University of Alberta

Time series processing: stratigraphic and paleoclimatic implications

by

Karol Jakub Rohraff

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Geophysics

Department of Physics

Spring 2012
Edmonton, Alberta

Abstract

Three sedimentary drilling cores from Lake Baikal were used to build a new composite magnetic susceptibility record for the Brunhes and upper Matuyama chrons. The developed age model, based on the constructing of the composite susceptibility signal and orbital tuning, shows a substantial improvement to the previously published timescales. The susceptibility spectrum approaches the expected continental climatic response with precession cycles being clearly resolved compared to the previous studies. The correctness of the new timescale is confirmed with the published ages of beryllium dating and geomagnetic reversals. Since many of the tuning techniques have difficulties in resolving short periods, a completely new method has been subsequently developed. The method improves the high frequency components by allowing nonlinear sedimentation rates which results in an accurate timescale. Additionally, the technique enables tuning to specific periods what can be advantageous since various regions in the world record orbital periods in a different way.

Acknowledgement

The work presented in this thesis would not have been made possible without the support and assistance of many people.

Firstly, I would like to thank Dr. Vadim Kravchinsky and Dr. Mauricio Sacchi. They welcomed me warmly after my arrival in Edmonton and introduced me to the geophysical community at the university. They were extremely supportive throughout my degree. Our frequent discussions coupled with their intellectual curiosity about geophysics contributed to my education and made my research advance as swiftly and fruitfully as possible.

I would also like to thank the committee members, my professors as well as the Department of Physics for their contribution to the completion of my degree.

A special appreciation goes to my family and friends for their continuous support throughout this work.

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List of Abbreviations and Symbols

BDP - Baikal Drilling Project

BMB - Brunhes/Matuyama boundary

ETP - Eccentricity–Tilt–Precession

GPTS - Geomagnetic Polarity Time Scale

ODP - Ocean Drilling Program

PISO-1500 - Relative paleointensity and oxygen isotope stack (Channell et al. 2009)

SPECMAP - Spectral Mapping Project

SINT-2000 - Composite Record of Relative Paleointensity (Valet et al. 2005)

κ - magnetic susceptibility

1. Introduction

1.1 Orbital Cycles and Insolation

Past climates of Earth are often investigated in terms of warm and cold periods. The latter i.e. the Ice Ages are short spanning only up to 10% of the Earth's history (Berger and Loutre 2004). The analysis of deep-sea and land records showed that the changes between glacial and non glacial periods show a cyclical behaviour (Berger 1978). The understanding of this periodicity with the help of astronomical theory is one of the objectives of paleoclimate. The main contribution to the understanding of the periodic behaviour was given in the first half of twentieth century by Milankovitch (Milankovitch 1941). His mathematical analysis of insolation at different latitudes was the foundation of the theory that Earth's orbital parameters, namely eccentricity, obliquity and precession are responsible for the changes in the amount of irradiation that reaches Earth what is reflected in geological records (Berger and Loutre 2004). Milankovitch's theory was not very popular for many decades after its birth and only gained merit after improvements of the analysis of geological cores and development of climatic models. Hays et al. (1976) was the first one who confirmed the dominant presence of 100, 41, 23 and 19 kyr periods in sedimentary sequences. Shortly afterwards these periods were associated with theoretical calculation of orbital changes (Berger 1977) which gave rise to orbitally forced stratigraphy, a new branch of science. For the last thirty years geologists and geophysicists have been looking for sediment properties that would exhibit high sensitivity to orbital forcing (Hinnov 2000). In the past, geological records most commonly came from the deep-sea. It was due to eccentricity signal being very profound in marine data. However currently, more and more attention is given to continental records and a wide range of sediment properties, with their advantages and drawbacks.

