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Annual and inter-annual magnetic variations in varved clay

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Annual and Inter-annual Magnetic Variations in Varved Clay

by

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ABSTRACT

The Swedish foil piston corer is perfect for taking long oriented sediment cores. The paleomagnetism in three Swedish varved clay cores record the annual changes during periods of about 100-150 years. An 11-yr sunspot cyclicity is well established in the magnetic records. The amplitude variations are large. In thick varves (proximal varves and drainage varves), the inter-annual magnetic variations are recorded. The intensity shows a clear annual cyclicity (independent of sedimentological variations). Declination and inclination show an annual cyclicity, too. The amplitudes of the sunspot and annual cyclicities are too large solely to be the effect of ionization changes. Chemical-physical environmental changes must have played an important role in both cases. The recorded annual and seasonal magnetic (NRM) fluctuations are so large in amplitude that they in unvarved sediments without good dating control might have been classified as "excursions" or major secular variations.

INTRODUCTION

The first paleomagnetic studies in varved clay were made by Ising in 1926 (Ising, 1942). Johnson (McNish and Johnson, 1938; Johnson et al., 1948) made pioneer studies of the varves in New England. Griffiths (1935, 1955) and Granar (1958) made further studies of Swedish glacial varves.

Improved magnetic measuring technique during the 50-ies and 60-ies gave new interest to studies of paleomagnetic changes in young sediments. This fact together with the existence of the Swedish foil piston corer (Kjellman et al., 1950) capable of taking 11 m long cores (undisturbed and in one piece) made the author (in 1970) apply paleomagnetic measurements on a 14.5 m long sediment core form Gothenburg of a Pleistocene/Holocene boundary-stratotype (Mörner, 1973, 1976). The results

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inspired amplified studies of paleomagnetic changes in young sediment cores and sections.

Up to now, 36 cores and sections have been analyzed, covering the last 32,000 years, especially the last 13,700 years: 19 Swedish cores, 2 Swedish sections, 1 Danish core, 1 Atlantic core, 13 Canadian sections (8 in Ontario and 5 in Quebec).

Besides the recording of the Gothenburg Magnetic Excursion and Flip (Mörner et al., 1971; Mörner and Lanser, 1974; Mörner 1975b, 1977) and the secular magnetic variations in long Holocene cores (Mörner 1975a), numerous records (15 of the Swedish cores and sections and all the Canadian sections) represent glacial varve sequences. This paper will be confined to the varved clay records of annual and inter-annual magnetic changes in selected Swedish cores (cf. Mörner 1975b, 1975d).

METHODS

All cores were taken with the Swedish foil piston corer and carefully oriented. Ten of the Swedish cores and sections (and all of the Canadian and Atlantic samples) were measured by Lanser on astatic magnetometers in Utrecht and Amsterdam. All samples (3.6 cm high plastic cylinders) have been treated with progressive demagnetization in alternating fields of up to 2000 0e peak values (50 c.p.s.). Concerning varve records, the samples are usually too thick to give a good registration of the magnetic variations between the single varves and verve units.

Fourteen of the Swedish cores were measured (every 2 cm) in Newcastle upon Tyne on the Digico long core magnetometer system, later to be completely analyzed (demagnetization and inclination). This technique is very useful for studying the annual and inter-annual magnetic variations in varves.

RESULT

The location of the sites in Scandinavia studied paleomagnetically is given in Fig. 1. Core B 873, which is partly varved, is fully described (Mörner, 1973, 1976). Cores B 890, 891 and 893, all consisting of varved clay, are discussed separately (Mörner 1975c). The secular Holocene magnetic variations are illustrated by the records from the long cores B 903 and 907 (Mörner 1975a, Figs. 5-6).

Figs. 2-4 give the intensity and declination records of cores B 893, 908 and MLL-20, all being measured at 2 cm intervals on the Digico Balanced Fluxgate Magnetometer system. The first column gives the varve measurements: every single varve when the varves are thick and every 5 varves when the varves are thin. The second column gives the division in core segments, because low intensity and irregular declination were found usually to be associated with these boundaries (due to drying at the tops and bottoms of the core segments and/or because the lateral intensity influence, which extends over some 5 cm, at the core ends decreases to zero from one side).

