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Principal features (master curve) of geomagnetic field variations in Belorussia during the last 12 thousand years

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Abstract. This paper presents the results of the paleomagnetic studies of the Naroch and Svir lake bottom deposits in Belorussia. The objects of study were nine columns of lake-floor sediments, totaling 6.50 m in thickness, collected using a special-type core sampler which did not disturb the structure of the sample material. The absolute dating of the sediments was performed by a radiocarbon method using the macroremains of the organic matter (grass). The columns of the sediments were correlated using their absolute ages, lithologies, and magnetic susceptibility values. All sedimentary rock columns showed a good agreement of the inclination and declination components of the natural remanent magnetization (ChRM) distinguished in all sedimentary rock columns using alternative magnetic field cleaning. The data obtained for all rock columns were summed up to produce the composite curves of ChRM declination and inclination variation for the sediments of these lakes. These data were compared with the archeomagnetic and limnomagnetic data available for Central and East Europe. All records of the paleosecular geomagnetic variations (PSV) showed a good agreement in terms of the morphology of the ChRM declination and inclination. At the same time the sediments of the Belorussian lakes showed a systematically older age and the lower magnitudes of the ChRM declination and inclination variations compared to the other PSV records available. These effects can be explained by the presence of some postdeposition remanent magnetization (PDRM) in the sediments of the Belorussian lakes and by the addition of some “aged” carbon (without ^{14}C) to the lake from the surrounding carbonate rocks. The basic features of the geomagnetic field variations in Europe are discussed for the last 10–12 thousand years.

Introduction

The acquisition of information for geomagnetic field variations is among the fundamental problems of geophysics, which allows the geologists to solve some very important problems associated with the state and evolution of the Earth's core and core-mantle boundary [*Bloxham et al.,* 1989]. Of great interest are the geomagnetic field variations with periods of 10^2–10^3 years, which are caused by processes that operate in the deep geospheres [*Korte and Constable,* 2003]. Paleosecular geomagnetic variations (PSV) of such periods were discovered using historical [*Jackson et al.,* 2000], archeomagnetic [*Daly and Le Goff,* 1996], and limnomagnetic [*Mackereth,* 1971] data. The longest PSV records were obtained using the deposits of modern lakes, which had usually accumulated throughout the Holocene (the last 10–12 thousand years). By the present time about a hundred records of this kind have been obtained. Some of them reflect fairly reliably the geomagnetic field behavior during the Holocene and have been used to derive geomagnetic field models [*Constable et al.,* 2000; *Hongre et al.,* 1998; *Korte and Constable,* 2003]. Some of the models derived for the

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geomagnetic field and its secular variations, obtained from archeomagnetic and limnomagnetic data are far from being perfect ones [*Korte and Constable,* 2003]. This stems from a number of reasons, the most important of them being the small number of sites with high-quality records of declination (D) and inclination (I); the substantial distortion of PSV magnitudes and their morphologies at the expense of various processes operating in the sediments during their deposition and diagenesis, as well as in the course of drilling and collecting samples from the cores; the not sufficiently exact dating of the sediments because of the inability to account for carbon of different genesis; differences in the ages of ChRM and the sediments, caused by the effect of postsedimentation magnetization (PDRM).

Presented in this paper are the new curves of the paleomagnetic declination and inclination of the geomagnetic field in Belorussia, derived as a result of generalizing the PSV records in the sediments of the Naroch Lake [*Nourgaliev et al.,* 2003] and in the sediments of the Svir Lake [*Borisov et al.,* 2003]. Also discussed in this paper are the problems of the isotopic dating of sediments in modern lakes and of the PSV magnitude smoothing in the case of the PDRM effects.

Brief Description of the Study Objects

The Naroch Lake (54°51′ N, 26°51′ E) is situated in the northwestern part of Belorussia, in the zone of the typical topography produced by the Valdai glaciation. The Naroch Lake [*Yakushko,* 1971] is the largest lake of Belorussia, measuring 79.6 km^2 in area with an average water depth of 9 m, the maximum depth being 24 m. The lake has an isometric form and consists of two parts. Its southern part, as deep as 24 m, has a floor of complex topography. The bottom current operating there is responsible for the washout and redeposition of the sediments. The lake has a flat bottom topography in its northwestern part. In low-water periods these parts of the lake might have been almost separated, being connected by a narrow channel situated in the middle of the modern lake. The topography of the surrounding territory and the types of the water streams flowing into the lake suggest the poor addition of the terrigenous material into this basin. The paleobiological and lithological data suggest the following history of the water level oscillations in the lake [*Tarasov et al.,* 1996]: the water level was very low (1) from 13600 to 13150 years ago, varied from low to intermediate one (4) from 13150 to 10900 years ago, had a low level (2) from 10900 to 9500 years ago, had a high level (6) from 9500 to 8500 years ago, had an intermediate level (5) from 8500 to 5120 years ago, had a very high level (7) from 5120 to 3850 years ago, a relatively low level (3) from 3850 to 2360 years ago, and a high level (6) from 2360 years ago to the present time. The figures in the parentheses denote the numeric values of the Naroch Lake relative level after [*Tarasov et al.,* 1996]. In terms of lithology this lake is of interest as an intracontinental basin of intensive carbonate accumulation. All sedimentary material is highly calcareous, being represented mainly by calcareous gyttia, except for the lower part which includes a layer of calcareous sand overlain by highly calcareous clay (almost marl).

The Svir Lake (54°47′ N; 26°30′ E), located 15 km southwest of the Naroch Lake, has an elongated shape which suggests that this lake might have been a well-drained basin at some periods of time. At the present time the lake is 18 km long, its width varying from 1.5 km to 3 km with the maximum water depth of 8 m. The lake floor topography has a simple U-shaped form. The territory surrounding the lake is fairly flat with minor elevations, less than a few tens of meters high, yet the river and springs flowing to the lake carry significant amounts of terrigenous material. In contrast to the sediments in the Naroch Lake, the sediments in the Svir Lake are poor in carbonate and consist of sapropel with the high content of organic matter. The maximum thickness of the sediments is 7–8 m. The rock sequence begins with dark green compact clay which is overlain by sapropel (organic mud) with the high content of argillaceous material at its base. The sedimentary material is not stratified, this precluding the visual correlation of the core samples in lithology. The top of the sedimentary material is distinguished by its patchy pattern. The sapropel color varies downward from dark green to almost black.

Sampling Procedure

Samples of lake floor sediments were collected using a piston corer designed and manufactured at the Kazan University [*Borisov,* 2000]. Used as a prototype was a piston corer which had been designed and used by F. J. H. Mackereth [*Mackereth,* 1958, 1971]. The Borisov corer is equipped with a bell-shaped sucking disk used to fix the tool at the lake floor. After the lowering of the tool to the lake floor, the bell is hermetized and calls for a significant effort to tear it off from the lake floor. Attached to its upper hole is an outer pipe with an internal movable pipe inside. The top of the outer pipe is hermetically closed by a lid to which a steel line is connected to fix the piston inside the movable pipe at the level of the upper end of the bell. Fixed to the top of the movable pipe is a piston with collars. After this equipment is fixed at the lake floor, the compass located in the upper part of the bell is arrested. The compressed gas is fed into the top of the outer tube, and the piston is lowered, together with the mobile tube, until the piston reaches the lower part of the outer pipe where it joins the bell, and the whole of the mobile tube enters the lake floor sediments. Thanks to the presence of a fixed piston the sedimentary material enters freely into the mobile pipe and does not fall out of it during its lifting. This sampling device differs from the known analogs [*Mackereth,* 1958] by the fact that after the inner pipe is driven into the rock material it can be drawn into the outer pipe again by delivering compressed air into the lower segment of the outer pipe equipped with a special coupling. This is an important advantage of our sampling device compared to the Mackereth sampler which can collect core samples 6 m long only in the lakes with the water depth not less than 6 m, whereas our sampling device does not require any

Table 1. General characteristics of the core samples examined in Naroch and Svir lakes

Column no.	Coordinates	Depth of water, m	Core column length, m	Number of samples
Naroch Lake N-1	54°50′28.6″ N 26°45′18.7″ E	19.9	5.85	287
Naroch Lake N-2	54°52′20.55″ N 26°42′05.9″ E	14.8	5.88	286
Naroch Lake N-3	54°50′25″ N 26°45′20″ E	20.4	4.18	200
Naroch Lake N-4	54°52′20″ N 26°42′10″ E	12.7	5.44	267
Naroch Lake N-5	54°52′20.25″ N 26°42′12.54″ E	12.8	4.09	200
Naroch Lake N-6	54°50′27″ N 26°45′10″ E	20.8	4.06	196
Svir Lake S-1	54°47′02.50″ N 26°30′15.8″ E	6.4	6.23	305
Svir Lake S-2	54°46′48.80″ N 26°30′18.7″ E	6.5	6.34	309
Svir Lake S-3	54°47′15.92″ N 26°29′34.8″ E	6.6	6.50	316

limitations of this kind. It can be used in shallow lakes with a water depth of 1.5–2 m. The pressure, not higher than 15–20 atmospheres, is usually created in our system using cylinders filled with some compressed gas (air, CO_2, and the like). However, recently, like in the case of the project described in this paper, we used a hydraulic system for intruding the inner pipe into the rock material and its subsequent removal. This system prevents the sediment from deformation and is more safe. To prevent the rotation of the mobile tube in the course of its sinking into the ground, this tube has a figure profile, conformable with the form of the piston cup. This simplifies the orientation of the core in terms of its inclination because of the fixed positions of the compass and the profile on the tube. After this equipment is raised to the ground surface the internal pipe with the core is removed and placed into a horizontal position and the cores are squeezed out of the pipe through its upper part using a special device. The upper segment of the pipe is equipped with cutters which cut cubes with a side of 20 mm from the central part of the core samples, each cube passing immediately into a nonmagnetic (polystyrene) container. This container is marked, closed, and hermetized. All cubes are placed into hermetic plastic bags and are transported carefully to the laboratory. As a rule several core columns are collected in each lake for laboratory and paleobotanic studies and 1–3 columns for paleomagnetic analysis. The Naroch and Svir lakes were investigated in 1997. Twelve columns of their bottom material cores were collected, nine of which were used for paleomagnetic studies (Table 1). The positions of the core samples in the lake were determined using a GPS receiver, the water depth was measured using an echo sounder. The rock material that remained after collecting cubes for isotopic analysis was used to carry out paleomagnetic analyses. The surface of the core remains was removed using a clean knife and placed first into aluminum foil and then into a hermetic plastic packet. The core lumps were usually 4–6 cm long.

