varve chronology from Lake Gościąż, originally constructed by Tomasz Goslar, was transferred to the sediment sequence. The chronology was extrapolated to cover the upper parts containing a less pronounced varve structure. The aim of the study was to evaluate the stability of the natural remanent magnetization and validity of relative palaeointensity estimates. The alternating field (AF) demagnetization measurements showed the presence of two or possibly three stable NRM carriers. It was established via the pseudo-Thellier technique that the sediments were not suitable for reconstruction of palaeointensity. The principal component analysis technique (PCA) was used to estimate the best fit inclination and declination on a vector component diagram. The data were evaluated and rejected based on the line fit coherency and the angle with which it diverges from the origin. All declination data were rejected due to very high scatter. The resulting inclination curve was compared to a previous study of Lake Gościąż, the output of a geomagnetic model (CALS7K.2) and a Northern Sweden PSV master curve. A significant inclination divergence taking place between 1500 and 500 BC was identified between the CALS7K.2 model and the Northern Sweden master curve. Both Gościąż data sets show similar trends as the CALS7K.2 model, supporting the notion that the divergence is real and of regional character.

Keywords: Palaeomagnetism, Holocene varved lake sediments, varve chronology, geomagnetic models.

Andreas Nilsson, Department of Geology, GeoBiosphere Science Centre, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: an.nilsson@gmail.com

Studier av småskaliga variationer i jordens magnetfält baserat på analyser av varviga sediment i Lake Gościąż, Polen: ett test av stabiliteten i den naturliga remanenta magnetiseringen och tillförlitligheten av relativa paleointensitetsbestämningar

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Sammanfattning: Fyra två meter långa borrkärnor, med sjösediment från Gościąż, Polen, analyserades med hjälp av den s.k. Pseudo-Thellier metoden, en metod som används för att utvärdera tillförlitligheten av variationer av styrkan i det jordmagnetiska (palaeointensiteten) fältet över tiden. Den ursprungliga varvkronologin, framtagen av Tomasz Goslar, överfördes till lagerföljden av honom vid ett besök i Lund 2003. Kronologin extrapolerades till den övre delen av lagerföljden då varven var mindre tydligt utbildade här. Målet med studien var att utvärdera stabiliteten av den naturliga remanenta magnetiseringen (NRM) och tillförlitligheten av de relativa paleointensitetsberäkningarna. Mätresultaten från demagnetisering i alternerande växelströmsfält (AF), visade på två till tre separata stabila NRM bärare. Baserat på pseudo-Thellier tekniken bedömdes att sedimenten inte är användbara för att rekonstruera förändringar i det jordmagnetiska fältets styrka. S.k. principalkomponentanalys (PCA) användes för att beräkna regressionslinjer för inklinationen och deklinationen i ett s.k. Zijderveld diagram. Baserat på denna analys kunde oanvändbara prover förkastas. Deklinationen uppvisade för stor spridning och ansågs oanvändbar. Den resulterande inklinationen jämfördes dels med en tidigare opublicerad studie från Gościąż, dels med en geomagnetisk modell (CALS7K.2) och slutligen med en sammansatt paleomagnetisk regionalkurva för norra Sverige. CALS7K.2 modellen och den regionala kurvan för norra Sverige skiljer sig markant åt mellan 1500 till 500 år f Kr. Såväl den här studien som den tidigare studien av de laminerade sedimenten i Gościąż visar en likartad trend, vilket antyder att variationerna i inklinationen är reella och representerar en regional trend.

Nyckelord: Paleomagnetism, Holocena varviga sjösediment, varvkronologi, geomagnetiska modeller.

Andreas Nilsson, Geologiska Institutionen, Centrum för GeoBiosfärsvetenskap, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: an.nilsson@gmail.com

1 Introduction

Palaeosecular variation (PSV) of the Earth's magnetic field is often reconstructed from volcanic rocks (e.g. Pasquale *et al.,* 2005) or "magnetic" artefacts such as ceramics (e.g. Gallet *et al*., 2002). Both proxies rely on the alignment of the domains in magnetic grains to the Earth's magnetic field as the material cools, either as lava crystallizes or as ceramic artefacts cool after burning (a thermal remanent magnetization, TRM) (Butler, 1992). These proxies provide excellent data for certain locations but only at a certain time. In attempts to construct continuous PSV records lake sediments are often used (Snowball & Sandgren, 2002). The theory is that magnetic grains transported to the lake will align themselves to the prevailing magnetic field during or shortly after deposition (a detrital remanent magnetization, DRM) (Butler, 1992). A continuous reconstruction of PSV in lake sediments can help calibrate models of the Earth's magnetic field and improve our general understanding of how the geodynamo works. Instrumental observations of the geomagnetic field indicate that the geodynamo does not behave as a simple dipole (Jackson *et al*., 2000). Regional differences in both intensity and direction reveal a more dynamic mechanism involving non-dipole contributions. To register small variations on a regional scale, high resolution archives are needed. This has turned the interest towards varved lake sediments (e.g. Saarinen, 1998).

PSV studies can also help correlate and relatively date geological archives, such as the varved Gościąż lake sediment sequence. The Gościąż varve chronology is "floating", which means that the top does not have a secure absolute age. Attempts have been made to fix the chronology to the present by wiggle matching ^{14}C ages and comparing with tree ring data from Germany (Goslar, 1998b). By correlating the palaeomagnetic data from Gościąż to other data with known ages it may be possible to verify or disprove the ages given by the ^{14}C wiggle match.

The natural remanent magnetization (NRM) of sediments is dependant on two major factors: (i) the strength of the Earth's magnetic field at the time of remanence acquisition and (ii) the content of magnetic particles (i.e. the concentration, type and grain size of the minerals carrying the NRM). To successfully reconstruct variations in the Earth's magnetic field it is necessary to correct for differences in the magnetic particle content. This can be done by normalizing the NRM to one or several mineral magnetic parameters that reflect concentration. Another associated aim is to find a magnetic acquisition process which most resembles the NRM acquisition, and where the same range of particles is affected. Magnetic susceptibility (MS) and saturation magnetization, for example, are not suitable parameters as they tend to activate a disproportionately large fraction of superparamagnetic (SP) and multidomain (MD) particles. SP grains do not contribute to remanence and MD grains are not efficient NRM carriers. Like NRM, isothermal remanent magnetization (IRM) and anhysteretic remanent magnetization (ARM) are measured in a field as close as possible to zero. A comparative study of the demagnetization curves of these parameters was performed by Levi and Banjeree (1976), which revealed a very strong resemblance between ARM and NRM. They therefore suggested ARM as the most suitable parameter for normalization of NRM, and it has been frequently used since. Considering the frequent magnetic mineralogy differences between study sites, it would be ideal (although quite time consuming) to measure more than one parameter and by comparison of the demagnetization spectra select the best one for the NRM normalization (Tauxe *et al.,* 1995).

The pseudo-Thellier technique was used to determine a relative palaeointensity (RPI). As suggested by Tauxe *et al.* (1995) this technique can (i) remove unwanted viscous overprints, (ii) provide an error estimate and (iii) detect subtle changes in the coercivity spectrum, which can imply some sort of environmental influence on the RPI.

The use of laminated (not necessarily varved) sediments for palaeomagnetic studies has been debated, the reason being that the sediments have not undergone any form of bioturbation and will suffer from unwanted effects such as inclination shallowing. According to Tauxe (1993) bioturbation will mix the sediment into a slurry where the magnetic grains can align themselves better to the prevailing magnetic field. However, so far no test results have successfully shown this to be necessary (Katari *et al*., 2000). On the contrary, studies by e.g. Ojala & Saarinen (2002) and Snowball & Sandgren (2002) have built upon the study by Saarinen (1998) and further demonstrated that varved lake sediments can contain high resolution PSV records (including palaeointensity).

An earlier attempt at a palaeomagnetic study on Lake Gościąż was performed by Per Sandgren in 1987. This study showed promising results but unfortunately due to core rotation the declination data were not usable. In 2002 a second attempt was made, by Sandgren among others, to recover new sediments for PSV work from Lake Gościąż.

The aim of this study is to evaluate the stability of the natural remanent magnetization acquired by the sediments cored in 2002. The result may compliment the larger study of Finnish and Swedish data sets and extend a N-S transect into central Europe. The study will try and determine possible sources for unreliability and error in the palaeomagnetic result. The result will also be used to discuss the newly published model of geomagnetic field evolution over the past 7000 years, CALS7K.2 (Korte *et al*., 2005).

1.1 Short description of selected magnetic parameters

Below is a list of magnetic parameters, each with a short description to help the reader throughout the paper (after Butler, 1992).