Core B 893 (Fig. 2) is 963 cm long and includes 156 varves deposited at around the boundary between the Vintapper Interstadial and the Low Baltic Stadial or zones Vi/LB at about 13, 150 yr BP (Mörner 1969, 1971). The Swedish Time Scale is not extended this far back in time and hence it is impossible to establish an absolute varve date. The intensity fluctuates with distinct peaks and bottoms occurring at approximately every 11 yr (the cycle-histogram shows a sharp peak at 10-11 yr), hence recording the sunspot cycle. The intensity variations within individual varves seem to differ in amplitude and seasonal position in the lower (varves 1-7) and upper (varves 130-156) parts. The declination is generaly reversed, which may be consistent with the chronological position within the irregular part one of the Gothenburg Magnetic Excursion (Mörner and Lanser, 1974; Mörner, 1975b). The declination record exhibits a sunspot cyclicity that is out of phase with the intensity cycle by about one half cycle. The declination record also includes typical scatter; rapid fluctuations related to low intensity. On a whole, this 156 yr record shows surprisingly large variations in natural remanent magnetism (intensity and declina-

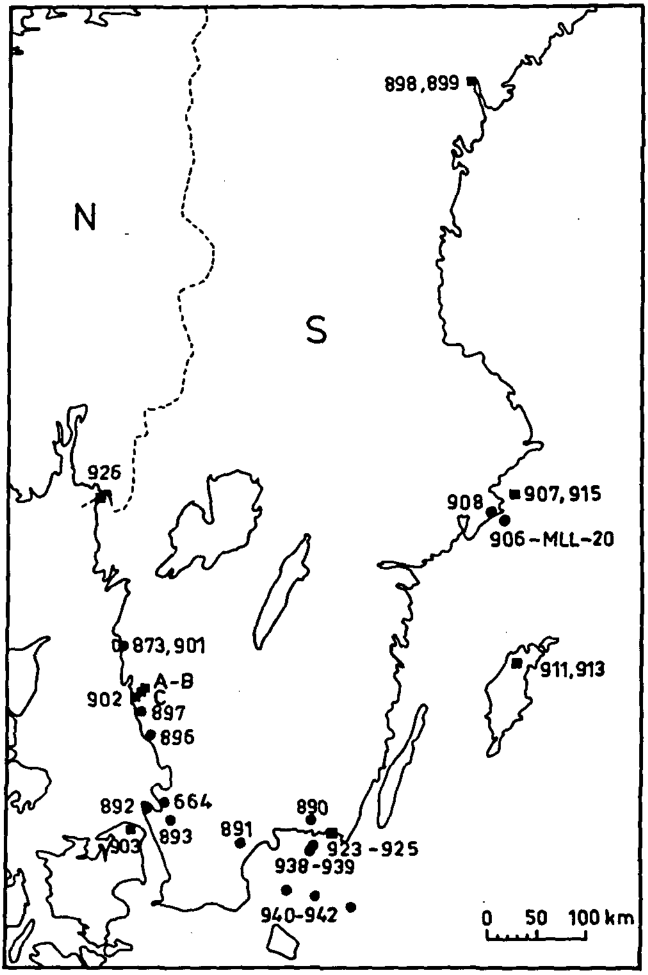

Fig. 1. Location of sites in Scandinavia that have been paleomagnetically analyzed by the author (often in collaboration with Lanser). Dots refer to Late Glacial (uppermost Pleistocene) sequences and squares to Holocene sequences. Core B 893, B 908, MLL-20 and B 906, and a thick varve in core B 892 are discussed in the present paper.