1.2 Magnetic Susceptibility as a Climatic Proxy[1]

In the present study, magnetic susceptibility (κ) as a sediment property has been chosen for the investigation of the orbitally forced stratigraphy from Lake Baikal. Peck et al. (1994) showed in their paper that magnetic susceptibility is an excellent climatic proxy as it is influenced by both biogenic and terrigenous factors which are the main sedimentary processes. Figure 1-1 represents a general behaviour of magnetic properties based on the studies of Core 340 Composite from Lake Baikal done by Peck et al. (1994). Interglacial stages are characterized by dominance of diatomaceous sediments with low concentration of magnetic minerals with high proportions of low coercivity such as magnetite and maghemite. Glacial sediments, on the other hand, are mostly composed of clayey lithology with large concentration of magnetic minerals that have high coercivity such as hematite and goethite.

During warmer periods, the sedimentation rate of terrigenous minerals is low and gives a weak susceptibility signal. At the same time the amount of diatoms increase resulting in higher concentration of silica. Since the silica is

[1]A version of this chapter together with Chapter 3 is in the stage of submission for publication. Rohraff, Kravchinsky, Sacchi 2011. Geophysical Research Letters.

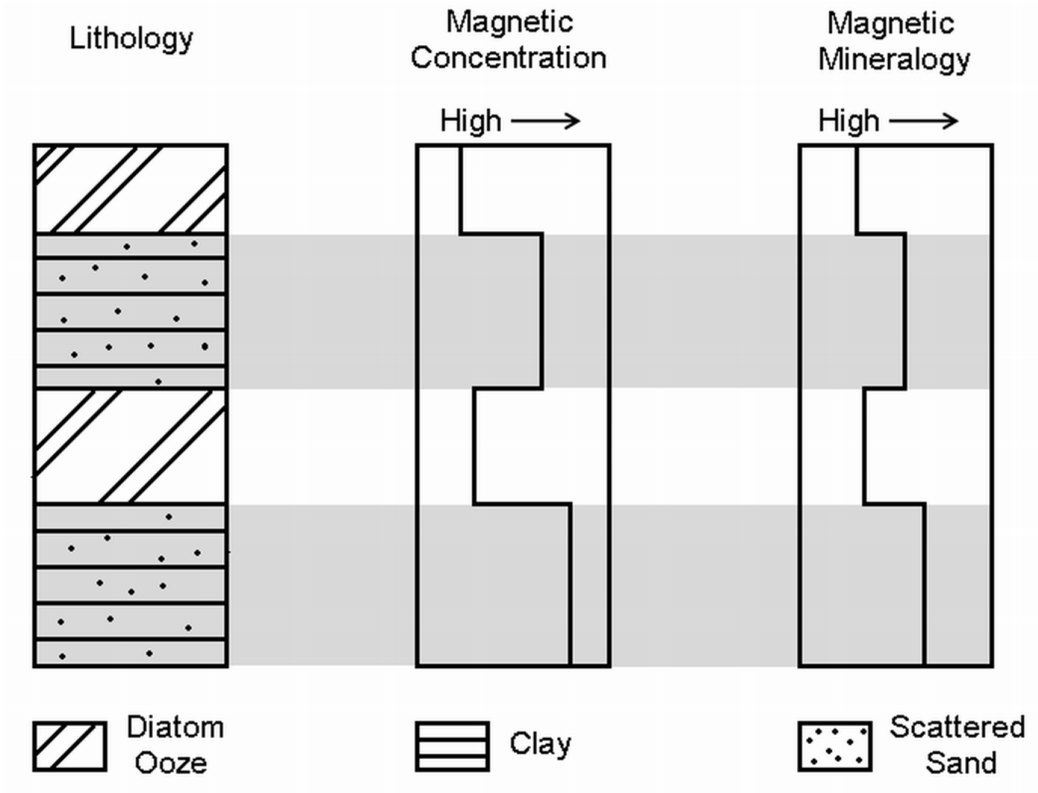

Figure 1-1. Schematic description of magnetic properties of sediments from Lake Baikal based on the Core 340 Composite from Peck et al. (1994). The shaded area shows glaciation periods. The middle graph corresponds to the concentration of magnetic minerals whereas the magnetic mineralogy plot represents the concentration of high coercivity minerals.

diamagnetic, it decreases the magnetic susceptibility record. On the other hand during Ice Ages the deposition of terrigenous sediment increases and the silica supply decreases resulting in higher susceptibility values. Since the location of the drilled cores is a structural high, the deposition down the slope can be excluded. The windier, colder and drier winter conditions during glacial intervals suggest sedimentation caused by aeolian processes. As pointed out by the authors and reference therein, this is confirmed by large concentration of high coercivity minerals during glacial stages.