Natural remanent magnetization (NRM): The remanence acquired in nature through different processes, such as detrital (DRM), thermal (TRM) or chemical remanent magnetization (CRM).

Anhysteretic remanent magnetization (ARM): The magnetization acquired in a decreasing alternating field (AF) in the presence of a weak direct field. The alternating field produces random magnetizations in two directions (positive and negative). Without the superimposed direct field the net remanence would be zero. However, the direct field causes a small statistical preference for one direction, resulting in a net remanence.

Isothermal remanent magnetization (IRM): The magnetization acquired in a given (direct) field.

Magnetic susceptibility (MS): A measure of the ease with which a material can become magnetized in the presence of a magnetic field.

2 Site description

2.1 Location and hydrology

Lake Gościąż (52˚35'N, 19˚21'E, 64,3m a.s.l.) is a part of the Na Jazach lake system located in the small lake district of Gostynińskie, northwest of Warsaw (Fig. 1). Na Jazach consists of four lakes and drains directly into the closely situated Vistula River. This lake system formed at the ice margin during the Last Glacial Maximum (LGM). The area surrounding Lake Gościąż is dominated by a thick forest (both pine and mixed forests) which shields the lake surface from strong winds. Precipitation is the lowest in Poland (<550 mm/yr during the period 1891-1980) and the main supply of water comes from groundwater drainage of the Kujawy Upland. The combined effect of low precipitation and a continuous groundwater input leads to stabile conditions concerning water table, temperature and sediment accumulation rate (Churski, 1998; Wojcik & Przybylak, 1998).

2.2 Previous work and nature of the varves

The present lake surface covers an area of 41.7 ha. The bottom topography consists of two troughs, one deeper than the other. The thickness of sediments varies from

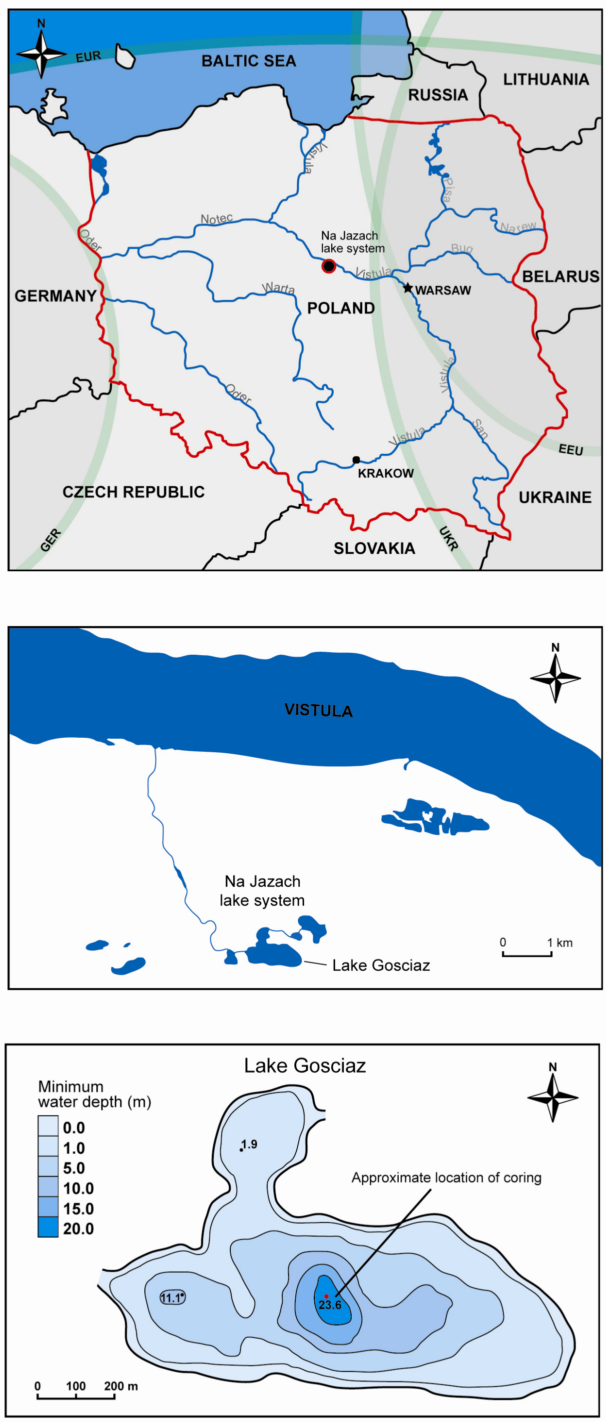

Fig. 1. Simplified map of Poland (a and b) showing the location of the Na Jazach lake system. The shadowed areas with a green outline represent the distribution and coverage of archeomagnetic data sets used for the CALS7K.2 geomagnetic model (Korte *et al*., 2005). Also shown is the bathymetry of Lake Gościąż (c), the red dot represents the deepest part of the lake (from: Bydgoszcz, 2002). The cores were collected at approximately the same location used by Per Sandgren in 1987, close to the red dot.

ca. 7 m to ca. 18 m in the depressions. The Gościąż lake sediments contain one of the best preserved sequences of annual lamination known from Central Europe. Although the upper sediments contain diffuse

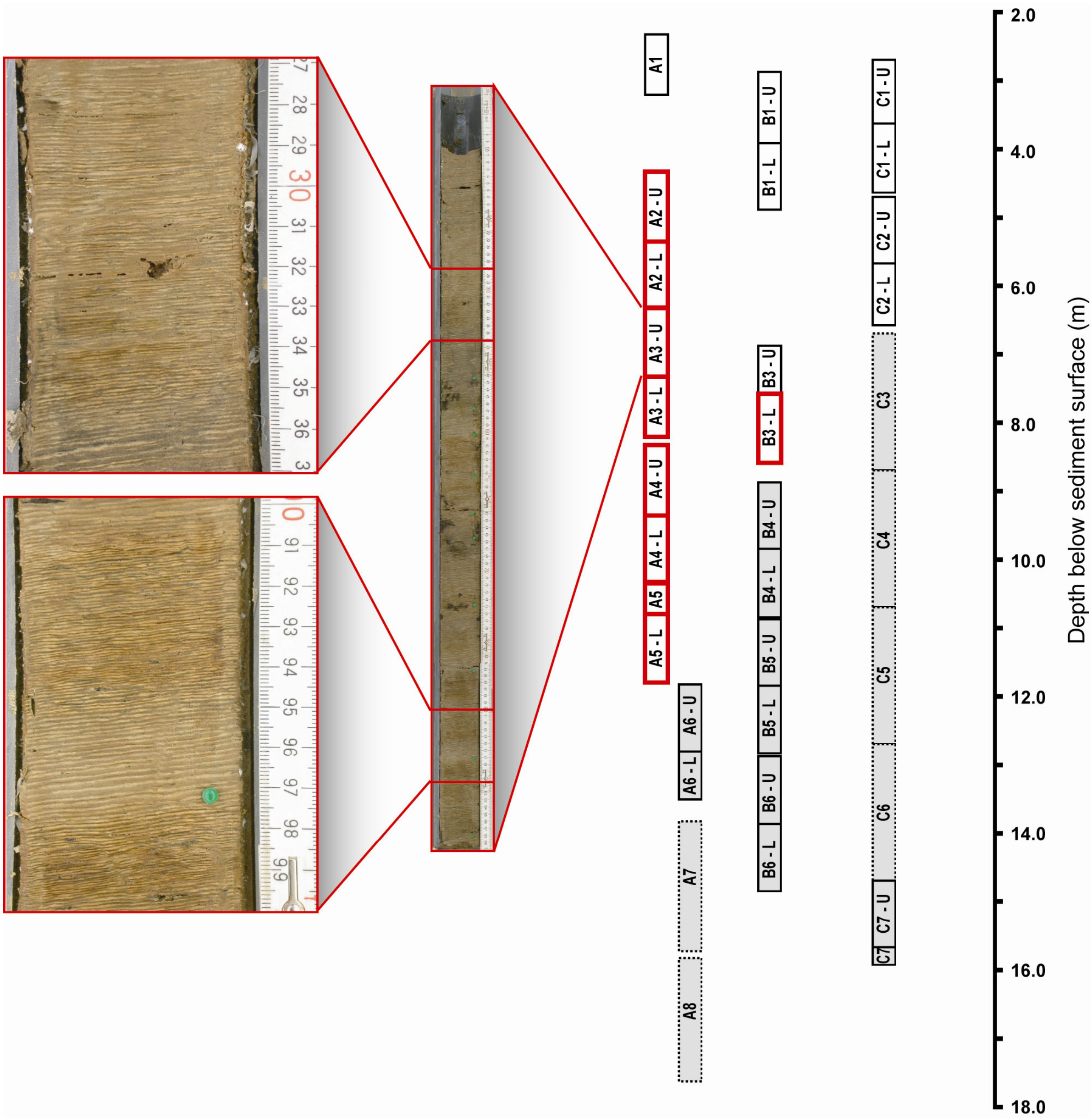

Fig. 2. Schematic illustration of the cores retrieved from Lake Gościąż in 2002. Cores used for this study are marked out in red. A grey background represents cores recovered in metal liners and a dotted line represents cores which were taken to Warsaw instead of Lund. Also shown is an overview picture of the upper half of A3 and close up pictures of two 10 cm sections photographed for varve counting. Note in the lower close up picture a pin, which denotes a visible marker

and disturbed varves, the underlying varved sequence is believed to stretch as far back as 15,000 cal yrs BP (Ralska-Jasiewiczowa *et al*., 1998). The sediment accumulation rate remained steady more or less until about 1000 years ago when it increased rapidly (Goslar, 1998b). The largest change occurred sometime during the 17th century and is believed to be associated with the settlement of a nearby village, which lead to eutrophication of the lake (Goslar, 1998c).