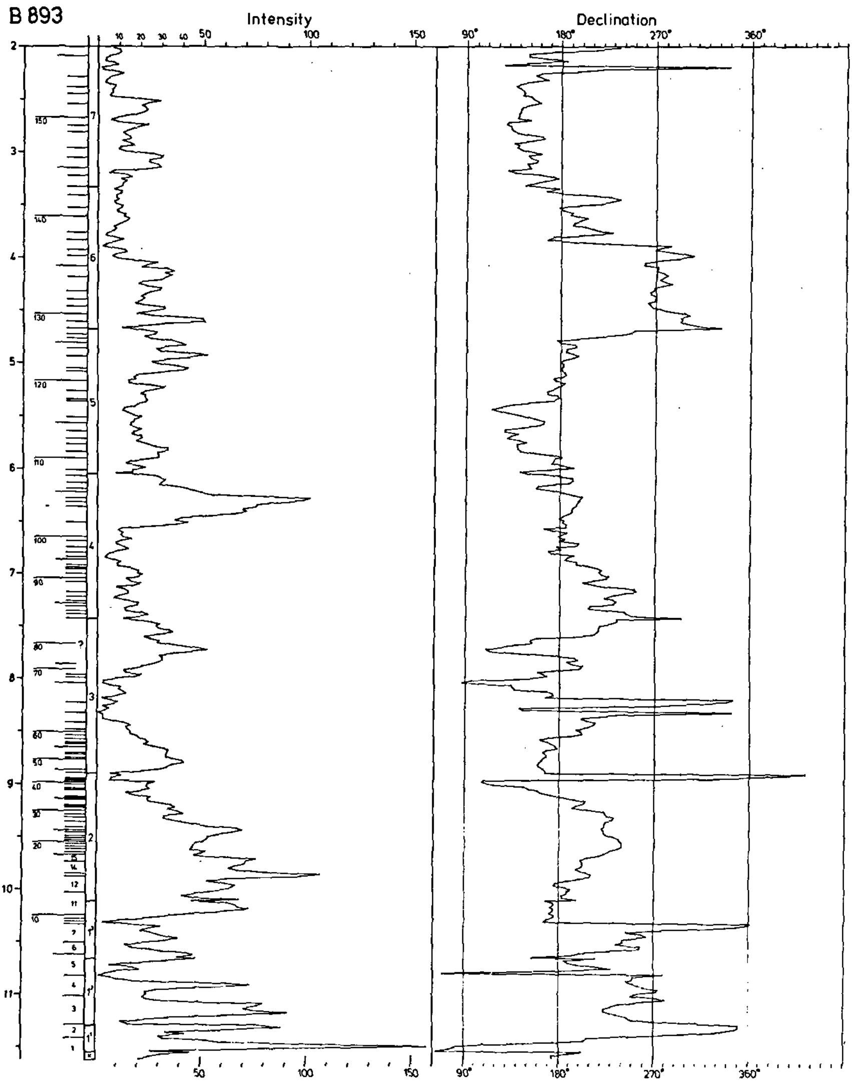

Fig. 2. Core B 893 includes 156 varves (noted in the left column) deposited at about 13,150 BP. Inclination and declination show a clear sunspot cyclicity (with the declination peaks and bottoms being out of phase with the intensity peaks and bottoms by about 5 yr, or half the sunspot cycle). This cyclicity must partly be the effect of the sunspot cycle on the ionization and partly the effect of chemical-physical environmental changes related to this cycle. The thick varves at the base and top record seasonal inter-varve changes. The declination is generally reversed (Mörner, 1975c).

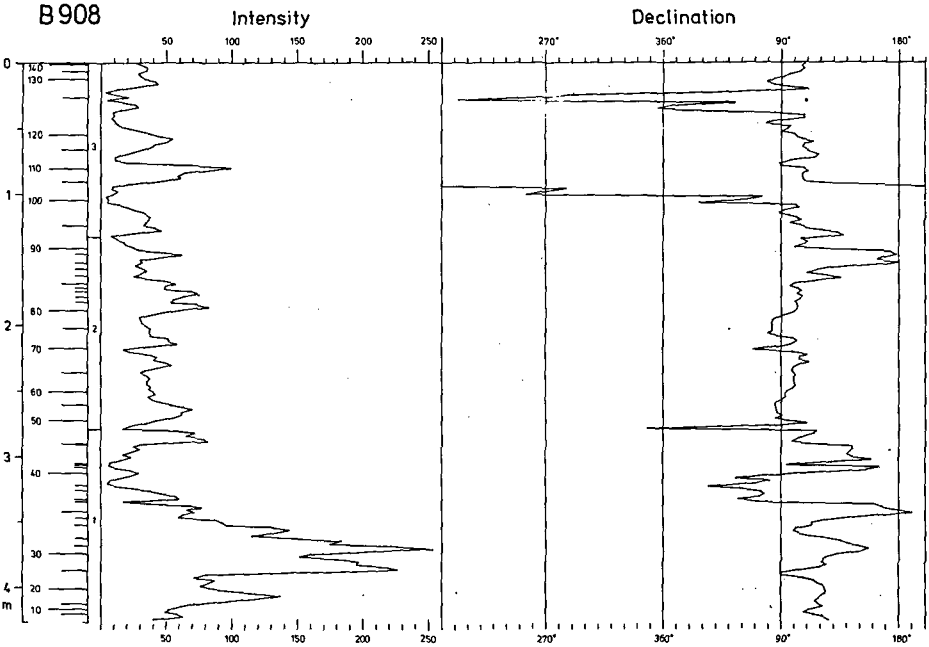

Fig. 3. Core B 908 includes 141 varves deposited 9,995-9,984 varves BP. The sunspot cycle is well registrered. The strong intensity peak in varves 16-38, "the Gålön Magnetic Intensity Maximum", is a marker of the Pleistocene/Holocene boundary and is also established in 14 other cores (Mörner, 1973, 1976).

tion). Many reported excursions in unvarved sediments do not exceed the amplitude of these sunspot cycle fluctuations.