Magnetic susceptibility is an excellent proxy which is sensitive to even short term climatic changes. From Figure 1-2 one can clearly notice that the susceptibility is

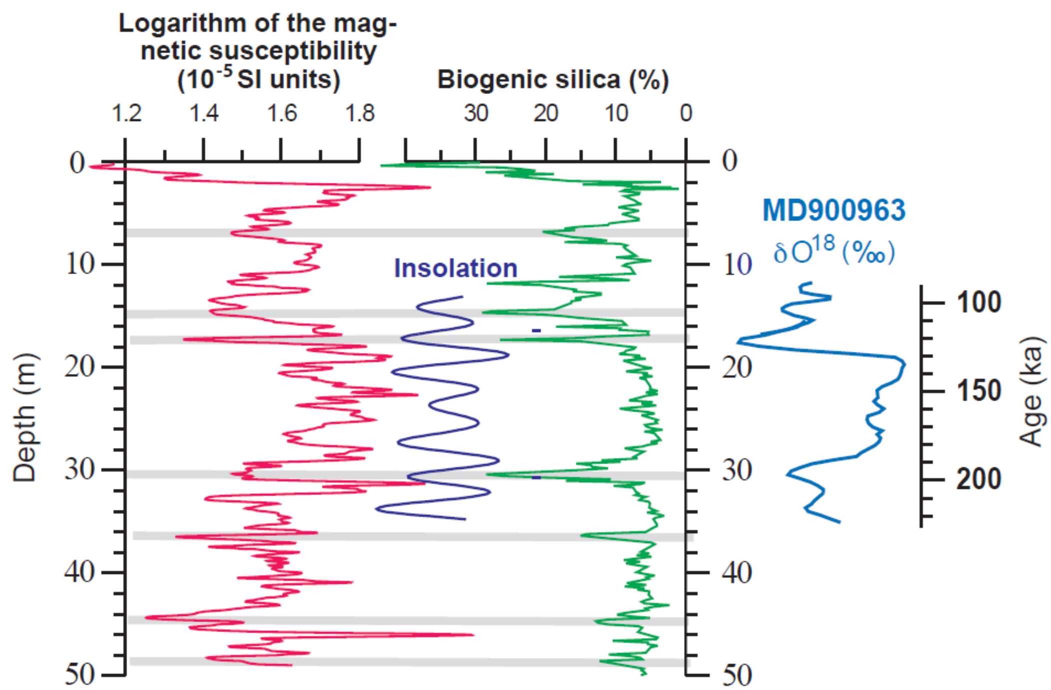

Figure 1-2. Figure modified from Kravchinsky et al. (2007) showing correlation between magnetic susceptibility and biogenic silica data sets from the BDP-93-2 core. Oxygen isotope profile (Bassinot et al. 1994) was added to show the correlation of the data with the insolation curve (computed with the software of Paillard et al. 1996 using the solution of Laskar et al. 2004).

more responsive to high frequencies than biogenic silica or oxygen isotope. Oxygen isotope is usually obtained from sediments from the bottom of the ocean which has a huge damping effect on short term climatic changes. Biogenic silica is primarily a factor of the water temperature only. On the other hand susceptibility not only depends on the silica but also on the on-shore sources of the sediments.

1.3 Major Goals of the Thesis

The major goals of my thesis are as follows:

- to construct a high-resolution age model for the sedimentary sequences from Lake Baikal,
- to investigate the presence and behaviour of Milankovitch cycles and compare them with previous studies,
- to analyze differences in climatic responses to orbital forcing inside the continent and in the ocean,
- and to develop and test a new orbital tuning method that would improve the climatic response at high frequencies of the orbital parameters.

The research done to achieve the above goals is presented in this thesis and has resulted in two manuscripts that are currently in the stage of submission to peer-reviewed journals. They are as follows:

Rohraff, K., Kravchinsky, V. A., Sacchi, M. D., Sakai, H., 2011. The Brunhes and upper Matuyama high-resolution timescale of Lake Baikal sediments with an automatic orbital tuning technique: highlight of the continental climate response to orbital forcing. Submitted for publication to *Geochemistry, Geophysics, Geosystems*.