Laboratory Studies

After their transportation to the laboratory the rock samples were stored during 1–3 months arranged in the position "along the field" in order to keep the values and directions of their remanent magnetization as close as possible to their natural state. Their magnetic susceptibilities were then measured using a KLY-1 instrument, and their natural remanent magnetization (NRM) (module and direction) were measured using a JR-4 magnetometer. The NRM values of the samples varied from 0.67–79.4 mA m^{-1} to 0.94–97.6 mA m^{-1}, and the values of magnetic susceptibility varied from 1×10^{-6} to 268×10^{-6} SI units and 2.75–153.8×10^{-6} (after correcting for the magnetic susceptibility of the plastic bags) for the sediments of Lake Naroch and Lake Svir, respectively (Figure 1). Prior to these measurements the rock samples were demagnetized using an alternating magnetic field and 3 to 5 samples from each core column from different rock layers differing in magnetic susceptibility. Demagnetization was carried out using intervals of 5 mT to the maximum value of 60 mT. The NRM trend was almost invariable in the course of the magnetic cleaning. The average NRM destruction field was 20–40 mT. The minor NRM viscous component was removed by the effect of the alternating field with a magnitude of 15–20 mT, which was discovered by slight bends in the vector demag-

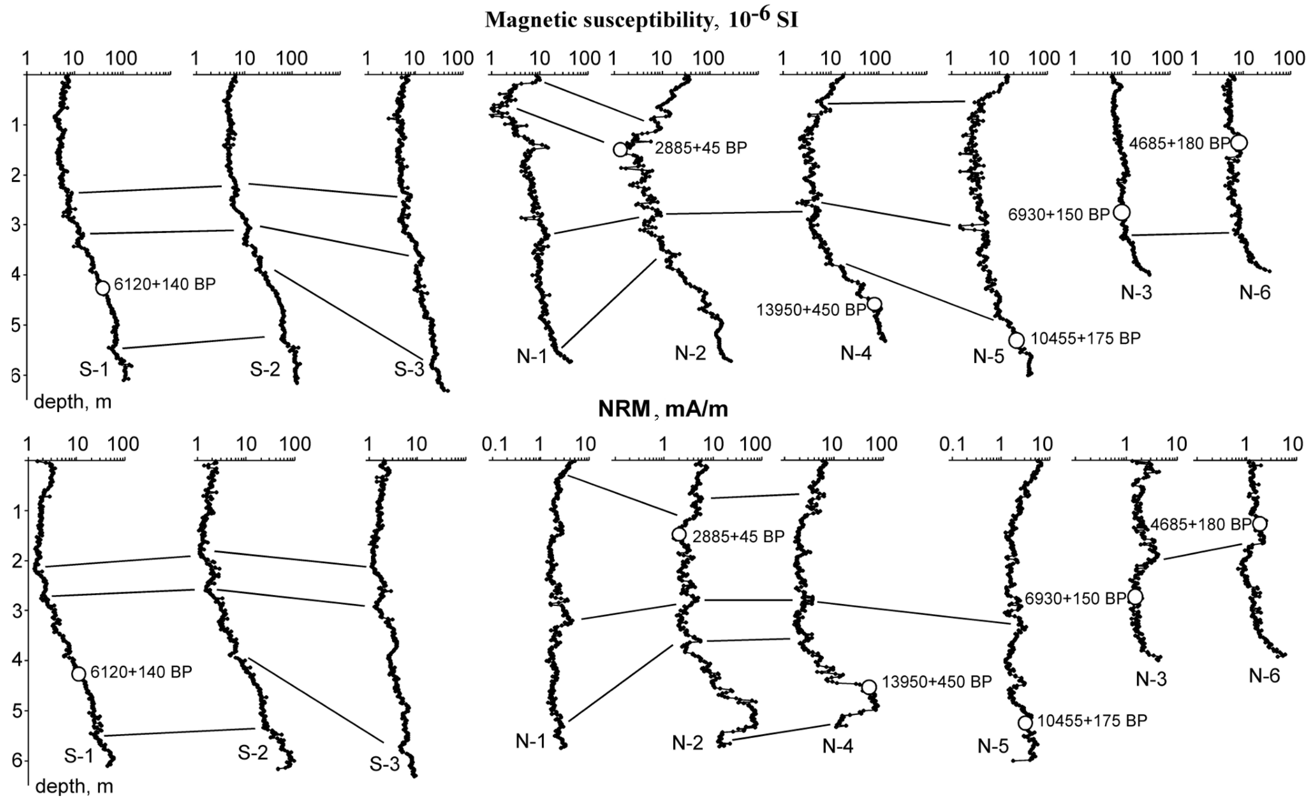

Figure 1. Magnetic susceptibility variation of the module of the natural remanent magnetization (NRM) in the sediment cores collected from the Svir Lake (S-1, S-2, and S-3) and from the Naroch Lake (N-1, N-2–N-6). Marked in the curves are the sites of collecting cores for radiocarbon dating and the calibrated radiocarbon ages of the sediments. The limes show the correlation of the rock column segments using the characteristic peaks of the magnetic parameters.

netization diagrams. As a result of these tests, magnetic cleaning with the maximum value of the magnetic field being not higher than 20 mT was chosen for detecting ChRM. The minerals carrying natural remanent magnetization were studied using the curves of normal remanent magnetization and the methods of thermomagnetic analysis using the normal remanent saturation magnetization (J_{rs}) and saturation magnetization (J_s) in the field of 200 mT. All measurements were made using original instruments [*Burov et al.,* 1986]. These measurements proved that the saturation field of normal remanent magnetization was not higher than 100 mT. These values are characteristic of "magnetically soft" minerals, such as magnetite and magnetic iron sulfide (greigite) [*Snowball,* 1991]. The small sizes of the specimens allowed us to get thermomagnetic curves $J_s(T)$ at a high heating rate (100 grad min^{-1}) (Figure 2). Almost all samples showed higher magnetization after the heating and cooling of the specimens: $J_{s2}(T_0)/J_{s1}(T_0) = 0.87$–15.2. The $J_{s1}(T)$ curves showed that beginning with the temperature of 450°C inductive magnetization began to grow (or its decline slowed down in some cases), caused by the formation of magnetite from other iron-bearing minerals [*Burov et al.,* 1986]. Usually,

Table 2. Isotopic dating of the core samples

Column no.	Laboratory no.	Depth of sample in the column, m	Depth correlated with column N-2, m	Directly calculated isotopic ages using ^{14}C values, in years ago	Calibrated isotopic ages, in years ago
N-2	ETH-18632	1.42–1.50	1.42–1.50	2720±50	2868±70
N-3	ETH-18634	2.72–2.80	3.42–3.46	6045±60	6930±140
N-4	ETH-18639	4.60	4.90	11890±90	–
N-5	ETH-18640	5.32	4.14	9235±70	10243±160
N-6	ETH-18641	1.28	2.60	4105±70	4633±150
S-1	ETH-18642	4.22–4.30	3.19	5320±60	6085±95