Core B 908 from Gålön (Fig. 3) is 429 cm long and includes 141 varves, dated at varves -1102 to -962 in De Geer's Swedish Time Scale (De Geer, 1940) which corresponds to varves 9994 to 9854 BP (in another core from the same locality, the bottom varve was dated at -1307 or 10,199 varves BP). The suddenly increased varve thickness beginning with varve 30 corresponds to the drainage of the Baltic Ice Lake at varve -1073 or varve 9965 BP (Mörner, 1976, Chapter XX). There is a distinct intensity peak in varves 16-38 with the high-peak in varves 26-33 (the drainage ± 4 varves). This intensity peak has been recorded in 14 other cores and is found to be a useful marker of the Pleistocene/Holocene in southern Scandinavia (Mörner, 1973, 1976). The peak is termed the "Gålön Magnetic Intensity Maximum" (Mörner, 1976, Chapter XX) after the location of core B 908 where the peak is fully recorded and exactly dated. Besides the drastic peak, the intensity fluctuates rhythmically with distinct peaks and bottoms at approximately every 11 yr, hence recording the sunspot cycle. The declination swings around 90-120° with a less distinct 11-yr cyclicity (and two major departures at around varves 105 and 125).

Core MLL-20 from Ornö (Fig. 4) is 497 cm long and includes some 300 varves dated at varves -1394 to -1030 in the De Geer chronology and varves 10,286-9,922 in the BP-chronology. The intensity fluctuates fairly drastic with peaks and bottoms

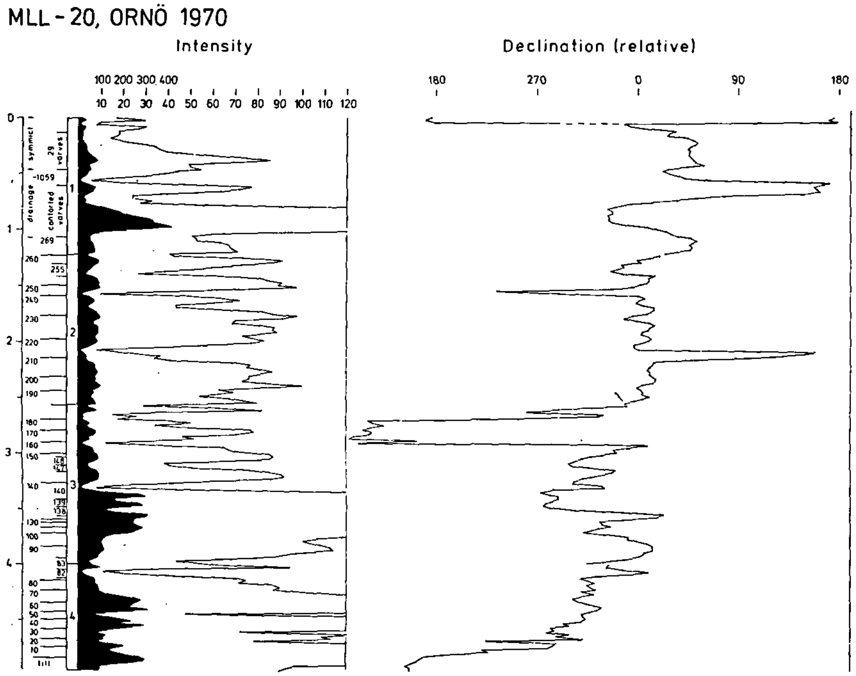

Fig. 4. Core MLL-20 includes some 300 varves deposited 10,286-9,922 varves BP. The intensity is shown in two scales (the scale of the black curve being ten times larger than the other). An 11-yr cyclicity is recorded. The declination curve also record a continuous eastward shift and additional large fluctuations. In varves 160-180, there is a distinct (reversed) westward swing, "the Ornö Declination Departure", which is also found in 8 other cores.

occurring at approximately every 11 yr (the cycle-histogram is broader than in the case of B 893 and B 908). The declination records a similar 11-yr cyclicity besides a continuous eastward shift and additional larger fluctuations, including the distinct (reversed) westward swing in varves 160-180. The reversed swing - also recorded in 8 other cores - occurs 150 ± 10 yr before the Pleistocene/Holocene boundary and is termed the "Ornö Declination Departure" after the location of this core (Mörner, 1976, Chapter XX).