The annually-laminated sediments of Lake Gościąż are composed of a light layer deposited in spring and summer and a darker layer formed during autumn and winter. The light layers are defined by their high concentration of calcium carbonate which is precipitated when water temperature rises and the lake plankton bloom. The dark layers, rich in organic matter and iron, also contain smaller amounts of calcium carbonate which has a finer grain size (Goslar, 1998b).

3 Methods

3.1 Sediment core recovery

Sediment cores were collected from Lake Gościąż in August 2002. The cores were collected using an Usinger corer and a floating platform made by Uwitech, both borrowed from the Geological Survey of Demark and Greenland (GEUS). The Usinger corer is a fixed

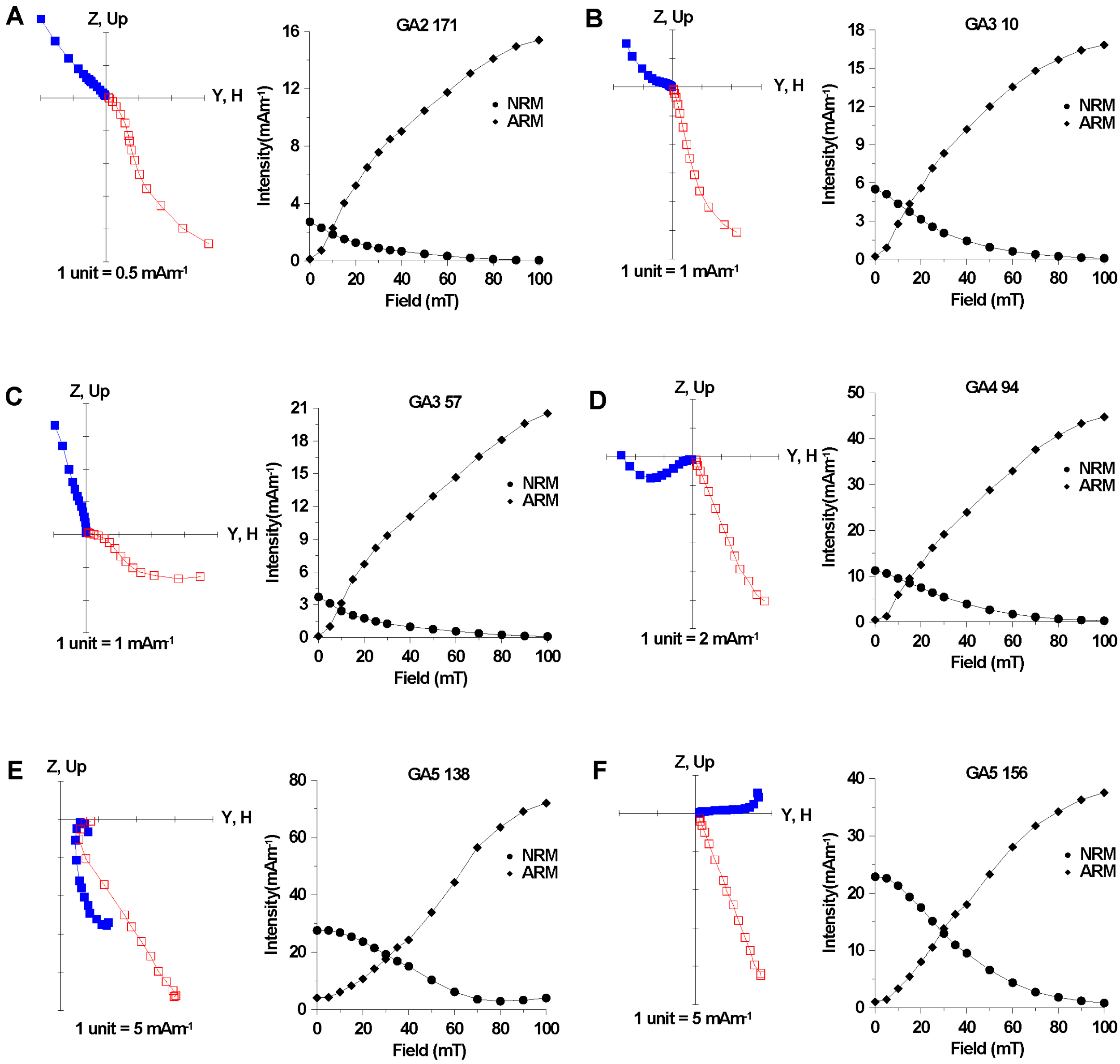

Fig. 3. Vector component diagrams (Zijderveld plots) obtained from the AF demagnetization of the NRM of six pilot samples (a-f). These plots show the presence of two and sometimes three components. Also shown is the stepwise acquisition of an ARM.

piston corer (Günzel, 2004). The sediments were recovered either directly into PVC tubes or by metal tubes and then transferred into PVC tubes for transport and storage (Fig. 2).

A series of seven cores, each approximately two meters in length, was collected near the deepest part of the lake (21.4 m below the water surface) as close as possible to the G1/87 site (see Goslar, 1998a). Four cores (A2, A3, A4, A5) between 4.36-11.83 m depth below the sediment surface were chosen for the study. In addition, a small section (B3) from another series was selected to provide an overlap at a depth of 6.91-8.62 m below the sediment surface. Taking into account that the sediments were intended for palaeomagnetic analysis, great care was taken to prevent the cores from rotating and to maintain a vertical descent during coring. Unfortunately, certain sections of sediment may have sustained some deformation due to the extrusion process from metal to PVC tubes. Considering this risk, only sections recovered directly into PVC tubes were chosen for the study. In most cores the lamination was slightly tilted (apparent angle 5-7°). Whether or not this was a real feature or due to non-vertical coring was - and can still be - debated. The sediment cores were then transported to the GeoBiosphere Science Centre at Lund University and stored there under cool and humid conditions for three years.

3.2 Varve counting

The varves of Lake Gościąż were first counted by Tomaz Goslar using seven cores from different parts of the lake (Goslar, 1998a). A floating varve chronology was established, which spans a period of 9662 years with the upper varve set to 3211 years BP using a “wiggle-matching procedure” between radiocarbon analyses and a tree-ring radiocarbon calibration data set (Goslar *et al*., 1998; Goslar, 1998b). The varves in the upper part (corresponding to depths of less than 6.54 m below the sediment surface) are deformed and could not be as accurately counted. The cores used for this study were examined by Tomasz Goslar during a visit to Lund in October 2003, and distinct marker varves of “known” age were identified and marked with steel pins.

All the cores were photographed in Lund with a fixed digital camera (the Nikon Coolpix 4500). The photographs were taken in segments of ten cm with an overlap of one cm on each end (Fig. 2). By recounting the varves with the continuous series of digital photographs the validity of the marker varves ages was double-checked, and the chronology could successfully be transferred to the new sequence of cores.

3.3 Subsampling for palaeomagnetic analyses

Each piston core was divided into ~1m sections and cut longitudinally into two parts: one comprising the top third of the cross-section, which was kept as a reference sample; and the other two-thirds as the working section. The surfaces of the working sections were gently cleaned with a razor blade to remove a distinct crust (probably an iron oxide) that had most likely formed due to oxidation of iron sulphides during storage. Standard palaeomagnetic sample cubes (external dimensions 2.2×2.2×2.2 cm, and internal volume 7 cm^3) were placed at 3 cm intervals (leaving a gap of 0.8 cm between each cube wall) and carefully oriented with respect to the long core axis prior to pushing them in. Each cube had a small hole drilled into one corner to let the air out as the cube was pushed down. This hole was later sealed with glue to prevent drying. Great care was taken not to disturb the sediments while the cube was cut out using a non-magnetic knife and a razor-blade. The undisturbed varve structure could be seen through the cube indicating that no significant deformation (the so-called “push-effect”) had occurred.