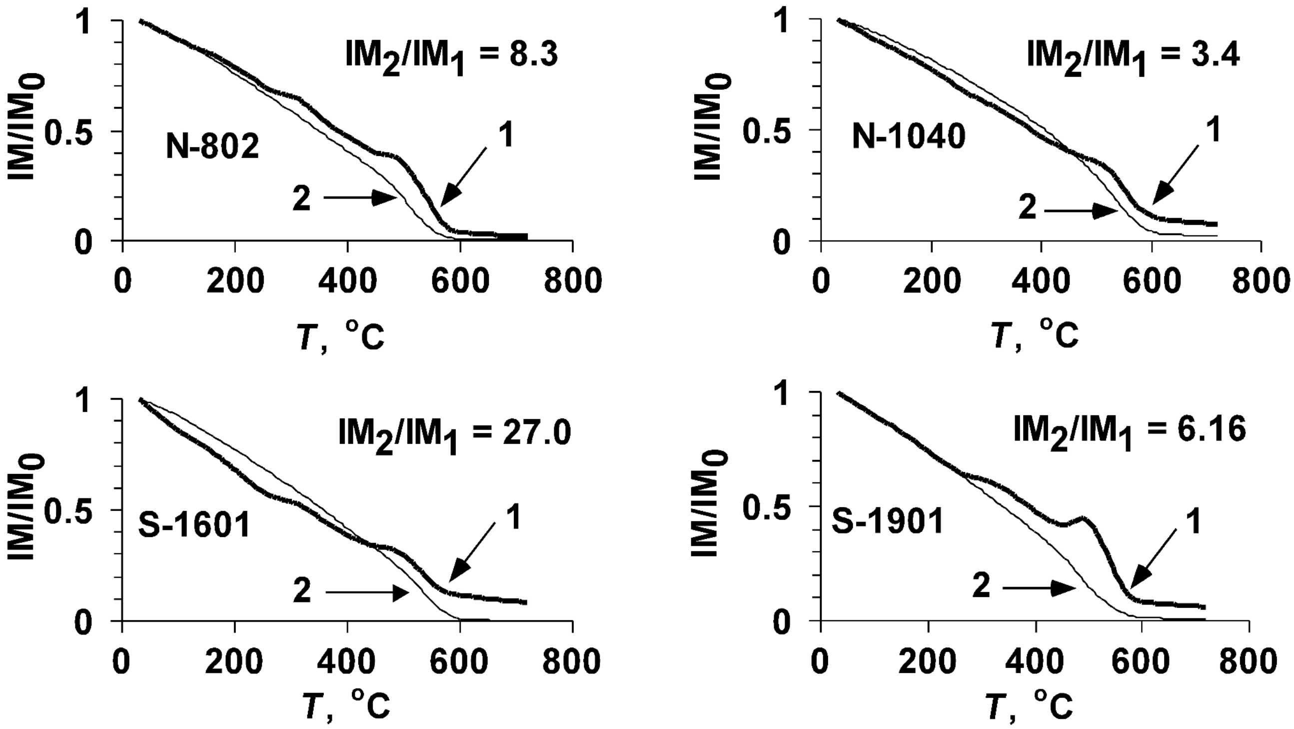

Figure 2. The thermomagnetic curves plotted for the induced magnetization in the pressure field of 0.2 T of the rock samples collected in the Naroch Lake (N-802 and N-1040) and in the Svir Lake (S-1601 and S-1901). The curves of the first (1) and second (2) heating were normalized using the maximum magnetization value. Shown for each sample is the ratio between the induced magnetization values at room temperature in the field of 0.2 T before and after the heating to 700°C.

where organic matter was present, heating resulted in the reduction of iron and in the formation of magnetite. Moreover, all curves showed a very weak yet clearly recorded change of $J_{s1}(T)$ in the temperature range of 260°C–300°C which is typical of magnetic iron sulfide (greigite). The $J_{s2}(T)$ curve showed a mineral phase with the Curie temperature of 570°C to 580°C and a small knee in the curve in the region of 350°C–380°C. This behavior of the thermomagnetic curves in the temperature range of 260°C–380°C is typical of iron sulfides which are transformed to magnetic iron sulfide (pyrrhotite) and magnetite [*Burov et al.,* 1986]. Therefore, the primary magnetic minerals of the studied sediments were magnetite and possibly small amounts of magnetic iron sulfide (greigite).

The Age of the Sediments and Correlation of Their Core Samples

We reconstructed changes in inclination and declination in time using the data available (Table 2). We had six isotopic datings: one for each core column collected in the Naroch Lake area (except for the column N-1) and one dating for the S-1 core column collected in the Svir Lake.

The isotopic dating of the sediments was carried out at the Institute of Elementary Particle Physics of the Federal Technological University of Switzerland using an acceleration-type mass-spectrometer. The results of this work are presented in Table 2. The isotopic ages of the samples were calculated using the relative concentrations of ^{14}C in the rock samples. However, this dating is not correct, because the initial ^{14}C contents in the rock samples varied in time as a function of various factors. The correct dating could be performed using a calibration curve obtained as a result of using a large number of various methods, such as, the other types of dating, dendrochronology, varvometry, historical dating, and the like. In our case we calculated the isotopic ages using a calibration curve and the OxCal program [*Bronk Ramsey,* 1995]. This calibration curve has a fairly complex shape and can be used to find different versions for the most probable time intervals. Listed in Table 2 are the dates falling in the 2σ interval (with 95% falling into this time interval). We chose the time intervals of the highest probability.

An important stage of this study was the compilation of the composite curve of the paleosecular geomagnetic field variations (PSV) using all core columns that were examined in this study. The correlation of all core columns was performed in two stages [*Nourgaliev et al.,* 2003]. During the first stage we correlated the core columns using the lithological data available, that is, using the rock layers identified. The best correlation was achieved for the rock columns lo-

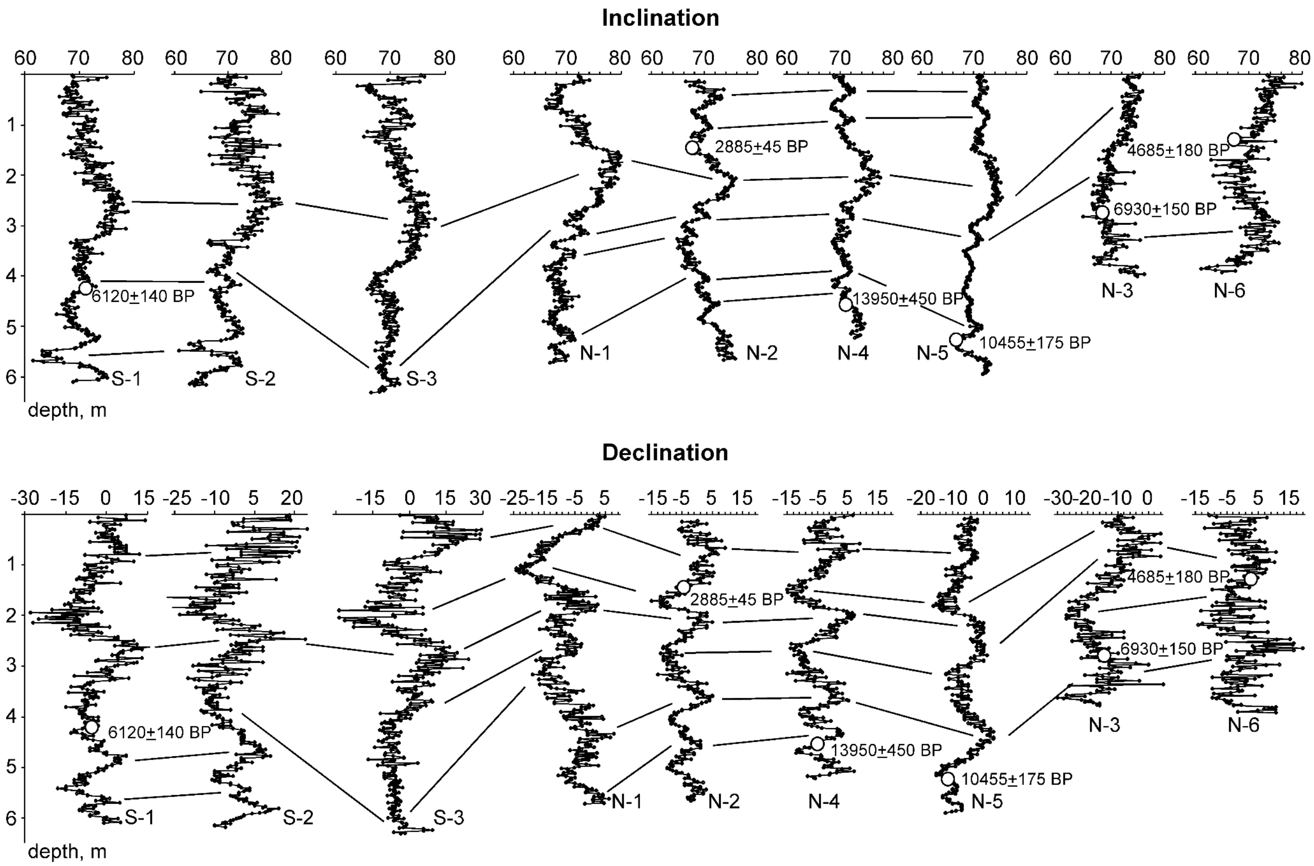

Figure 3. Variations of the ChRM inclination and declination of the sediments in core samples collected in the Svir Lake (S-1, S-2, S-3) and in the Naroch Lake (N-1, N-2–N-6). Indicated in the curves are the cites of collecting samples for the radiocarbon dating of the sediments. The lines mark the correlation of the core column segments in terms of characteristic peaks in the ChRM direction variations.

cated closely to one another. In the case of the Naroch Lake area we selected two groups of core columns (Table 1): in the southern deep part of the lake (columns N-1, N-3, and N-6) and in its northwestern basin (N-2, N-4, and N-5). The upper 4.5–5 m of the sediments did not show any visible layering and, hence, were correlated using changes in the rock color (from light greenish gray to dark green) and in some cases using their mottle color. It was only in the lower segment of the core column that we were able to carry out some correlation because of the appearance of distinct layering. At the second stage of our study we correlated the rock columns inside the layers using the magnetic susceptibility and NRM module values of the rock samples (Figure 1). The magnetic susceptibility of the sediments reflects directly changes in the sedimentary material accumulation (deposition rate, sediment type, and other parameters) and, indirectly, changes in the climate, environment, and other conditions), including the conditions of the sedimentary material burial. These conditions were found to have been very stable for the whole lake, and the events responsible for abrupt changes in magnetic susceptibility, to have been simultaneous for the whole sedimentary basin. This allows one to use magnetic susceptibility as a correct correlation basis. This is confirmed by the good correlation between the changes in the magnetic susceptibility of the rock samples between the sedimentary rock columns. The rock columns of the Svir Lake showed a good correlation in terms of their magnetic susceptibility values [*Borisov et al.,* 2003] (see Figure 1). These two lakes were correlated using the D and I variations (Figure 3). An additional correlation basis was provided by the isotopic dating of the core samples. As a result of their correlation, the depths of the core samples collected in different holes were recalculated using the N-2 column as a reference one. The data available for all columns were combined and used to plot the summarized inclination and declination variation curves (see I and D curves in Figure 4).