In thick varves (proximal varves, drainage varves, etc.) it is possible to study the seasonal inter-varve changes. The magnetic changes within single varves are illustrated by Figs. 5-7, representing proximal varves in core B 893, thick varves in core B 906 and a drainage varve in core B 892. Because of the differences in summer and winter ionization in the atmosphere above high latitudes, one may suspect that summers correspond to higher intensity and winters to lower intensity. Therefore, intensity peaks within single varves have been correlated with summers (S) and intensity bottoms with winters (W) in Figs. 5 and 6.

Fig. 5 gives the intensity variations in the lowermost 15 varves in core B 893 (cf. Fig. 2). The varves consist of silt with some coarser parts (dotted) and clay (black

B 893 Magnetic intensity in varves 1 - 15

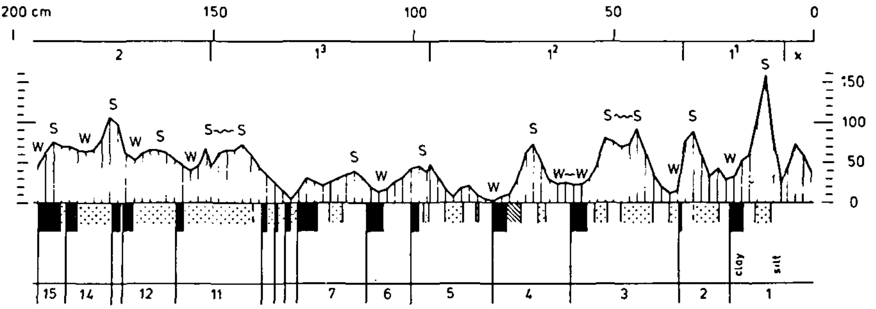

Fig. 5. The intensity variations in varves 1-15 in core B 893 show a clear annual cyclicity that is independent of the sedimentological variations within the varves (S = summer, W = winter). Varvity: black = clay, white = silt, dots = coarser. The recorded cyclicity is a combined effect of real seasonal ionization changes and seasonal chamical-physical environmental changes (pH/Eh, temperature, main circulation).

in Fig. 5) thought to represent the winter. The number of magnetic intensity cycles corresponds very well with the number of varves. There is no systematic relation between varve units and magnetic results. Instead, the peaks and bottoms appear differently from varve to varve, indicating that the subunits of the varves were not as strictly tied to certain seasons as generally believed, especially not the subunits of the proximal varves. Nevertheless, the intensity record shows a clear annual cyclicity that agrees with the varve record. This means that paleomagnetism can be used to decipher annual portions in sediments.

Fig. 6 gives the intensity fluctuations in the first five varves in core B 906 and the corresponding division into varves and subunits of the varves. The intensity cycles correspond to the varves. The intensity peaks and bottoms, however, do not show a strict correlation with coarser "summer" units and finer "winter" units. The magnetic intensity cycle probably gives a better record of the seasonal changes than do the grain size variations within the varves. Consequently, paleomagnetism can be used to increase the understanding of the deposition of single varves and varve units. Varves 1-3, dated at varves -1071-1069 or 9963-9961 BP, have an exceptionally high intensity and represent the aforementioned "Gålön Magnetic Intensity Maximum" (Mörner, 1976, Chapter XX).

Fig. 7 gives the complete magnetic analyses of varve 432, a 42 cm thick drainage varve, in core B 892. Eleven separate samples (126-116, plus half of 115) were measured from this single varve. The varve consists of sand, silt and clay (the clay being finest at the top). Consequently the magnetic variations in varve 432 could, a priori, be the effect of both true seasonal magnetic changes and sedimentological differences in the subunits. The intensity shows partly a continuous decrease from the thin varves below (127) to the thin varves above (115), and partly an annual cycle like those in Figs. 5 and 6 with high intensity (= summer) in the coarser lower portion and lower intensity (= winter) in the top portion. The inclination shows a low dip in the lower 2/3 of the varve and a steeper dip in the top portion. Totally, the inclination fluctuates within 50° in varve 432. The declination shows an eastward shift at the