Rohraff, K., Kravchinsky, V. A., Sacchi, M. D., 2011. Climatic forcing during the Brunhes and upper Matuyama: high-resolution age model of Lake Baikal sedimentary records based on a novel automatic orbital tuning method. In stage of submission to *Geophysical Research Letters*.

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2. The Brunhes and upper Matuyama timescales of Lake Baikal sediments[2]

2.1 Introduction

As presented by various authors such as Imbrie et al. (1984) and Shackleton et al. (1990), changes in Earth's orbital parameters (i.e. Milankovitch periodicities) are encoded in ancient stratigraphic records. By analyzing the properties of a geological core and correlating them with orbital responses, an accurate identification of the age model for the core can be obtained. The construction of such age scale is called orbital tuning and may be obtained from the comparison of some known time–dependent and depth–dependent data sets. The technique utilizes computer modeling which is cost and time effective.

It has been shown in the literature that different types of data may be used for tuning as long as the measured data set is related to orbital forcing. Martinson et al. (1987) employed the fact that solar insolation (i.e. the amount of solar irradiation that reaches Earth) is closely related with the amount of ice volume. On the other hand, the global ice volume influences the concentration of the oxygen isotope in deep–sea sediments. The depth–dependent oxygen data were compared with the time–dependent insolation curve. This was used to construct an age model. Kravchinsky et al. (2003, 2007) correlated the magnetic susceptibility record obtained from the Lake Baikal sediments with time-dependent oxygen isotope data. The comparison could be made as during warmer periods, in contrast to colder periods, the number of diatomaceous organisms that

[2]A version of this chapter together with Appendix A has been submitted for publication. Rohraff, Kravchinsky, Sacchi, Sakai 2011. Geochemistry, Geophysics, Geosystems.

are the source of biogenic silica increase. Since the silica causes the dilution of susceptibility, the later produces the weaker susceptibility record in sediments during warmer time intervals. On the other hand, the concentration of oxygen in water diminished with the increase of temperature (and thus with the increase of insolation). Therefore there exists a relationship between the oxygen and susceptibility data.

Many of the orbital tuning methods employ visual correlation of extrema between two series to obtain the timescale. Tuning in such way yields a timescale of a very limited resolution. Also a problem with this approach occurs if the peaks in one curve are broader than the maxima in the other curve or if the peaks lie closely to each other making it difficult to correlate the proper extrema. Then the resulting age models may have large errors and thus be inaccurate. Prokopenko et al. (2001) and references therein suggest that there might be a small delay between the maxima of solar irradiation and climatic responses recorded in sediments. In this way, the ages assigned by extrema correlation might be slightly underestimated. Prokopenko et al. (2001) suggested matching the insolation peaks to the middle of most rapid changes in climatic records.

Age models with higher accuracy can be obtained by more sophisticated methods. Martinson et al. (1982) constructed a mapping function that represents depth–time relation using a linear trend with a truncated Fourier series. The unknown coefficients of the mapping function could be found by maximizing the coherence between the input curves. The authors point out that highly variable signals require additional filtering of the data. Brüggemann (1992) in his tuning method was looking for the age model of a specific shape. The author built an objective function with different weights. By minimizing the objective function the optimal depth–age relation could be calculated. The method requires much testing of the final solution in order to find the optimal results. This is due to the choice of the weights that must be defined by a user. Ochiai and Kashiwaya (2005) proposed to build an age model by introducing an intermediary function with some common dominant periods between the input curves. The authors also put some restrictions on sedimentation rates and amplitudes of the signal during correlation of curves. Optimal solutions are found by applying Genetic Algorithm. The algorithm yields many optimal solutions due to the aforementioned restrictions. The final result is found by additional methods such as finding solutions that satisfy genetic variety. Yu and Ding (1998) introduced an automatic procedure for creating their age model. The authors filtered the input series and then tuned them to some known theoretical curves. Their tuning procedure squeezes or stretches the climatic record until the best matching with the tuning target is obtained. The best age model was found when correlation between the curves was maximized.