The Construction of a Time Scale in the Sedimentary Rock Columns

To represent declination and inclination variations in a time scale we used the isotopic age datings available (Table 2). We had six values of dating: one for each rock column in the Naroch Lake, except for the N-1 rock column, and one isotopic age value for the S-1 column of the

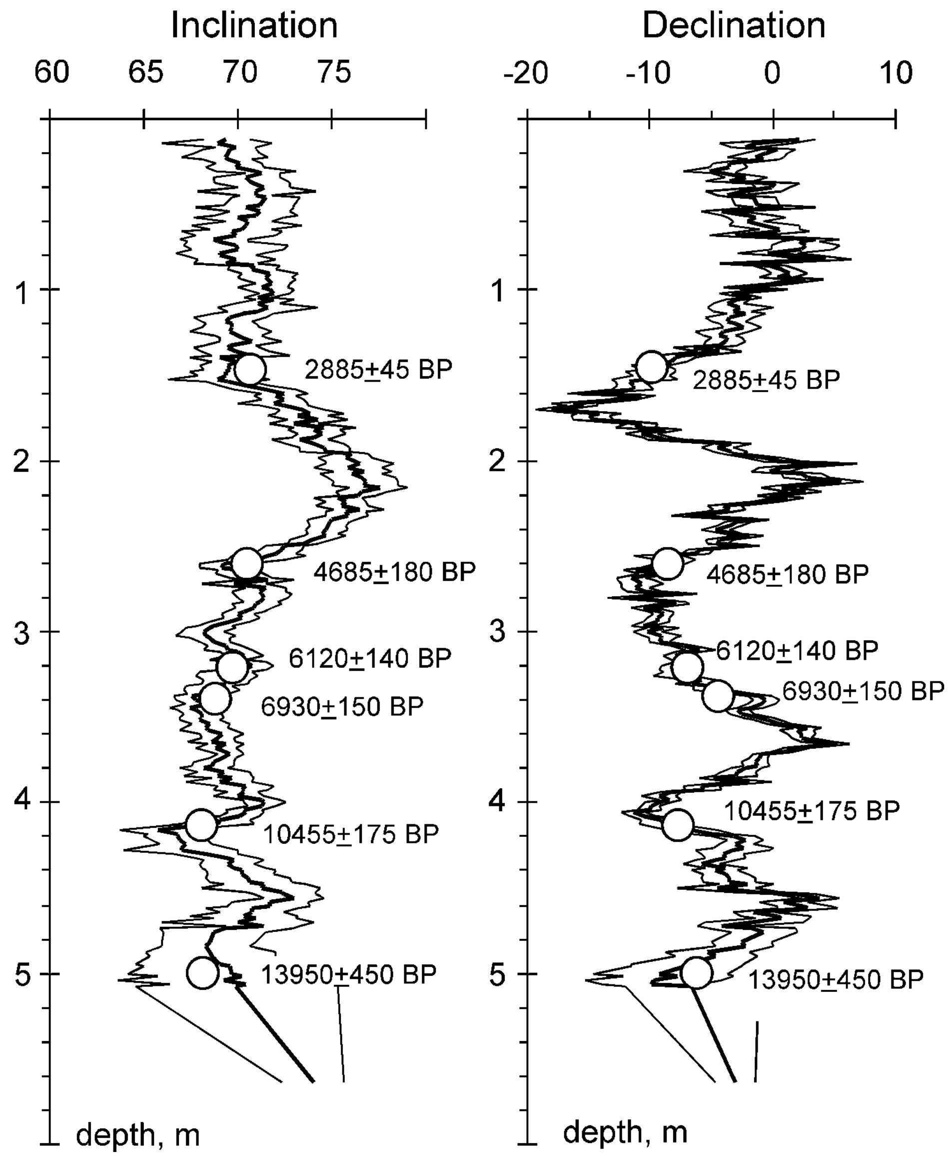

Figure 4. The generalized record of ChRM declination and inclination variations obtained from summing up all of the sample columns available for the Svir and Naroch lakes in the depth scale of the N-2 column. The thick lines show the average values, the thin ones, the $\pm\alpha_{95}$ boundaries.

Svir Lake. Proceeding from the results of correlating the magnetic susceptibility in the rock columns, all isotopic age datings were transferred to column N-2. In all cases this operation was correct because very distinct specific features were discovered in the magnetic susceptibility variation curve. This was also proved by the good correlation of the other parameters obtained from the core columns (Figures 1 and 3).

The uppermost date obtained from our rock columns was found to be 2885±45 years (Column N-2), that is, the age of the uppermost sediments remained undetermined. For this reason we found it be correct to correlate our records of the D and I variations with the archeomagnetic records available for the nearby regions of Bulgaria, Ukraine, Moldavia, Hungary, and also for France and Great Britain. In one of our previous publications [*Nourgaliev et al.,* 2003] we discussed the similarity of the basic features of the D and I variation curves recorded in the sediments of the Naroch, Plesheevo, and Aslikul lakes and those recorded in the archeomagnetic data available for West Europe [*Daly and Le Goff,* 1996]. The correlation presented in Figure 5 proves a significant similarity between the records obtained for the Naroch Lake sediments and the archeomagnetic data. It should be noted that the dating of the ETH-18632 sample (see Table 2), collected from a depth of 1.42–1.5 m, dated the sediments to be 2885±45 years old, whereas the correlation with the archeomagnetic data showed the magnetization age at this depth level to be about 2100 years (Figure 4). This is associated with the well-known phenomenon of the postsedimentation magnetization [*Verosub,* 1977]. The time shift

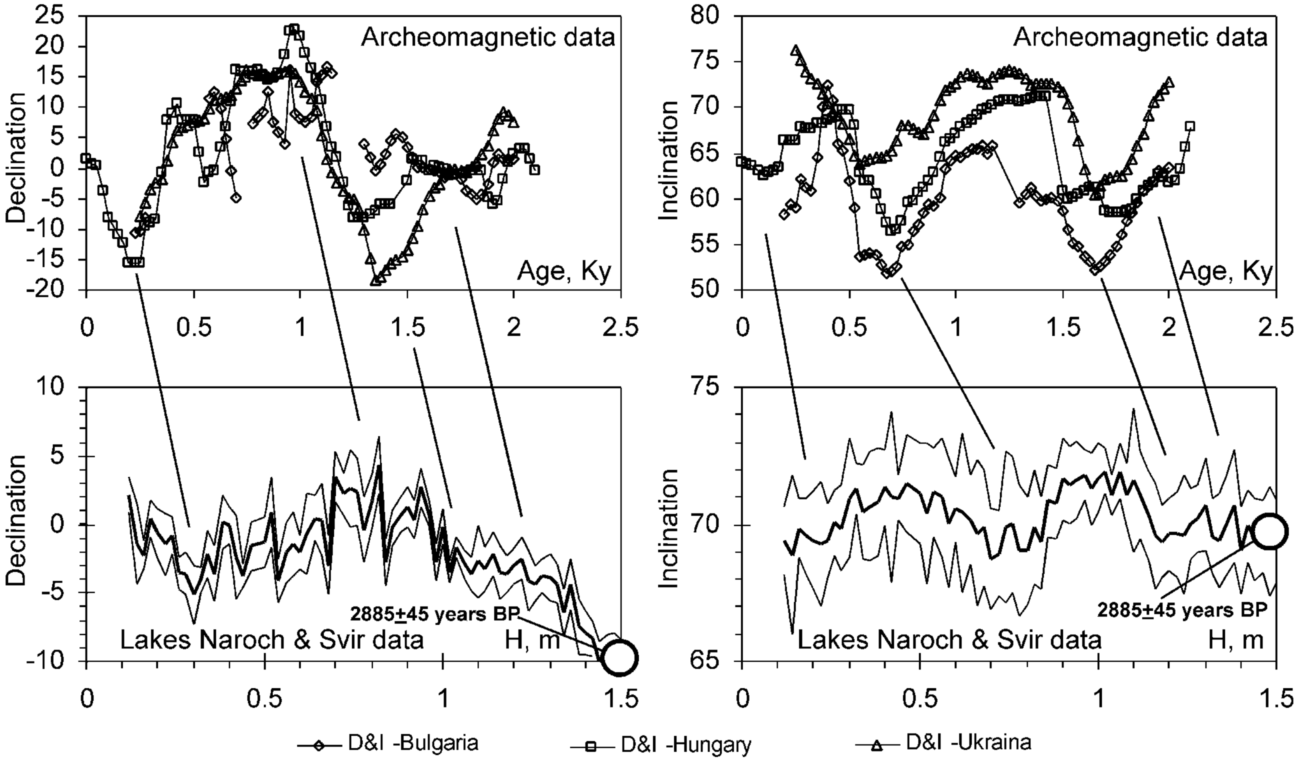

Figure 5. Comparison of the archeomagnetic data available for Bulgaria, Hungary, and Ukraine [*Daly and Le Goff,* 1996] with the generalized records obtained for the sediments of the Belorussian lakes. The bold lines in the ChRM declination and inclination variation curves show the average values, the thin lines, the $\pm\alpha_{95}$.