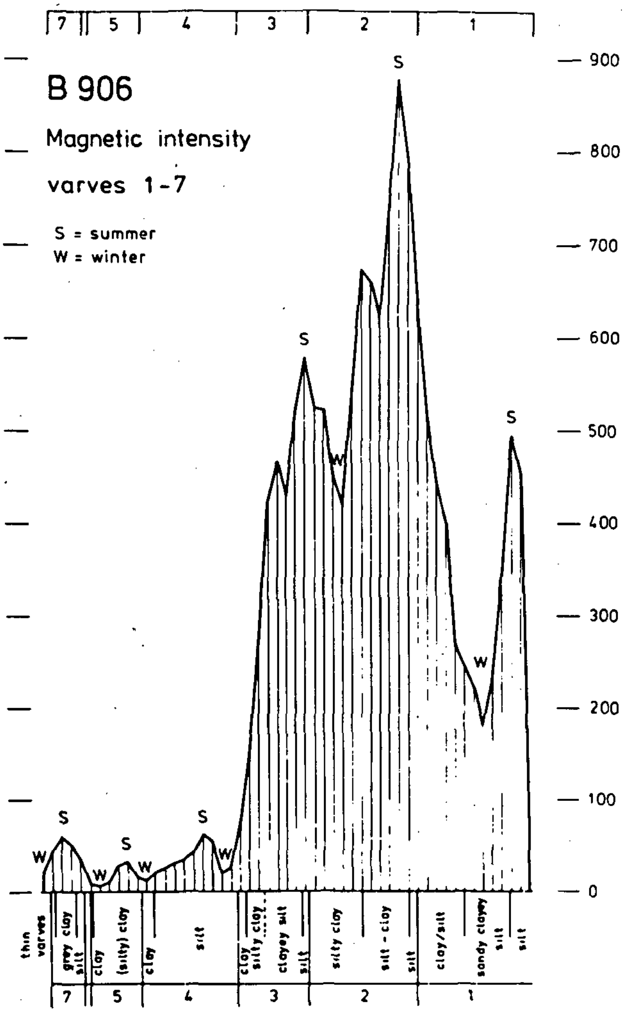

Fig. 6. The intensity variations in varves 1-7 in core B 906 show a clear annual cyclicity that is independent of the sedimentological variations within the varves and the strong intensity peak in varves 1-3 (reaching a peak of 878 x 10^{-6} emu/cc and representing the "Gälön Magnetic Intensity Maximum"). This cyclicity is quite similar to the one recorded in B 893.

base and a more western position in the upper 2/3 (the clay) of the varve. Totally, the declination fluctuates within 60°. Seasonal changes in intensity, inclination and declination are to be expected as a function of the seasonal ionization changes at high latitudes. The amplitude of the changes in varve 432 is too large, however, and must mainly be the effect of sedimentological-depositional variations. All three

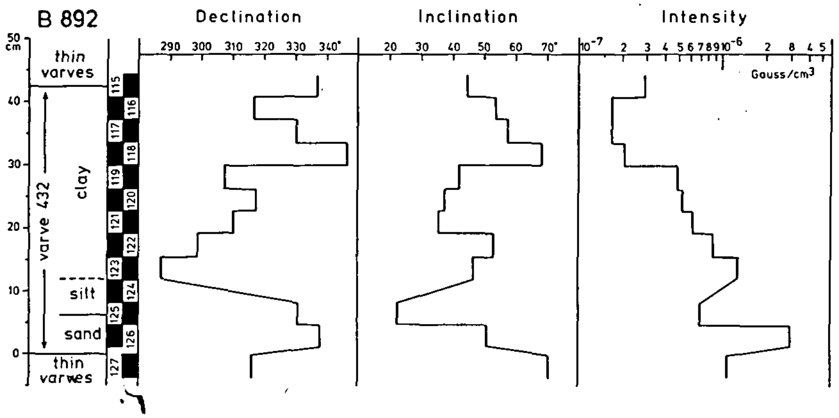

Fig. 7. Complete magnetic analysis of varve 432, a 42 cm thick drainage varve in core B 892. Black rectangles and figures give the stratigraphical position and number of the individual samples. All three magnetic curves exhibit seasonal fluctuations. These fluctuations must mainly be the effect of the different mode of deposition of the subunits of the varves, and of the grain size variations and seasonal velocity changes. The varve subunits of Agterberg and Banerjee (1969) are given at the right margin.

curves in Fig. 7 show a fairly drastic shift between samples 118 and 119, which may justify and threefold division of the varve like that proposed by Agterberg and Banerjee (*1969*, p. *647*): unit 1 = samples 126-124 (coarser), unit 2a = samples 123-119 (stagnating turbidity currents) and unit 2b = samples 118 to the top (slowly setting "winter" clay).

On the whole, varve 432 gives an extremely interesting record of the variations in remanent magnetism during the period of one year due to a combination of true annual cyclic changes, variations due to the grain size composition, variations due to the mode of deposition of the various units of the varve, and variations due to chemical-physical environmental changes. The amplitude of the recorded seasonal inter-varve fluctuations are surprisingly large. Many reported "excursions" in unvarved sediments do, in fact, not even exceed the amplitude of these cyclic annual fluctuations.