3.4 Palaeomagnetic analyses

All analyses were undertaken in the Palaeomagnetic and Mineral Magnetic Laboratory (PMML) at the GeoBiosphere Science Centre, University of Lund, Sweden. Bulk magnetic susceptibility (MS) was measured on all of the samples using a Geofyzika KLY-2 Kappabridge AC susceptibility bridge. Natural remanent magnetization (NRM), alternating field (AF) demagnetization and anhysteretic remanent magnetization (ARM) acquisition measurements were performed using a 2G-enterprises model 755-R SQUID magnetometer equipped with automated AF coils and a DC bias coil.

The pseudo-Thellier technique was applied for determination of relative palaeointensity (Tauxe *et al.,* 1995; Snowball & Sandgren, 2004). Pilot samples (n=44) were selected at a pre varve-count estimate of one every 200 years. AF-demagnetization was carried out at 5-10 mT increments up to a total of 100 mT. The samples were then given an ARM (DC bias field of 0.05 mT) with the same steps used for the AF-demagnetization. These operations are time consuming and were therefore only carried out to full extent on the pilot samples. The results of both AF demagnetization and ARM acquisition help to identify the characteristic remanent magnetization (ChRM), as well as the interval during which this is demagnetized. The remaining samples can then be processed more efficiently using the information obtained from the pilot samples (See below).

Four characteristic vector-component diagrams are shown in Fig. 3, which demonstrate the variation of NRM stability throughout the sequence. The horizontal data (blue lines) are in general composed of two components: a soft magnetization which was demagnetized between 0 and 20 mT; and a more stable one, which trends towards the origin.

In the vertical (red lines) data there are typically two, but sometimes three, stable vector components with different coercivities. The first component detected in nearly all samples is most likely a soft (~viscous) component, erased between 15 and 20 mT. The second component is the most dominant and was found in all the samples between 20 and 40 mT. In the

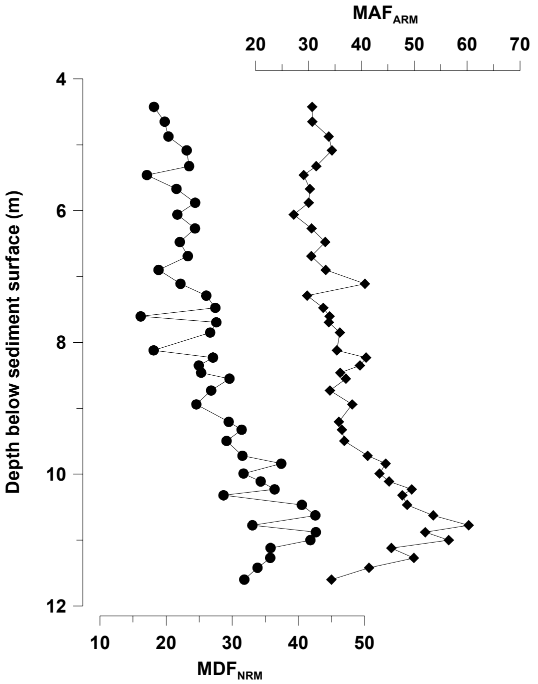

Fig. 4. Median destructive field (MDF) of the NRM demagnetization and Median acquisition field (MAF) of the ARM acquisition plotted against depth below the sediment surface.

lowermost sediments a magnetization appeared to be acquired in a plane perpendicular to the last magnetometer demagnetization axis (z) at relatively high AF values (See results). Certain samples, which did not acquire this magnetization, showed traces of another relatively hard and stable component typically found between 60 and 100 mT.

The demagnetization plots of the 44 pilot samples were normalized to their respective maximum NRM intensity in order to determine the median destructive field (MDF). The MDF is the quantity of the demagnetization field required to reduce the initial NRM intensity by half. The nature of the NRM demagnetization curve gives valuable information about the overall palaeomagnetic stability of the NRM carriers. The MDF is a crude quantification of this stability (or coercivity). High MDF values indicate high coercivity, and therefore a stable NRM carrier (Collinson, 1983). In a similar fashion the ARM acquisition sequence was normalized to the ARM acquired at the maximum AF field. The median acquisition field (MAF) is the strength of the field required to produce half of the maximum ARM, and is interpreted in a similar way to MDF. The median destructive field (MDF) ranges between 16 and 43 mT, and there is a decreasing trend up core. Similarly the ARM AF acquisition spectra (MAF) range between 27 and 60 mT, and show a decreasing trend up core, with a peak around a depth of 10.5 – 11 m (Fig. 4).

The pseudo-Thellier technique was designed to determine the reliability of relative palaeointensity estimates (PT-RPI). To illustrate the method, Fig. 5 shows "ARM gained" and "NRM left" plotted against each other for two pilot samples. By processing the information of all 44 pilot samples, a best fit regression line was found using the field steps between 20 and 40 mT or between 30 and 50 mT. Since the "window" between 20 and 40 mT included more measurements (five) it was considered more reliable. PT-RPI check values were determined the same way as PT-RPI but in this case the NRM and ARM values were normalized to their respective maximum values for each sample. As suggested by Tauxe *et al.* (1995) the "PT-RPI check" parameter could work as an evaluation tool to assess the reliability of the palaeointensity estimate (i.e. to determine if the RPI estimate has been biased by changes in magnetic mineralogy or grain size).

Based on the pilot sample study half of the remaining subsamples (n=107) were subjected to NRM demagnetization and ARM acquisition at 5 mT field increments between 20 and 40 mT. The other half of the samples was preserved for the eventuality of a more detailed PSV study of the lake sediments. Finally, the samples were given an ARM at 100 mT used for the normalization of the ARM acquisition to the NRM demagnetization.

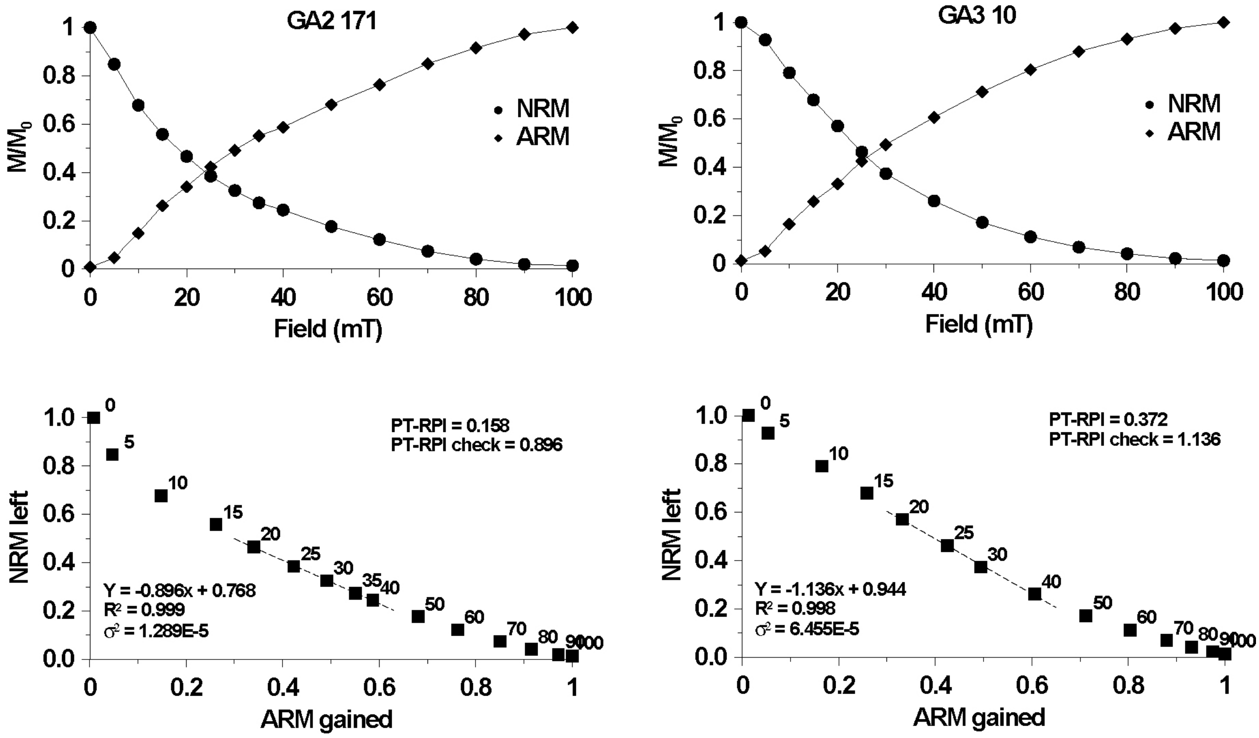

Fig. 5. A graphic representation of the pseudo-Thellier technique applied to two pilot samples. The NRM lost and ARM gained data between AF fields of 20 – 40 mT were used for the regression line analysis. Raw data were used for the PT-RPI estimate and normalized data were used to determine the PT-RPI check value. The regression line coherence (r^2) is high and standard error (σ^2) low. PT-RPI and PT-RPI check values were all multiplied with -1.