between the age of the sediment and the age of its magnetization is around 600–800 years or 40–50 cm (using the average sedimentation rate). The shift value as great as this was caused in this case by the fact that the sediment consisted mainly of a carbonate material which had been fixed, like its magnetization, at a significant depth [*Bleil and von Dobeneck,* 1999]. For these reasons, the estimate of the sediment age cannot be used directly to plot the geomagnetic parameter variation in time. This phenomenon is highly typical of the object discussed, yet, seems to be characteristic of other sediments. This calls for a necessity of introducing corrections for a difference between the age of the sediments and the age of their magnetization. We attempted to introduce corrections of this type using the data available for the ages of the PSV curve peaks, obtained for the objects located not far from Lake Naroch and Lake Svir (54°50′ N, 26°40′ E). The objects of our study were the archeomagnetic data available for East and Central Europe [*Daly and Le Goff,* 1996], the records available for the sediments of the Nautajarvi Lake, Finland (61°48′ N, 24°41′ E) [*Ojala and Saarinen,* 2002], and also for the sediments of some British lakes (53–57°N, 3–5°W) [*Turner and Thompson,* 1982]. Figure 6 shows the comparison of the records obtained for the sediments of the Belorussian lakes and for the sediments of the Nautajarvi Lake, Finland [*Ojala and Saarinen,* 2002]. Very good correlation was observed for the inclination variation and fairly good correlation was found for the declination variation with the exception of the period of 6000-4000 years ago (in the time scale of Lake Nautajarvi). One of the versions of our correlating the specific declination behavior is shown by a broken line in Figure 6. Worthy of mention, however, is a substantial difference (about 1500–2000 years) between the isotopic ages of the main PSV peaks was observed when the Belorussian records were compared with the master curve available for the British lakes (Figure 6), although the distance between these observation sites was different ($\sim 30°$ in longitude). In this case, too, the D and I curves showed a good agreement in their morphology, except for the time interval of 10000–6000 years ago (in the time scale of the British record), where the inclination variation showed a substantial difference in the magnitudes of different variations (Figure 7). This precluded any correct correlation of the Belorussian and British records [*Nourgaliev et al.,* 2003]. Using the above mentioned data we dated the major D and I variation peaks in the PSV records obtained for the sediments of the Belorussian lakes. The comparison of the absolute datings of the Belorussian lake sediments and the NRM age determined by the PSV correlation with the other records available (Figure 8) showed a substantial time shift between the magnetization age and the age of the sediments in the Belorussian lakes. The resulting PSV peak datings were used to plot a time scale for the summarized D and I variations using the Naroch and Svir lake sediments (Figures 9 and 10). It should be noted

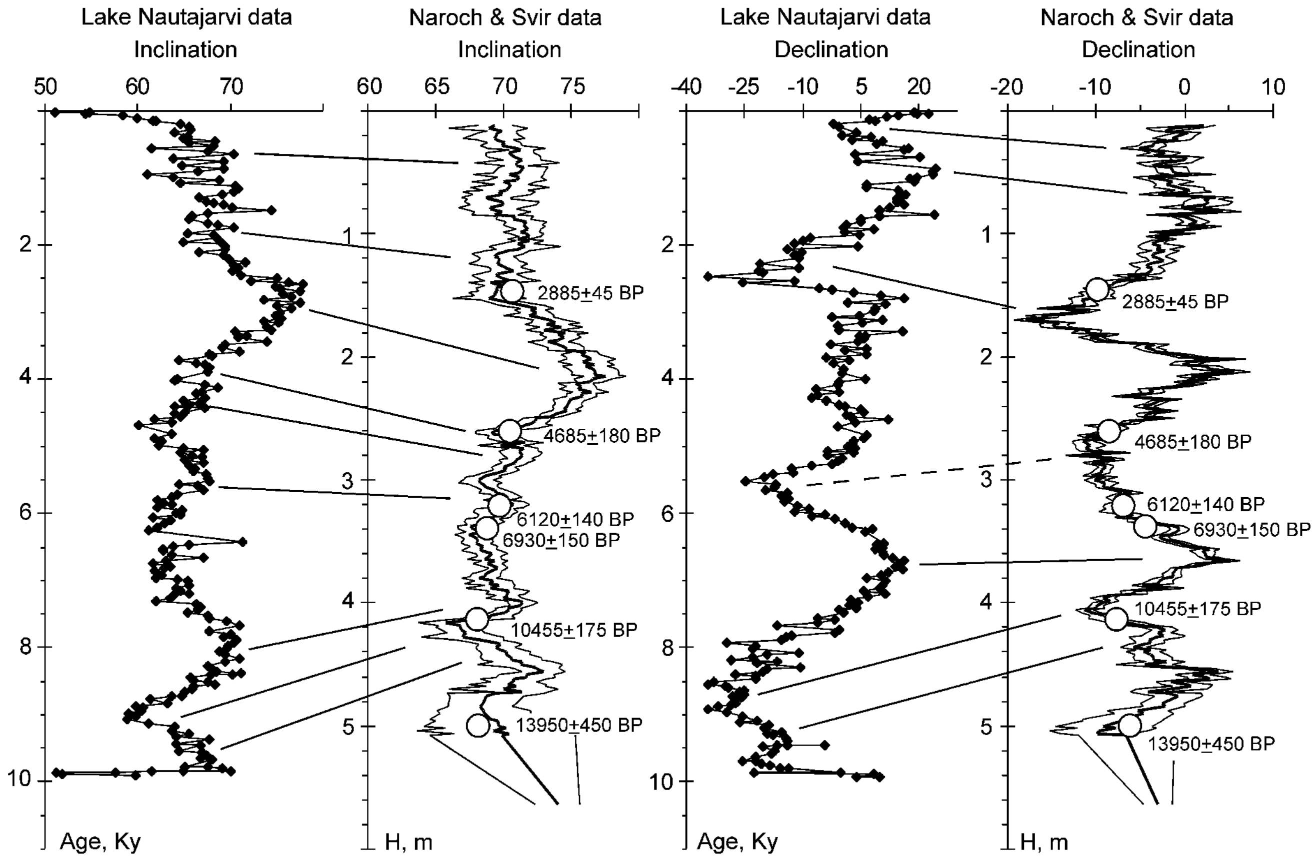

Figure 6. Comparison of the PSV records for the sediments of the Nautajarvi Lake [*Ojala and Saarinen,* 2002] and the generalized record for the Belorussian lakes, all reduced to the depth scale of the N-2 column, with the indication of isotopic age values for six depth levels. The lines show the regions of good correlation.

that the single dating available for the Svir Lake sediments resides between the generalized curves showing a relationship between the NRM age and the age of the sediments (Figure 6), this suggesting a difference between the physical properties of the sediments in the Naroch and Svir lakes.

Results of the Study

The good agreement of the D and I variations among all of the study rock columns, as well as with the records obtained for the other objects, including the archeomagnetic ones, suggests that the observed D and I variations had been most probably caused by the perennial secular variations (PSV) and represent their records for the last ~12 thousand years. We also compared the geomagnetic field variations recorded in our study with the records reported in the literature for the sediments in the lakes of northern Sweden [*Snowball and Sandgren,* 2002] and with the sediments of three maar lakes from the West Eifel region (Germany). The inclination variation trend (the inclination growth toward the present time) discovered in the British record, is not as distinct in the other records. All declination records (Figure 10) show good correlation, yet, have some fairly significant differences. For instance, in the time interval of 6000 to 4000 years ago, the record for the Belorussian lakes differs from the records of the nearest objects, such the Nautajarvi Lake and the North Sweden lakes. This difference seems to have been caused by a real PSV difference even at a distance as small as this. At higher latitudes, this inclination behavior is possible because of the relatively small value of the horizontal component of the geomagnetic field intensity. The declination recorded for the West Eifel lakes correlates fairly well with all of the other records in spite of the high noise level. This is the longest record of all records available, its lower part correlating well, both in inclination and declination, with the records obtained for the Belorussian lakes. It can thus be inferred that the ChRM variations, identified in this study in the sediments of the Naroch and Svir lakes represent the PSV records for the last 12 thousand years. Proceeding from the general similarity and some minor differences of the Belorussian lakes compared to the other European records available, it can be concluded that the PSV master curve obtained in this study can be used to model Holocene geomagnetic variations.