DISCUSSION

Our paleomagnetic records show fairly large fluctuations in intensity and declination during periods as short as 156 (Fig. 2), 141 (Fig. 3) and 300 (Fig. 4) varves or years. Even the records from single varves exhibit large fluctuations.

The declination records (together with the inclination records from cores B 873 and B 892 which give normal inclination, at least during the periods corresponding to the B 906 and 908 records) indicate a position of the dipole north or a dominant non-dipole maximum far off the geographical poles.

The fluctuations in core B 893 show a clear sunspot cyclicity, where the intensity lows and highs are out of phase with the declination lows and highs by some 5 yr, or half the cycle (in core B 908, however, the sunspot cycle in intensity and declination seems to be in phase). The establishment of the sunspot cyclicity is not surprising considering the present day instrumental records indicating a close correlation between the number of sunspots (and hence solar-flares) and the frequency of the magnetic storms. The amplitude of the recorded changes, on the other hand, is surprising and far too large to be solely the effect of the sunspot cycle itself. The amplitude of the recorded sunspot cycle is about 30-80 units in intensity and 60-120° in declination. At present, it is very difficult to explain the cause of these changes. It must partly be a direct effect of the sunspot cycle and partly the indirect effect of some variations related to this cycle (e.g. chemical-physical environmental changes). Lithological and sedimentological changes cannot be responsible for this 11-yr cyclicity. At any rate, the recorded changes show the amplitude of the annual NRM fluctuations (regardless causation) that occur in sediments; a registration which should be remembered in the evaluation of supposed "excursions" and "secular variations" in invarved sediments.

These rapid and surprisingly large fluctuations during periods of about one century are interesting in comparison with, for example, the Gothenburg Magnetic "Flip" (Mörner and Lanser, 1974; Mörner, 1975b, 1977). The Gothenburg Magnetic "Flip", however, is quite another thing. It is a rapid polarity switch (with the VGP in the equatorial central Pacific) that is well documented by fully reversed inclination in all cores covering the Fjärås Stadial (Mörner, 1975 b, 1977) and that is established in numerous other parts of the globe, including New Zealand, the antipodes of Sweden (Mörner and Lanser, 1974).

With respect to the studies by Eddy (e.g. 1977) of the relationship between sunspot activity, atmospheric ^{14}C production and climatic changes, the identification of the sunspot cycle in paleomagnetic records may in the future perhaps even be used to study the frequency of past solar activity (i.e. sunspots). Periods like the Maunder Minimum may be identified and even used as paleomagnetic markers.

The thick varves analyzed separately (Figs. 5-7) reveal a clear annual cyclicity in intensity. The annual cyclicity of the thick varves in cores B 893 and B 906 is clearly independent of the sedimentological variations within the varves (Figs. 5-6). The annual changes in intensity, inclination and declination in varve 432 of core B 892, on the other hand, are linked to the sedimentological variations (Fig. 7).

There are several alternative explanations to the inter-annual cyclic changes in varves:

(1) A function of a true magnetic annual cyclicity due to the seasonal variations in the strength and distribution of the ionization layers in the upper atmosphere; especially at high latitudes. Recent instrumental measurements record cyclic annual fluctuations in intensity, declination and inclination, though of much smaller amplitude than those recorded in the thick varves.

(2) A function of the grain size variations, because the terminal modes of glacial comminution (the silt size) can be assumed to carry more magnetized fragments, and the annual velocity changes, because those fragments have a higher specific weight.

(3) A function of the physical deposition of the various subunits of the varves according to the model of Agterberg and Banerjee (1969, p. 647): (1) the coarse turbidity unit being strongly influenced by currents, (2a) the subsequent clay unit, representing rapidly setting particles in relation to the stagnation of the turbidity currents, also being quite strongly influenced by currents, and (2b) the uppermost clay unit being accumulated by slowly setting particles during calm conditions during the winter season.

(4) A function of seasonal pH/Eh changes leading to the formation of different

forms of iron precipitates with different magnetic properties.

(5) A function of seasonal temperature changes in the water possibly affecting the precipitation and the magnetization.

(6) A function of seasonal changes of the main circulation leading to inter-annual changes in provenance of the deposited particles.

The thick drainage varve 432 of core B 892 (Fig. 7) seems to be built up according to the model of Agterberg and Banerjee (1969, p. 647) and records magnetic fluctuations that are mainly the effect of changes according to points 3 and 2. Ising (1942, Fig. 8) demonstrated inter-annual fluctuations that were the function of grain size variations and seasonal velocity fluctuations (according to point 2).