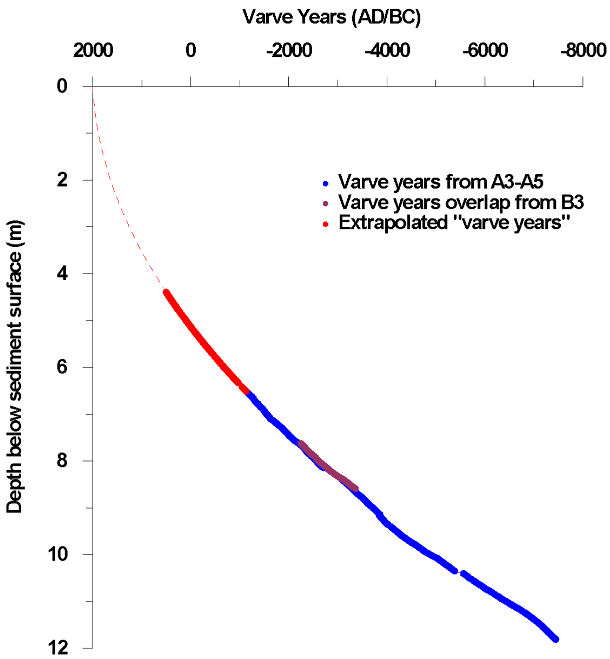

Fig. 6. The sediment accumulation rate shown as plot of time versus depth. Dots show the time-depth position of the samples. Red dots represent samples for which the varve chronology was extrapolated. The purple dotted line is the continuation of the extrapolation function.

4 Results

4.1 Varve chronology

Discrepancies were found between the original "*Goslar chronology*" and current chronology. Between two pins of "known" varve ages (corresponding to 3872 and 3739 BC) an additional 34 years were found that were not included in the original chronology. The range of errors while correlating varve ages with the pin marked varves identified by Tomasz Goslar was generally low (± 1 year per 100 years). However within sections containing cracks and deformed laminae, correlating between two pins was more difficult and the age determination error for a sample was higher (up to ± 2.5 years per 30 years). For the upper parts consisting of deformed varves an extrapolated chronology was used based on the linear trend from the uppermost varve-counted core (Fig. 6).

4.2 Mineral magnetism

Fig. 7a shows the bulk magnetic susceptibility (MS) plotted against the adopted varve time-scale (AD/BC). The susceptibility rises gradually from the bottom up to 6000 years BC with two distinctive peaks at 6400 and 6000 years BC respectively. The susceptibility then drops dramatically and remains stable with a slight decreasing tendency towards the top.

The two peaks in susceptibility seem to correlate with the pilot samples that acquired a magnetization during AF demagnetization. This magnetization is not random because it is aligned parallel to the last static demagnetization axis. This behaviour can be explained by the acquisition of a gyroremanent magnetization (GRM) during AF demagnetization, which is a well documented phenomenon associated with the presence of single-domain particles or anisotropy (Snowball, 1997). A GRM is acquired in the plane perpendicular to an imposed AF field and often has an intensity proportional to applied AF field strength. In Fig. 7b the intensity of the pilot samples at the 100mT AF demagnetization step is plotted against calendar years. This type of plot is a good way of distinguishing a GRM component, since the intensity will tend to rise as the sample is demagnetized in higher fields. As seen in Fig. 7b the positive correlation between GRM and susceptibility is quite obvious with the same trends of highs and lows. It should be noted, however, that the bottommost samples with high susceptibility do not appear to acquire a significant GRM.

4.3 NRM directions and intensity

NRM intensity values range between 2 – 50 mAm^{-1}, with noticeably higher values around 6000 years BC. The NRM inclination and relative declination are plotted against the calendar-year time-scale in Fig. 8a-b. All directional data were calculated using the orthogo-

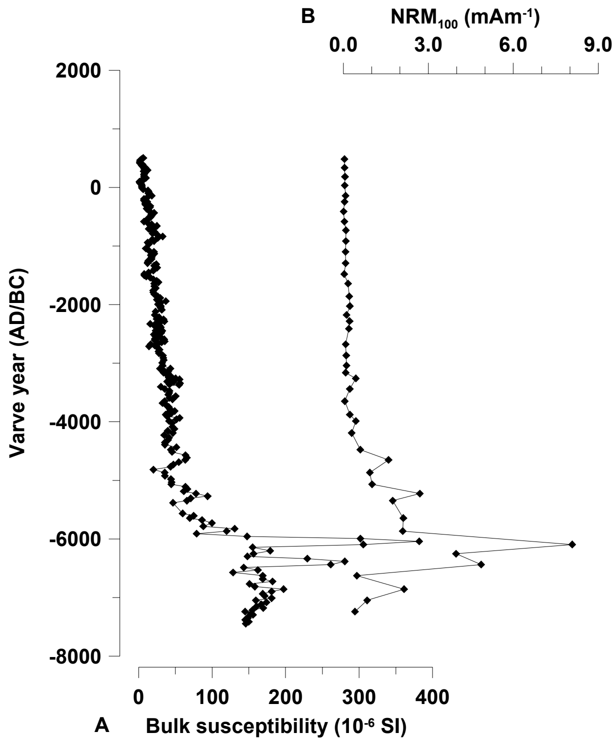

Fig. 7. Bulk susceptibility (a) (All samples collected) and NRM_{100} (b) (pilot samples) plotted on the calendar-year time-scale. There are two distinct peaks at 6000 and 6400 years BC.