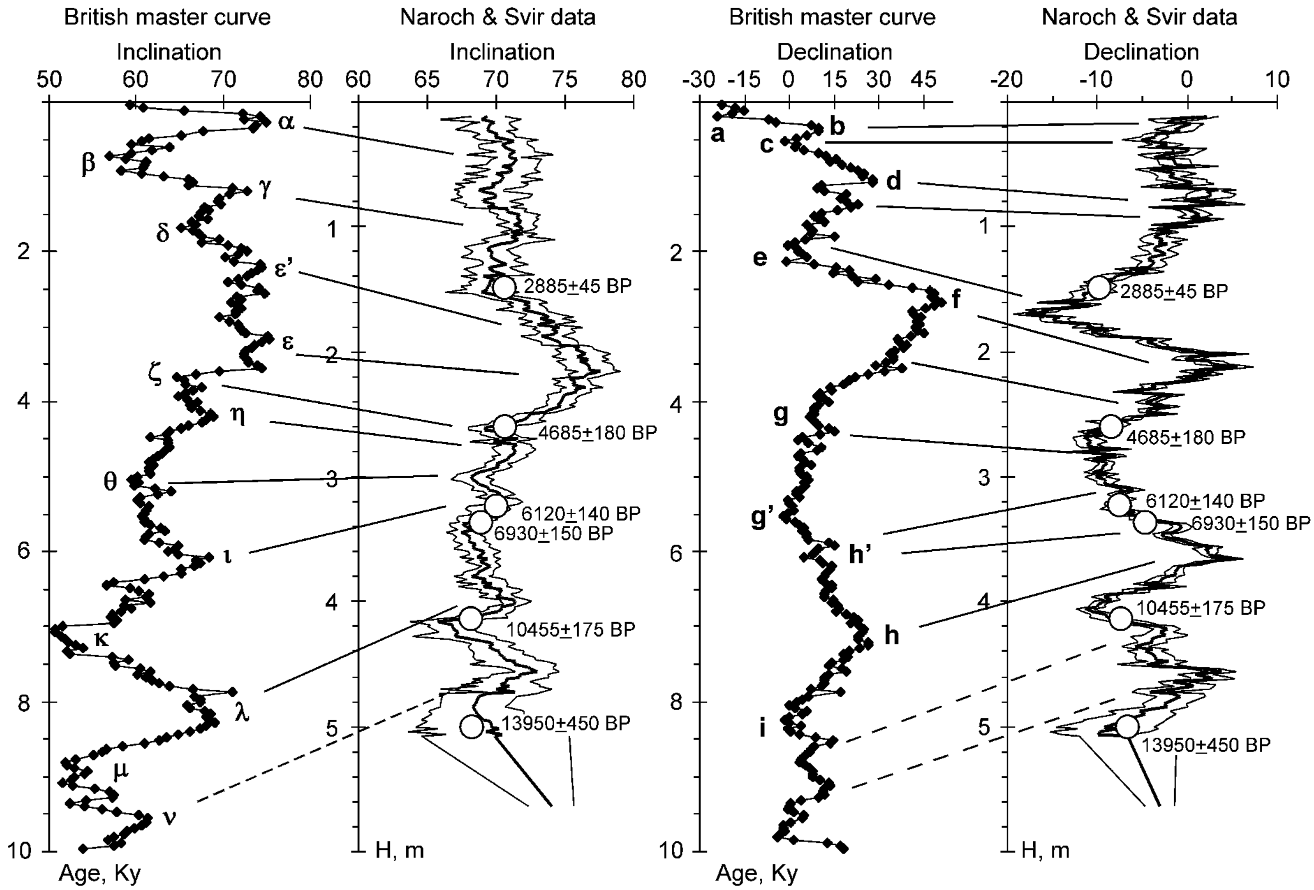

Figure 7. Comparison of the PSV records obtained for the sediments of some British lakes [*Turner and Thompson,* 1982] with the generalized record obtained for the Belorussian lakes, reduced to the depth scale of the N-2 core column with six levels dated by isotopic age determinations. The lines show the segments of good PSV record correlation.

Discussion of the Results

With a very good similarity between the PSV records obtained for the sediments of the Belorussian lakes and the data obtained for the other objects, our results show a substantial number of problems associated with the reconstruction of the PSV records obtained for modern lake deposits.

In the first place, this is the problem of ChRM dating. It has been demonstrated above that the ChRM age of the Belorussian lake sediments differs substantially from the radiocarbon ages of the sediments. The errors of dating the sediments of the Naroch Lake arise first because this lake water contains some "aged" carbon which is transported by ground and surface waters from the surrounding carbonate rocks. The lake plants the remains of which were used in this study for radiocarbon dating had used not only atmospheric carbon (CO_2), but also carbon from the water. As a result, the ^{14}C content in the organic remains turned out to be lower compared to the remains of terrestrial plants which absorb CO_2 only from the atmospheric air. As a result these plant remains show a higher radiocarbon age [*Deevey et al.,* 1954]. It follows that the radiocarbon dating of sediments should take into account the "effect of the water reservoir" (or the "effect of hard water") [*Deevey et al.,* 1954], especially in the lakes surrounded by carbonate rocks, and also in the lakes using subsurface water. The introduction of a correction for water hardness is a fairly complicated procedure [*Stiller et al.,* 2001] which can be used in very rare cases, where the evolution history of a basin is well known. Naturally, we could not introduce this correction in the course of our radiocarbon dating of the Naroch Lake sediments. Nevertheless, we can estimate the order of this value. The sediments of the Naroch Lake differ substantially in terms of their composition from the sediments of the Svir Lake because of its present-day carbonate accumulation. We can, therefore, assume that the "effect of hard water" in the Naroch Lake is greater than in the Svir Lake. Unfortunately, we have only one isotopic age dating for the Svir Lake sediments (Figure 8), yet, this date is actually ~350 years younger than that available for the Naroch Lake sediments and ~500 years older than the ChRM data obtained from correlating the Belorussian PSV curve with the records obtained for the other objects. This proves that at least ~40% of the difference between the ra-

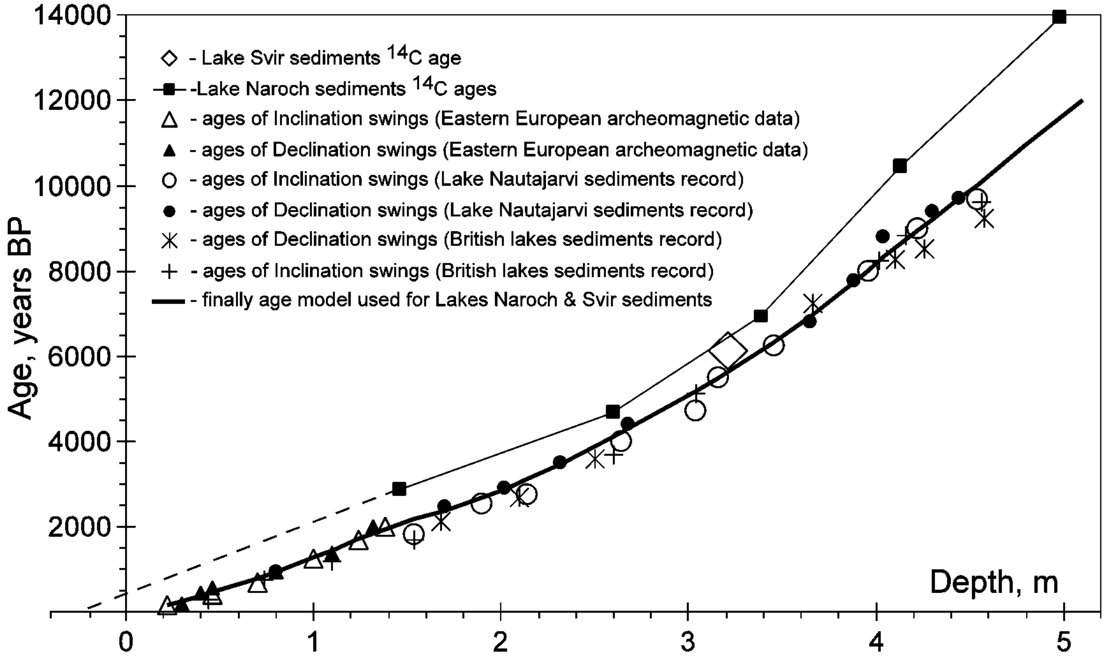

Figure 8. Variation of the radiocarbon age of the Belorussian lake sediments and their NRM age as a function of their depth in the N-2 rock column. The NRM age of the Belorussian lake sediments was obtained by correlating the generalized curve with the PSV records of archeomagnetic data available [*Daly and Le Goff,* 1996], with the records obtained for the sediments in some British lakes [*Turner and Thompson,* 1982], and with the records obtained for Lake Nautajarvi [*Ojala and Saarinen,* 2002]. The position of the radiocarbon dating curve is higher than that of the curve for the NRM age of the Belorussian lake sediments.

diocarbon age of the sediments and the ChRM age of the Naroch Lake sediments was produced by the "effect of hard water". The remaining part of the shift seems to have been caused by the fact that the bulk of the NRM, both in the Naroch and Svir lakes, has a postdeposition origin (PDRM).

Thus, we can now deal with the second problem discussed in this paper. This problem is concerned with the effect of the postdeposition magnetization (PDRM) of sediments on the character of the distortions introduced during PSV recording in the sediments. This problem has been discussed by many authors [*Franke et al.,* 2004; *Lund,* 1985; *Lund and Keigwin,* 1994], to name but a few, who proved that magnetization (NRM=PDRM) had been recorded beginning from some depth, where magnetic particles lose their mechanic mobility (magnetization fixing depth). In other words, a time shift (NRM fixation duration) arises between the age of the magnetization and the age of the sedimentation, the age of the sediments, where NRM is fixed, being substantially older than the age of the sediments. This phenomenon results in the smoothing of the PSV magnitudes [*Lund and Keigwin,* 1994]. This is caused by the fact that at each time instant NRM is fixed only by some of the magnetization carriers located in different parts of a fairly thick layer of sedimentary rocks. The thickness of this layer and the distribution of the rock particles that fix NRM at each time moment is controlled at each time instant by the physical and chemical properties of the sediments [*Franke et al.,* 2004], the duration of NRM recording being controlled also by the sedimentation rate. Based on the "rate of sediment accumulation" using radiocarbon data and the ChRM age, determined using PSV correlation, Figure 11 shows the duration and depth of NRM recording in the Naproch Lake sediments. The NRM fixing period (difference between the age of the sediments and the NRM age) was found to be 600 to 2300 years, the NRM depth being 0.6 m to 0.8 m. At least half of this time shift could be produced by the presence of PDRM in the sediments.