In the present study the tuning of the Lake Baikal data by visual correlation between the well known ages will be first done to construct an initial timescale. This initial age model will be subsequently supplemented with available age points from beryllium dating (Sapota et al. 2004). The obtained timescale will be further improved with the automatic tuning method of Yu and Ding (1998). The latter step is important as it significantly improves the correlation of the climatic record with a newly built age model and of the target curve. Additionally, the construction of initial timescale is required to maximize the operation of the automatic tuning method. The technique of Yu and Ding (1998) has been chosen due to its simplicity and the calculation of a high–resolution timescale in relatively short computational time. Also, the method does not require the construction of intermediary or objective functions and thus eliminates the need to choose proper weights or other restrictions that are defined by a user. It is also easily adjustable to include other well-known age points obtained by other absolute or indirect dating techniques.

The main purpose of the present study is to obtain a high-resolution timescale for the Lake Baikal composite magnetic susceptibility record by assigning an age to each measured data point independently. Our every data point represents ~0.8 kyr, such resolution is high enough to better resolve precession peaks compared to the timescales built using matching to the geomagnetic polarity timescale (GPTS) or even the SPECMAP/ODP timescales (Williams et al. 1997). Linear interpolation between magnetic reversals in GPTS or using extrema correlation between ODP records and insolation barely capture 19 kyr and a double 23 kyr peaks. Therefore our age model can be used as a timescale with better resolved high frequency Milankovitch frequencies. The aim of this study was to find the more effective than manual matching to the reference curve technique of dating the cores and to better resolve the Milankovitch, especially precession cycles. Although this study is based on the earlier published data we re-evaluate the age models for all three deep-drilling Baikal cores together for the first time and develop a composite of these cores (referred in the text as a stack). Such work is a large step further comparing to the previous publications on various climatic proxies from the same cores because it enabled us to step further in our analysis reducing the individual core sampling errors, eliminating missing intervals and cancelling a large portion of the white noise. We check our stack against marine data set and show the difference in spectral responses between continental and oceanic paleoclimatic records.

2.2 Data Description and Treatment

In 1996 and 1998 the cooperation of Russian, Japanese and American teams resulted in the Lake Baikal Drilling Project (drilling cores BDP-96-1, BDP-96-2 and BDP-98). Figure 2-1 shows the location of the drilled boreholes in the Academician Ridge. Sediments up to the depth of 601 m below the bottom of the lake were recovered. The core recovery was 95% in average. The cores BDP-96-1 and 2 were taken a few meters apart from the same drilling platform. The core BDP-98 was drilled ~7 km away. The sedimentary record is especially important since Lake Baikal is the largest and the oldest lake in the world and it has never been completely frozen during past ice ages resulting in a continuous stratigraphic record (Peck et al. 1994; Kravchinsky et al. 2003; Prokopenko et al. 2006).