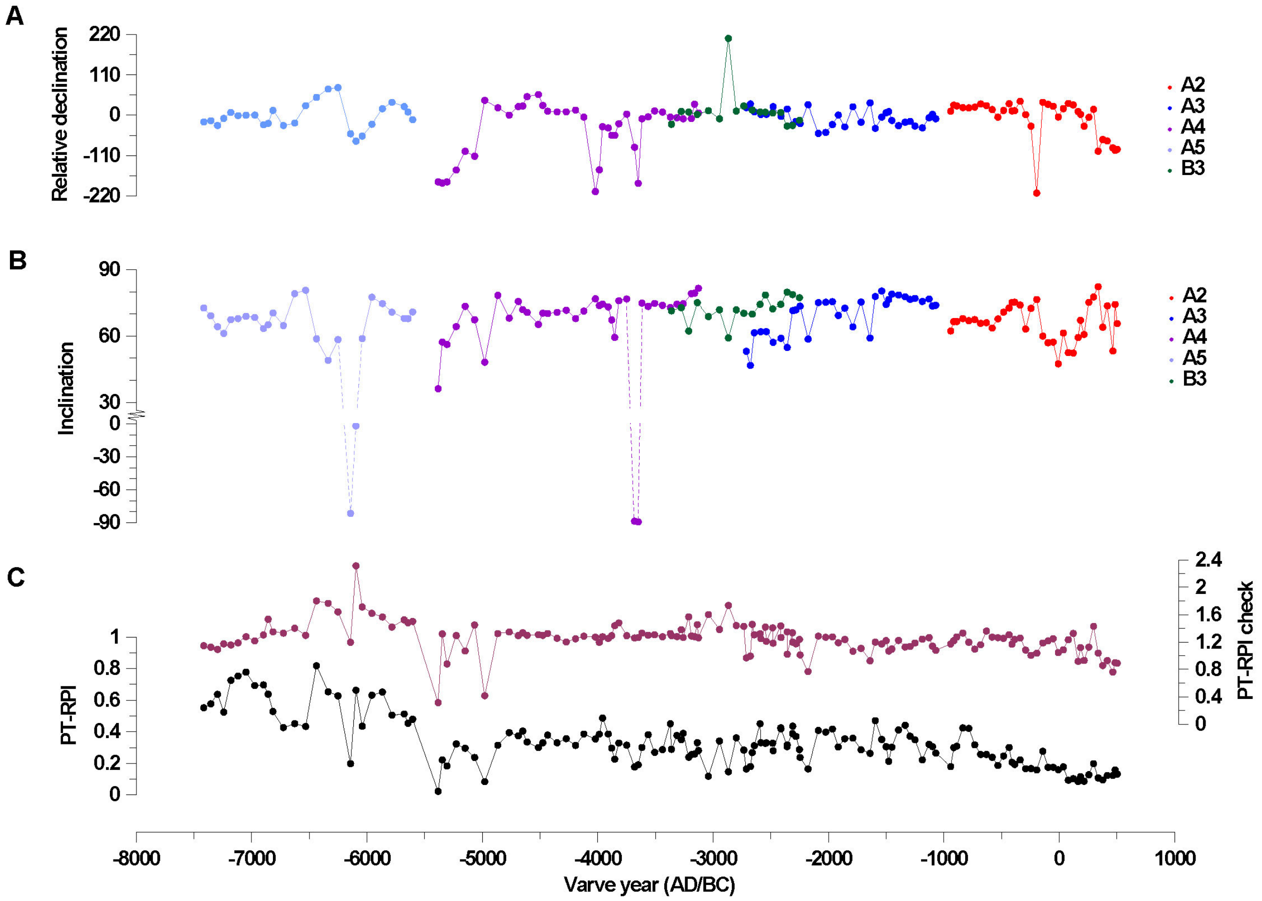

Fig. 8. Relative declination (a), inclination (b), PT-RPI and PT-RPI check (c) plotted on the calendar-year time-scale. Note the two different scales for inclination. Both declination and inclination are plotted separately for each core section to illustrate individual trends. PT-RPI and PT-RPI check are very similar, which indicates an environmental bias. All four graphs show high variation at 6000 years BC.

nal vector regression between AF demagnetization steps 20 – 40 mT.

Declination data were separated into the different core sections and normalized with respect to their core averages (core averages constructed from "filtered data", see below). The scatter around a mean of 0º is very high with peak values reaching more than ±60 degrees. Core section A5 shows higher amplitude variation around 6000 years BC, with the negative peak correlating well with the peak in susceptibility and GRM occurrence in Fig. 7. Core section A4 shows the most unstable signal of declination with abrupt variations and some indications of core rotation in the bottom. Section B3 overlaps A4 and A3 with fairly good precision and except for one value shows a generally stable trend. A3 and A2 seem rather stable except for an abrupt drop around 200 years BC.

The inclination data also have a fairly high variance. There is a notable increasing trend up cores for sections A4, B3 and A3. Similar to declination there are higher amplitude variations, which correlate with peaks in susceptibility and GRM (Fig. 7). Negative peaks around 6000 years BC and ca 3500 years BC are either the result of inclination vectors with very poor coherence or vectors with a negative angle. Core section A2 has very high amplitude variations.

4.4 Pseudo-Thellier relative palaeointensity

King *et al.* (1983) and Tauxe (1993) summarize different criteria for palaeointensity data obtained from sediments. The Gościąż sediments do not conform to a number of the criteria recommended for palaeointensity reconstruction, and the palaeointensity results should therefore be treated with caution (and possibly rejected completely). One of the criteria formulated by Tauxe (1993) requires that the natural remanence should be carried by magnetite of a grain size between 1 and 15 µm, with a single, well-defined vector-component of magnetization. As previously mentioned (Section 3.4, Fig. 3) this does not apply to parts of the Gościąż sediment sequence. The pseudo-Thellier technique offers a way to check for environmental bias caused by changes in magnetic mineralogy and grain size (Tauxe *et al.*, 1995). Fig. 8c shows the PT-RPI and "PT-RPI check" parameters plotted against a calendar-year time-scale. The PT-RPI curve has a trend of generally higher values in the bottom and lower values in the top. The "PT-RPI check" parameter has the same trend confirming that there is indeed an environmental bias in the palaeointensity signal. Ideally the PT-RPI check values would show a straight line with little or no variability. If variations do occur they should not be mirrored in the PT-RPI data. Thus, it can be argued that the RPI estimates obtained from the section older than ca. 4700 years BC are heavily impacted by other factors than changes in the Earth's past geomagnetic field intensity. The "PT-RPI check" parameter shows variability which also is reflected in the PT-RPI estimate. Sediments younger than 4700 BC have a more stable PT-RPI, although there is a slight trend towards lower values at 2500 years BC.

5 Palaeomagnetic data and sample rejection

Considering the high scatter in the directional data produced in this study, it was decided to evaluate the reliability of each sample and reject those not suitable. The wide range of MDF values and the vector component plots of some samples (Fig. 3) suggest that the remanence is not carried by a single stable component (as specified by Tauxe's criteria, 1993). The multi-component vectors show that more than one mineral contributes to the NRM.

Based on the stability of the vector diagram components a technique was devised to objectively reject individual samples regarded as not suitable. There are different ways of determining the inclination or declination from a sequence of demagnetization steps. The simplest method, which has long been the standard procedure, is to choose a single demagnetization step that best represents the NRM (and is often near to the MDF of NRM). However, due to occasional high scatter even in good data it is preferable to use as many demagnetization steps as possible. and to use a large proportion of the NRM rather than a point measurement (Butler, 1992). By calculating the average of several demagnetization steps (Snowball & Sandgren, 2004) one overcomes the effect of occasional scatter caused by analytical techniques, but this method only works with single stable components trending towards the origin. When dealing with more complex data, including multi-component remanences, it is necessary to take into account the trend of individual vector components and their stability. Kirschvink (1980) suggested the use of the principal component analysis technique (PCA) to estimate the best fit inclination and declination on a vector component diagram. Three optional procedures could be employed:

- "Anchored" line fit – Best fit line that must pass through the origin.
- "Origin" line fit – The origin is chosen as a separate data point for the best line fit calculation.
- "Free" line fit – The best fit line without the origin.

Butler (1992) points out the importance of a fitted line that trends towards the origin of a vector component diagram, which would indicate that a single stable component with constant direction is being progressively removed. However, several pilot samples showed the existence of three components where the characteristic vector did not trend towards the origin. The inclination of the most stable component of samples GA2_171 and GA3_57 (Fig 3a & 3c) typically had a lower angle compared to the "characteristic" magnetization. This could be an indication of a secondary magnetization caused by high-coercivity haematite, the lower angle being a sign of inclination shallowing caused by gravity acting on relatively elongated and "flaky" haematite grains (Tauxe, 2005). If the third component is indeed caused by haematite then it could be argued that the "characteristic" magnetization can be interpreted as a reliable NRM, even if it does not trend towards the origin. On the other hand, Zijderveld (1967) suggests that the use of a relatively low coercivity characteristic component in the presence of a higher coercivity component could be preferable. This would be the case of a secondary chemical remanent magnetization carried by greigite, which has a higher coercive force than "detrital" magnetite (Snowball, 1997). However, overlapping demagnetization spectrums and the lack of an anchor point might make it hard to distinguish a characteristic component from any additional secondary components, particularly when magnetite and greigite coexist (Snowball & Thompson, 1990).

In this study the "Free" line fit PCA-technique has been used to isolate the characteristic component from AF demagnetization steps between 20 and 40 mT. The aim is to reject samples with low trend line coherence (i.e. low stability) or samples where a third hard secondary component is found. Since the bulk samples lack the more detailed AF demagnetization data of the pilot samples it is hard to detect secondary components which would be demagnetized with fields above 40 mT or below 20 mT. Ideally, all samples should be treated as pilot samples, and this is recommended when automatic AF demagnetization can be undertaken and there is sufficient time.