To estimate the extent of the PSV smoothing effect recorded in the sediments of the studied Belorussian lakes, we compared their magnitudes with the magnitudes of the respective PSV peaks in the records obtained for some other objects, using historical data [*Jackson et al.,* 2000] and archeomagnetic data [*Daly and Le Goff,* 1996], using the data available for the sediments in the Nautajarvi

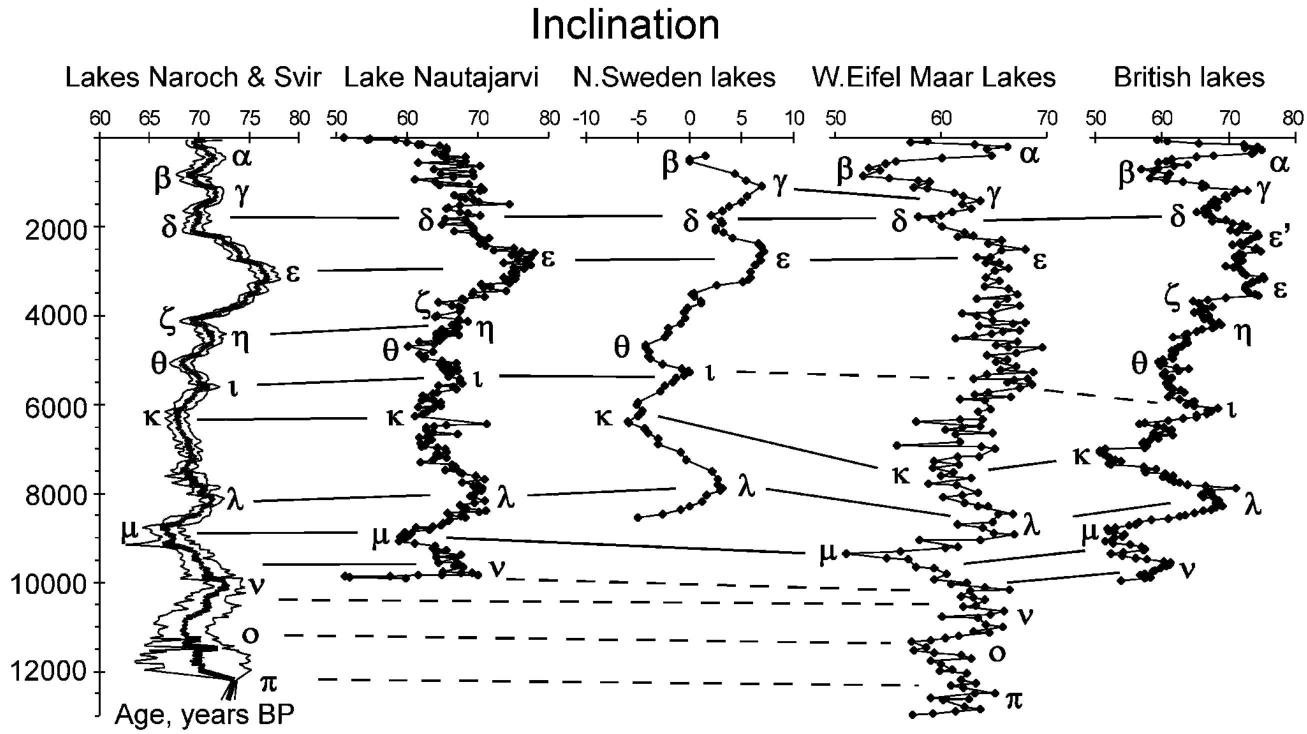

Figure 9. Comparison of the ChRM inclination variation curves obtained for the sediments of different European lakes. The Greek letters mark the specific inclination variations, recorded earlier in a British master curve [*Turner and Thompson,* 1982]. The solid lines show the segments of confident record correlation, the broken lines, the segments of inferred PSV correlation.

Lake [*Ojala and Saarinen,* 2002] and in the lakes of North Sweden [*Snowball and Sandgren,* 2002], and for the sediments of the volcanic lakes in the West Eifel area in Germany [*Stockhausen,* 1998]. Figure 12 shows the curves of D and I variations recorded in the sediments of some lakes in Belorussia and in some other objects of study. One can see that the PSV magnitudes recorded in the sediments of the Belorussian lakes are 5 times lower compared to the archeomagnetic and historical data, ∼1.75–2 times lower compared to the records obtained in the area of the Nautajarvi Lake, ∼1.25–1.75 lower compared to the records obtained for the West Eifel lakes, and ∼1.9 times lower compared to the records of the North Sweeden lakes. It appears that the PSV magnitudes obtained using archeomagnetic and historical data are most close to the real magnitudes of the geomagnetic variations. In this case it can be stated that the PSV magnitudes recorded in the lake sediments are ∼2.5 to ∼5 times too low. This means that we observe the high smoothing of declination and inclination variations by postsedimentation magnetization. A similar comparison of the data was made by *Turner and Thompson* [1982] who used a coefficient of 2 for the magnitudes of all variations, which seems to be incorrect. It can be assumed that even in the case of a significant shift between the age of the sediment and the average age of magnetization (as observed in our case), some variations, for example, those with a variation period larger than 2000 years, may have been undistorted at all. Using the same coefficient for the whole data series, we will get the artificial magnification of long-period variation magnitudes, without correcting the magnitudes of high-frequency variations. Knowing the type of sediment deposition rate variation, the type of the sediments (in terms of their carbonate content and grain size), and the variation of the magnetization type as a function of the sediment type, one can correct the magnitudes of declination and inclination variation, this being a subject of future research.

The difference between the age of the sediments and the age of magnetization, similar to the difference observed in the sediments of the Belorussian lakes, complicates any PSV correlation using the sediments of different lakes. In particular, where the difference between the age of magnetization and the age of the sediments varies over the rock sequence, the accuracy of correlating the characteristic peaks of the geomagnetic field elements becomes very low and does not allow one to estimate the spatial evolution of the field morphol-

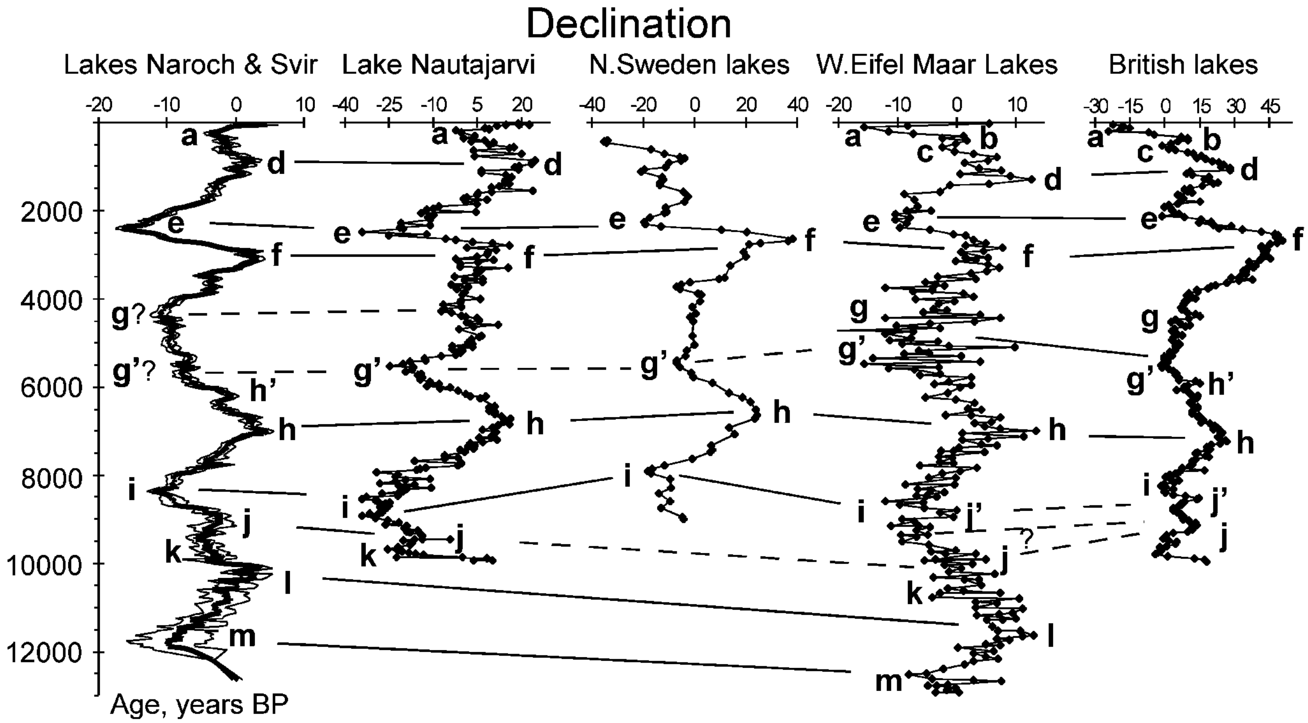

Figure 10. Correlation of the ChRM declination variation curves for the sediments of different European lakes. The Latin letters mark the specific inclination features that were recorded earlier by the British master curve [*Turner and Thompson,* 1982]. The solid lines show the segments of confident record correlation, the broken line, the inferred PSV correlation.