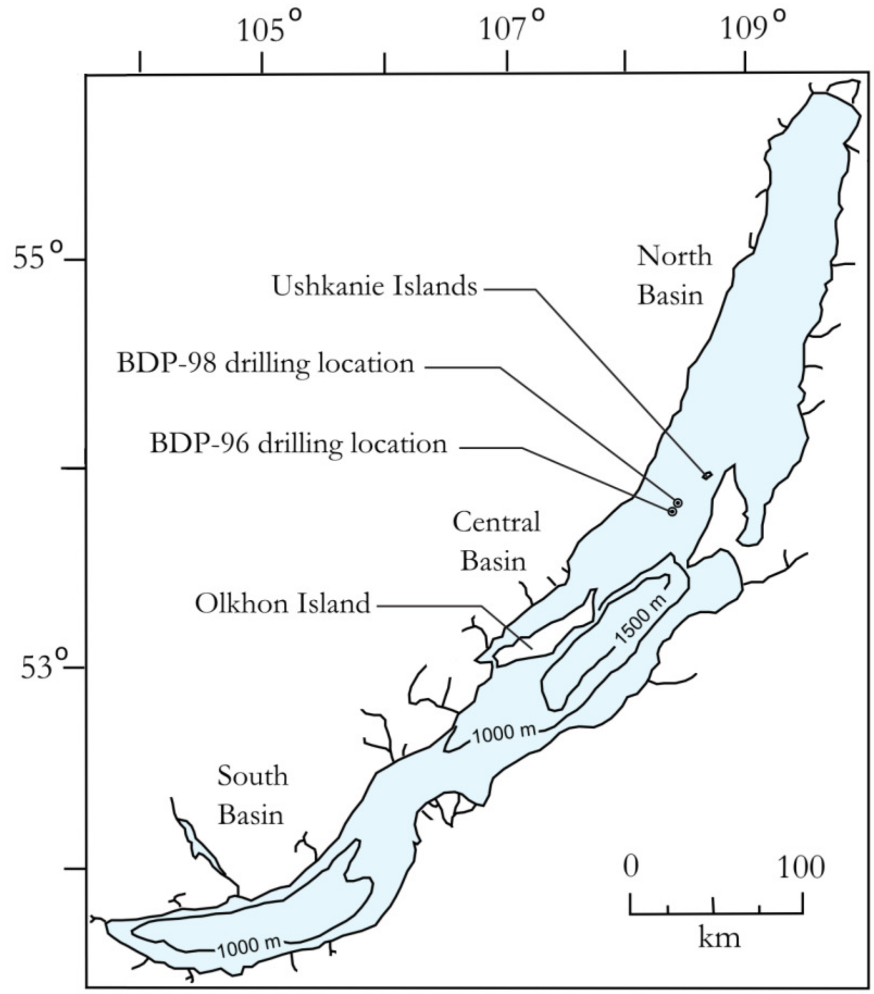

Figure 2-1. The location of drilling sites in Lake Baikal. Modified from Kravchinsky et al. (2003).

The first paper on the 5 Myr biogenic silica record from two twin BDP-96 cores (BDP-96-1 and BDP-96-2) by Williams et al. (1997) investigated Lake Baikal climatic response to solar irradiation. Subsequent studies of Lake Baikal sediments (Kashiwaya et al. 1998; Kravchinsky et al. 2003, 2007; Dawson et al. 2004) all showed the presence of Milankovitch cycles. Nevertheless the power in the spectral domain of precession peaks was small when compared with eccentricity maxima. This was mostly the result of low accuracy of the age model that was constructed based on geomagnetic polarity timescale and visual correlation of extrema of the climatic record with the oxygen isotope age scale by Shackleton et al. (1990). The low power of the climatic precession frequency response is not in agreement with modeling of Short et al. (1991). The authors showed that for the north central Eurasia the sensitivity to solar irradiation is the largest at 23 kyr, 19 kyr and 41 kyr, respectively whereas the eccentricity peak has much smaller power. Short et al. (1991) investigated that the solar forcing at eccentricity frequencies are more profound in the ocean than in the continent. This is due to heat capacity of the ocean which has a significant damping effect on seasonal precession resulting in eccentricity responses to be more profound (Short et al. 1991). In order to improve the spectrum of the climatic record and thus its age model, Prokopenko et al. (2001, 2006) constructed an alternative timescales based on the correlation of biogenic silica with the insolation curves. Though the obtained spectra show noticeable improvement at the precession frequencies by having higher powers, the peaks are still relatively small when compared with the expected obliquity or eccentricity ones. In this paper we further improve the spectrum and thus the age model of the long sedimentary record of Lake Baikal in order to explore the effectiveness of the automatic orbital tuning technique for paleoclimatic reconstructions.