Fig. 9a shows the raw inclination data and trend line-coherence (r^2) plotted against the calendar-year time-scale. For graphical reasons the trend line coherence is plotted on two separate scales. By studying pilot samples with different line-coherence values a limit ($r^2 = 0.96$) was decided for which the inclination error was acceptable. All samples with line-coherence less than this limit were rejected. Fig. 9b shows the inclination data remaining and an "angular deviation from the origin" parameter (ADO) plotted against a calendar-year time-scale. The ADO parameter is based on the difference between the inclination calculated from the trend line and the inclination that was calculated using the average. The ADO parameter can be combined with the characteristics of the pilot samples, and can successfully detect samples which contain a third high-coercivity component. A positive ADO parameter value would indicate that the third component

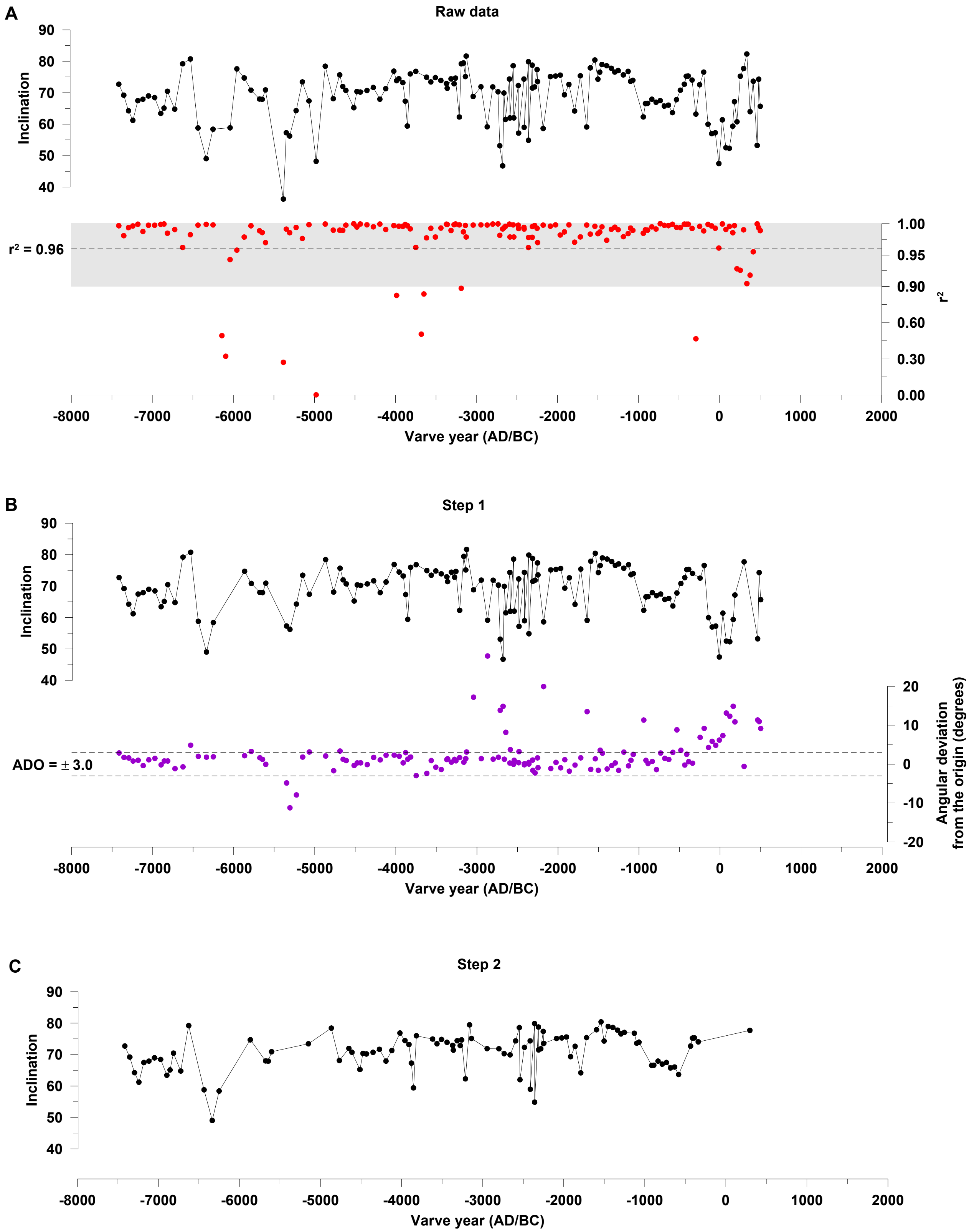

Fig. 9. Inclination and r^2 (a) plotted on the calendar-year time-scale. Note the lightly shaded area, which highlights a separate scale for the r^2. The dashed line represents the lower limit; samples with r^2 beneath this value were rejected. (b) The remaining inclination data and the *angular deviation from the origin* (ADO) plotted on the calendar-year time-scale. The dashed lines represent the upper and lower limit; samples with 3.0 < ADO < -3.0 were rejected. (c) The inclination remaining after rejecting samples according to (a) and (b), plotted on the calendar-year time-scale.

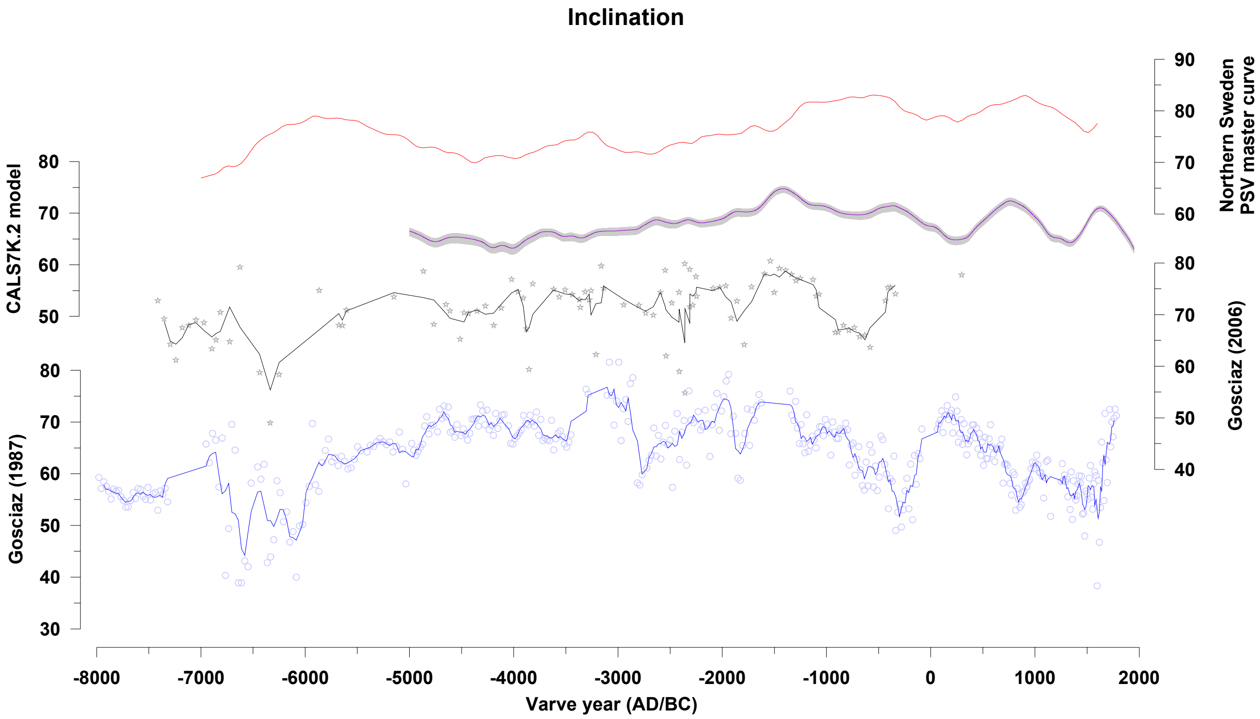

Fig. 10. Inclination data from Lake Gościąż with a five point running average (blue line; from Sandgren, unpublished data) and a three point running average (black line; present study). Inclination from the CLAS7K.2 model prediction (from Korte *et al.*, 2005) for the coordinates of Lake Gościąż (pink line). The shaded grey area show the maximum and minimum predicted inclination of four points situated 100km north, south, east and west of Lake Gościąż. Inclination from a Northern Sweden PSV master curve (red line; from Snowball & Sandgren, 2002).

has a shallower inclination (carried by haematite, for example). Noteworthy are the three points between 5500 to 5000 years BC which display a markedly negative ADO parameter value. As for the first step the limits for the ADO parameter were chosen using the appearance of pilot samples with high values (ADO = ± 3). Fig. 9c shows the inclination data after step 1 and 2. Most data with low inclination are removed. The mean inclination of the entire section is 71.0° compared to 69.1° determined for the lake coordinates with a geocentric axial dipole model (GAD) (Butler, 1992). The time period between 7000 and 5000 BC and the youngest sections from 0 – 1000 AD seem to have been most heavily affected, resulting in lesser density of data points.

A similar rejection technique has also been performed on the declination data. However, using the same limits as for inclination ($r^2 > 0.96$ and ADO = ± 3) resulted in a data loss of more than 80%. This high percentage of rejection arises because declination data tend to become very scattered when inclination values are steep. For example, at inclination values near 80°, an offset of a few degrees in sample alignment relative to the long core axis can cause declination values to change hemispheres (E-W). Taking in consideration the steep inclination values, new limits for declination were chosen to allow for a bit more line fit scatter ($r^2 > 0.8$). The loss of data was still very high, however (75%), and the declination data were therefore evaluated as being unsuitable for PSV studies.