The inter-annual cycle in cores B 893 and B 906 (Figs. 5-6) offers an explanation to the problems because (1) the changes are clearly independent of the lithological changes in the varves and the subunits of the varves, and (2) the seasonal changes are much larger than present day annual fluctuations as recorded with instruments. Consequently, we can in this case exclude points 2 and 3. Furthermore, point 1 cannot be the main factor because of the large amplitude of the intensity fluctuations (though, admittedly, the present amplitude may not at all be the same some 10,000-13,000 yr ago). Because ionization changes must at least be the main cause of the 11-yr cycle, it is reasonable to assume that the inter-annual intensity changes are at least partly the effect of seasonal ionization changes (at Lat. 56-59° N) according to point 1. Besides the seasonal ionization changes, there must be some other seasonal variation or variations to account for the recorded large intensity amplitude.

The inter-annual intensity cyclicity in cores B 893 and B 906 must, therefore, also be the effect of one or more of the variables in points 4-6. Geochemical analyzes of varves (e.g. Arrhenius, 1947) indicate that the pH/Eh fluctuated seasonally. The temperature must, of course, have changed seasonally, though its effect on the magnetization is hard to estimate. Seasonal changes of the main circulation may have played an important role in the case of cores B 893 and B 906 (in opposite to the lacustrine varves of B 892 and the varves of the Baltic Ice Lake analyzed by Ising) because the varves of core B 893 were laid down in the sea with heavy seasonal variations in the influence of fresh water and marine water, and the varves of core B 906 were laid down right after the drainage of the Baltic Ice Lake (in the Yoldia Sea) with heavy seasonal variations in the inflow of marine water to and the outflow of meltwater from the Baltic basin. At any rate seasonal chemical-physical environmental changes must have played an important role in the causation of the inter-annual cyclicity recorded in cores B 893 and B 906 (cf. Mörner, 1975d). This finding may have a wider implication as similar environmental changes lasting for longer periods (from several years to thousands of years) may cause corresponding apparent magnetic fluctuations that consequently do not record real changes in the magnetic dield (strength and direction).

Finally, the recorded distinct annual cyclicity is important, as it can be used in future works to test and decipher annual deposition of sediments.

CONCLUSIONS

(1) The Swedish foil piston corer, giving undistrubed and continuous 11 m long core segments, is excellent for taking oriented cores for paleomagnetic studies (the first core was taken in 1970).

(2) Varved clay is very suitable for paleomagnetic studies of annual and seasonal (in thick varves) magnetic fluctuations, and for exact dating of recorded marker

levels (e.g. the "Galon Magnetic Intensity Maximum" and the "Ornö Declination Departure").

(3) The Digico Magnetometer system records low intensity at the core ends.

(4) Three varve sequences covering 156, 141 and 300 varves (= years) and being of different age, reveal fairly large fluctuations in intensity and declination (NRM).

(5) The records show a clear sunspot cyclicity; the intensity lows (highs) being followed after some 5 yr by declination lows (highs) in core B 893 (whilst in core B 908, they seem to be in phase).

(6) The amplitude of the fluctuations in the sunspot cyclicity is often up to 80 units in intensity and 120° in declination (which is far too much to be the function solely of magnetic field changes in relation to the sunspot cyclicity). This cyclicity seems partly to be a direct effect of the sunspot cycle on the ionization and partly to be the indirect effect of some variable related to this cycle (probably chemical-physical environmental changes).

(7) Core B 908 records a distinct intensity peak in varves 16-38 (= varves 9979-9957 BP), which is also recorded in 14 other cores (e.g. B 906 and MLL-20) form southern Scandinavia and possesses a very precise marker level of the Pleistocene/Holocene boundary in this region.

(8) The magnetic (NRM) sunspot cyclicity exhibits annual fluctuations that are so large in amplitude that they in unvarved sediments may be confused with "excursions" and major secular variations.

(9) The inter-annual magnetic records from thick varves (Figs. 5-7) exhibit large seasonal fluctuations; i.e. an annual cyclicity.

(10) The annual magnetic intensity cycle may be used to decipher annual periodicity in sediments.

(11) The inter-annual magnetic fluctuations recorded in the thick drainage varve 432 of core B 892 are mainly the effect of the mode of deposition of the subunits of the varve, and of grain size variations and seasonal velocity changes.

(12) The inter-annual intensity cyclicity of cares B 893 and B 906 is clearly independent of the lithological-sedimentological changes in the varves. This cyclicity is the combined effect of real seasonal ionization changes and seasonal chemical-physical environmental changes (pH/Eh, temperature or main circulation).

(13) In analogy with the inter-varve records, chemical-physical environmental changes over longer periods may cause corresponding apparent magnetic fluctuations in sediments.

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