ogy. It is not inconceivable that these processes of postsedimentation magnetization can be observed in all types of sediments [*Bleil and von Dobeneck,* 1999; *Franke et al.,* 2004] causing a similar systematic error. For this reason, the datings reported in the literature may call for revision. For instance, the sediments of the Trichonis Lake in Greece [*Creer et al.,* 1981] showed a difference between the age of the sediments and the age of their magnetization to be more than 1000 years. This was clearly demonstrated by the comparison of the inclination and declination records obtained for this lake sediments with the records obtained for the British lakes [*Frank et al.,* 2002]. Yet, the latter cannot be used as a reference because their magnitudes and ages were not properly corrected [*Turner and Thompson,* 1982]. Therefore, at the present time we cannot estimate quantitatively the drifting of the geomagnetic field features using merely the data available only for the lake deposits of Europe. The shifting time of the morphological features of the declination and inclination variations, caused by the drifting of the specific features of the geomagnetic field, might have been substantially lower than the variations caused by the inexact dating of the magnetization.

Conclusions

1. The comparison and summation of the data available for the nine columns of the sedimentary rock samples collected in the Naroch and Svir lakes (Belorussia) resulted in plotting a PSV master curve for this region, which is similar in morphology to the archeomagnetic and limnomagnetic records obtained for some nearest regions and can be used to derive models of the geomagnetic field for the last ∼12000 thousand years.

2. The comparison of the resulting record of the paleosecular geomagnetic filed variation with the archeomagnetic data revealed a difference between the radiocarbon age of the sediments and their magnetization age, amounting to ∼2300 years, which was caused by the “ageing” of the carbon in the sedimentation basin, on the one hand, and by the postsedimentation magnetization, on the other.

3. The PSV magnitudes recorded in the sediments of the Belorussian lakes are 5 times lower compared to the archeomagnetic and historical data, this possibly having been caused by the large depth (up to 0.6–0.8 m) of the

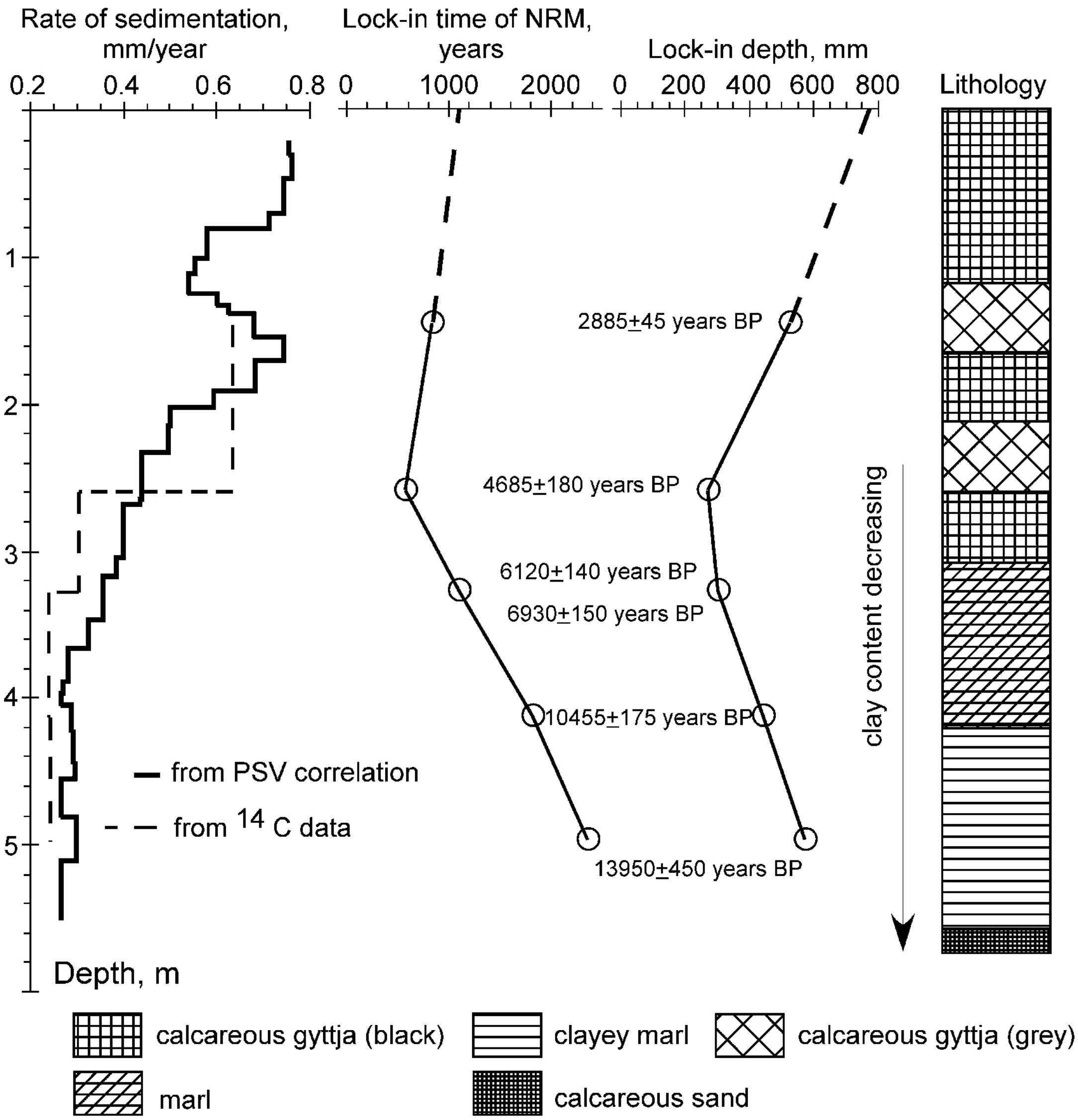

Figure 11. Variations in the depth and duration of NRM (PDRM) recording in the generalized column of the Belorussian lake sediments. The significant values of these parameters might have been caused partially by the assumption of the too old age of carbon in the sedimentation basin and also by the overestimated radiocarbon age of the sediments. No direct association has been between these parameters and the lithology of the sediments.

PDRM recording in the sedimentary rocks.

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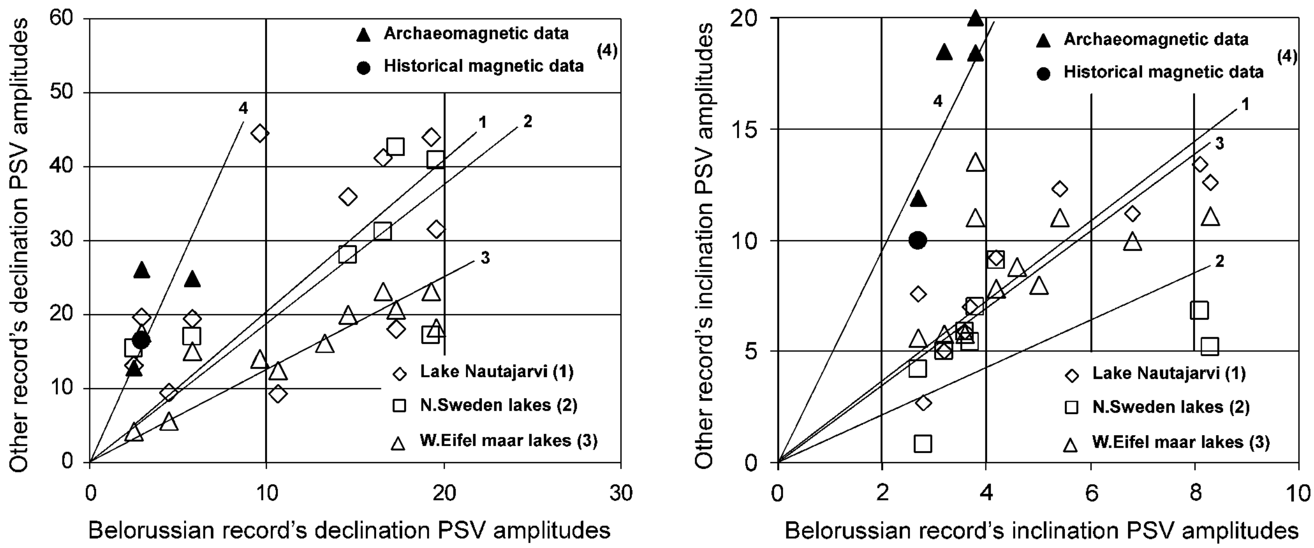

Figure 12. Correlation of the ChRM declination and inclination magnitude variation in the sediments of the Belorussian lakes with the magnitudes of the respective PSV records obtained from historical data [*Jackson et al.,* 2000], from archeomagnetic data [*Daly and Le Goff,* 1996], as well as from the records obtained in the Nautajarvi Lake [*Ojala and Saarinen,* 2002], in the West Eifel lakes (Germany) [*Stockhausen,* 1998], and in North Sweden lakes [*Snowball and Sandgren,* 2002].

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