6 Comparison with regional empirical data and model output

The previous PSV study of Lake Gościąż performed by Per Sandgren suffered from core rotation, rendering declination data useless. The inclination data, however, showed very promising results, and were the catalyst for both this study and for the use of a coring technique that was designed to prevent core rotation. In Fig. 10 the inclination data derived from Fig. 9c are compared to the previous results from the study. The varves from the previously extracted sediments were counted independently by Per Sandgren and later correlated with the floating varve chronology of Tomasz Goslar using the sequence of varve thickness. The trends are very similar, although the new inclination data is typically a bit steeper. The most prominent feature is the simultaneous trough centred at ca. 6400 year BC coinciding with the period of high susceptibility and GRM effect.

Also shown in Fig. 10 are the inclination data from CALS7K.2, a recently published model of geomagnetic field behavior (Korte *et al.,* 2005), and a PSV master curve for Northern Sweden compiled by Snowball & Sandgren (2002). The inclination predicted by CALS7K.2 is specific to the coordinates of Lake Gościąż. The directional data used to construct the CALS7K.2 model were collected from lake sediments (41 locations), archeomagnetic artifacts and lava flows (23 regions). The distribution of archeomagnetic data used is heavily dominated by Europe while the lake sediment sequences used are more globally distributed. For the immediate region of Lake Gościąż there are no lake sediment data and the model here is greatly dependent on a discontinuous series of archeomagnetic artifacts (Korte *et al.,* 2005) (Fig. 1).

The CALS7K.2 model predicts that inclination was steepest at 1500 BC, and this is confirmed by the new empirical data from Gościąż. This feature is not evident in the old Gościąż data set due to a gap between cores. However, the higher frequency agreement between the Gościąż data and the CALS7K.2 model is poor. Compared to the PSV master curve of Northern Sweden the new Gościąż data has an acceptable correlation between 5000 and 1500 BC, which is also the time period with the highest sample density. Between 1500 BC and 500 BC there is a tendency towards lower inclination, as seen in both the Gościąż data and the CALS7K model which is, however, a period of steadily increasing inclination in the PSV master curve from Northern Sweden.

7 Discussion

7.1 Varve chronology related issues

The varve chronology was transferred to the section with deformed varves using an extrapolation function (Fig. 6). Studies of laminae thickness show a steady sediment accumulation rate with a slight increase up to 1000 Cal BP (Goslar, 1998b). To accommodate for the increasing accumulation rate the extrapolation function was calibrated with a smoothed laminae thickness record. The youngest age yielded by the extrapolation function was 1448 Cal BP, which is well within the section of steady accumulation rate. Radiocarbon dates from previous studies (G1/87) also support the choice of extrapolation (Wicik, 1998).

The additional 34 varves detected during the varve counting imply that the sediment sequence counted by Tomasz Goslar contained one or more hiatus'. Another possibility is that marker varves were incorrectly identified. However, the fact that all the other marker varves were found to match with respect to each other (with only minor errors), suggests that the marker varves were accurately identified. It should be noted that the varves of the present study were only counted by one (relatively inexperienced) person, and the result could therefore be biased by systematic errors of either continuously overestimating or underestimating the number of varves.

7.2 Implications of the palaeomagnetic analysis

To summarize the results it can be concluded that the Gościąż sediments are not suitable for producing a relative palaeointensity record. The directional data (inclination and declination) are highly scattered, although there do appear to be systematic errors, which indicate some kind of experimental origin. Core rotation during drilling is common and often causes problems for the declination data during PSV studies of lake sediment. Although great care was taken to prevent rotation in this case it cannot be excluded that some rotation occurred, possibly in the core barrel during penetration and extrusion. However, assuming that there has been little or no deformation during the coring process could the scatter be explained differently?

The mineral magnetic results show a prominent feature of high susceptibility and GRM effects centred around 6000 to 6400 yrs BC. Earlier chemical analyses have shown that during this period the Gościąż sediments exhibit unusually high concentrations of iron, which would explain the high susceptibility (Wicik, 1998). The effect of a GRM can be caused by the presence of the greigite (Fe_3S_4). Greigite is a metastable ferrimagnetic mineral which forms authigenically in anoxic sedimentary environments as an intermediate stage during pyritization (Roberts & Weaver, 2004). However, during conditions with high concentrations of detrital iron-bearing minerals in combination with low organic carbon the pyritization process could be interrupted and greigite preserved (Kao *et al.,* 2004). Post depositional greigite would acquire a chemical remanent magnetization (CRM) during crystal growth. The geomagnetic field may change from the time of deposition to the time of crystal growth, resulting in an age delay between sediment deposition and NRM acquisition. Difficulties in distinguishing the remanence signals from each other could explain the poor inclination data found during this period. Although it is very likely that the anomaly at 6000 BC is due to the presence of greigite, further mineral magnetic studies would be necessary to establish this without doubt.

The longer, stable period of low susceptibility seen in Fig. 7a coincides with a shift towards $CaCO_3$ dominance in the lake, caused by lower concentrations of iron (Wicik, 1998). The uppermost core section (A2) has the lowest magnetic susceptibility. The rejection process of section A2 inclination resulted in a 64% loss of data indicating low suitability for palaeomagnetic analysis. Except for 30cm at the top of section A3, all the deformed varves are located in section A2. It is not unreasonable to suggest a coupling between the deformation and the low quality of palaeomagnetic data. However, one could also argue that the low susceptibility, indicating lower concentrations or increasing grain sizes of the magnetic minerals, could have lead to a weaker palaeomagnetic signal with higher uncertainties / larger amplitudes in the variations (i.e. a low signal to noise ratio).

It is very important to view the data critically and not to force results in an attempt to obtain a continuous PSV record. Considering the periodically poor sampling density in the inclination data remaining after the rejection process it is evident that only parts of the sequence (4500 to 0 BC) could be judged with some degree of reliability. There does not seem to be any problem with inclination flattening, at least not in the accepted data. In fact the mean inclination (71.0°) is steeper than that predicted by a GAD. The high scatter is also seen in the old Gościąż data set implying that the problem is not coring related but rather due to the DRM acquisition process. As Butler (1992) noted, there are different processes that may interfere with the alignment of magnetic grains to the Earth's magnetic field during deposition. Magnetic grains when placed in a fluid will be subjected to viscous drag, flocculation (more common in high salinity water) and thermally governed "Brownian" motions. The magnetic grains may also interact with other grains upon settling on the bottom surface, which could change the orientation to adjust for irregularities. All these processes could cause different inclination errors resulting in an increased scatter. However, no sedimentary process is known that can produce systematically steeper inclinations, other than true geomagnetic field directions.

Assuming that the sediments were deposited on a horizontal surface, the tilted varves (sections A3, A4 and B3) must either have been tilted tectonically or cored at an oblique angle. If the declination (γ) and inclination (μ) of the tilted surface is known, it is possible to correct for it (α = inclination and β = declination of the sample magnetization):

$$\alpha = \alpha_0 - \mu \cos(\beta - \gamma)$$

By using crude approximations of μ, inclination values for A3, A4 and B3 were corrected for (data not shown) providing a new inclination average of 68.9º, which is almost exactly what the GAD model predicted. We may tentatively suggest that the tilted varves were in fact deposited on a horizontal surface and that the steep inclination confirms this hypothesis. However, a more detailed study of the tilt would be required. On the other hand, if the tilt is real and the sediments were deposited on a slope, correcting for it would produce very irregular data indeed. It should also be noted that a few thousand years may not be enough time in which to obtain an axial dipole position from the mean direction of the PSV data. Based on these uncertainties it was decided to leave the data shown in Fig. 10 uncorrected.

The CALS7K.2 model does not include any of the lake sediment data used for the Northern Sweden PSV master curve. The general correlation between the two data sets is quite good, with the exception of a few divergences. The most significant divergence takes place between 1500 and 500 BC. Despite the high scatter, both Gościąż data clearly show the same trend as the CALS7K.2 model. The difference in latitude between the Northern Sweden PSV master curve and that of Lake Gościąż suggests that the divergence might represent a regional phenomenon. However, the lack of data in the region of Poland could perhaps provide an alternative explanation for the disagreement.

8 Conclusions

(1) Due mainly to variable magnetic mineral composition the Gościąż sediments are not suitable for palaeointensity reconstructions. The directional data could still prove useful but high scatter make any detailed observations impossible.

(2) Although not conclusively confirmed, there are strong indications that the anomaly seen around 6000 years BC is caused by greigite.

(3) Unfortunately the resolution of the Gościąż data is inadequate for reviewing the CALS7K.2 geomagnetic model.

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