In the present study magnetic susceptibility data measured by Kravchinsky et al. (2003) are used for orbital tuning. The susceptibility was measured on the whole core with a spacing of 3 cm. The data for the Brunhes and upper Matuyama chrons are used and analyzed in order to test the tuning technique and relate the results with the ones obtained by other authors. The Brunhes and upper Matuyama chrons were chosen to verify the differences between continental and oceanic records i.e. to confirm precession as a major factor in the climate change over land as predicted by the insolation power spectrum (Figure 2-2) or as shown theoretically by Short et al. (1991). Additionally, the chrons were chosen because, as described later in the text, geomagnetic polarity and paleointensity

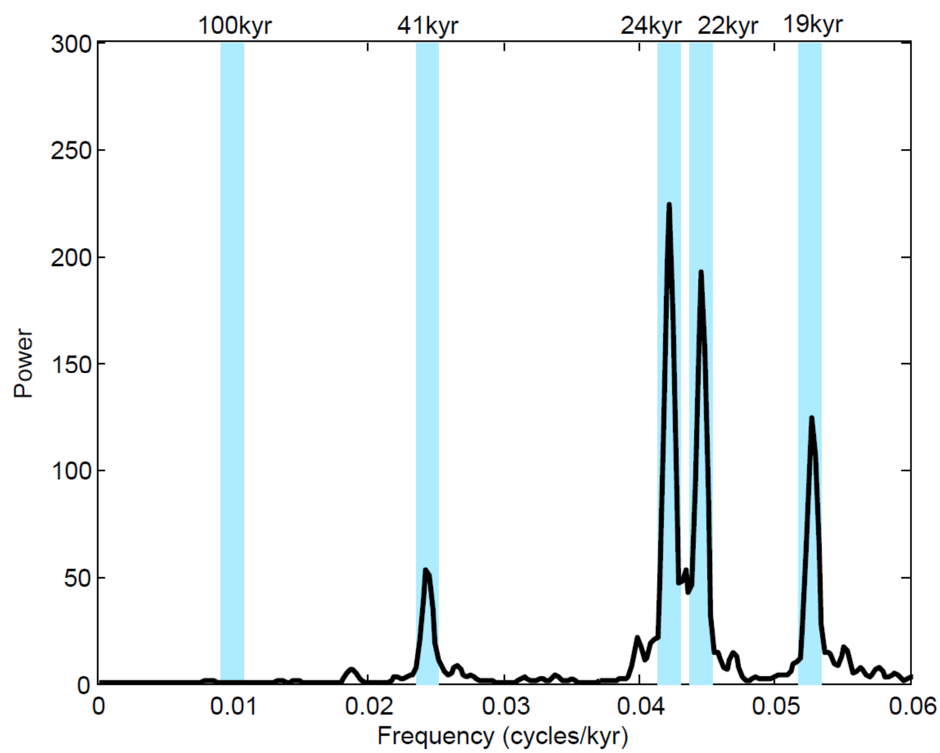

Figure 2-2. Smoothed periodogram (twice with Tukey-Hanning discrete spectral window) of solar irradiation for the last 1071 kyrs at the latitude of 65°N.

records provide us with reliable correlation for that time interval that can be used to obtain well dated points.

In Figure 2-3, the 30–48 m inclination profile using the dataset for BDP-96 from Sakai et al. (2000) and BDP-98 from Kravchinsky et al. (2003). The profiles were reanalyzed in order to reconstruct the characteristic remnant magnetization on the basis of multiple alternating field demagnetization step analysis (10, 20, 30, 40 mT). Unstable samples error angle more than 10° were removed from the final analysis. The inclination profiles were initially compared with the geomagnetic polarity time scale of Cande and Kent (1995) in order to identify the Brunhes/Matuyama boundary (BMB) and Jaramillo event. A few shorter upper Matuyama excursions could be also identified. The dating of the Jaramillo event and BMB is based on the matching of the top and bottom of the event registered in the Lake Baikal to SINT-2000 paleointensity record (Valet et al., 2005). The middle of the transition from the positive to negative inclinations was correlated to the paleointensity minimum. While such correlation is straightforward for the Jaramillo top and bottom, the assessment of BMB is much more delicate. The uppermost transition from the positive to negative inclinations is at about 33.8 m for BDP-96-1, 34.2 m for BDP-96-2 and 31.5 m for BDP-98. It corresponds to ~0.78 Ma (0.776 Ma) of the SINT-2000 minimum. We consider the next double minimum at the depth interval 34–35 m corresponding to the upper Matuyama event precursors reported in Coe et al. (2004), Macrì et al. (2010) and the references therein. It also a few cm different from the earlier published BMB age

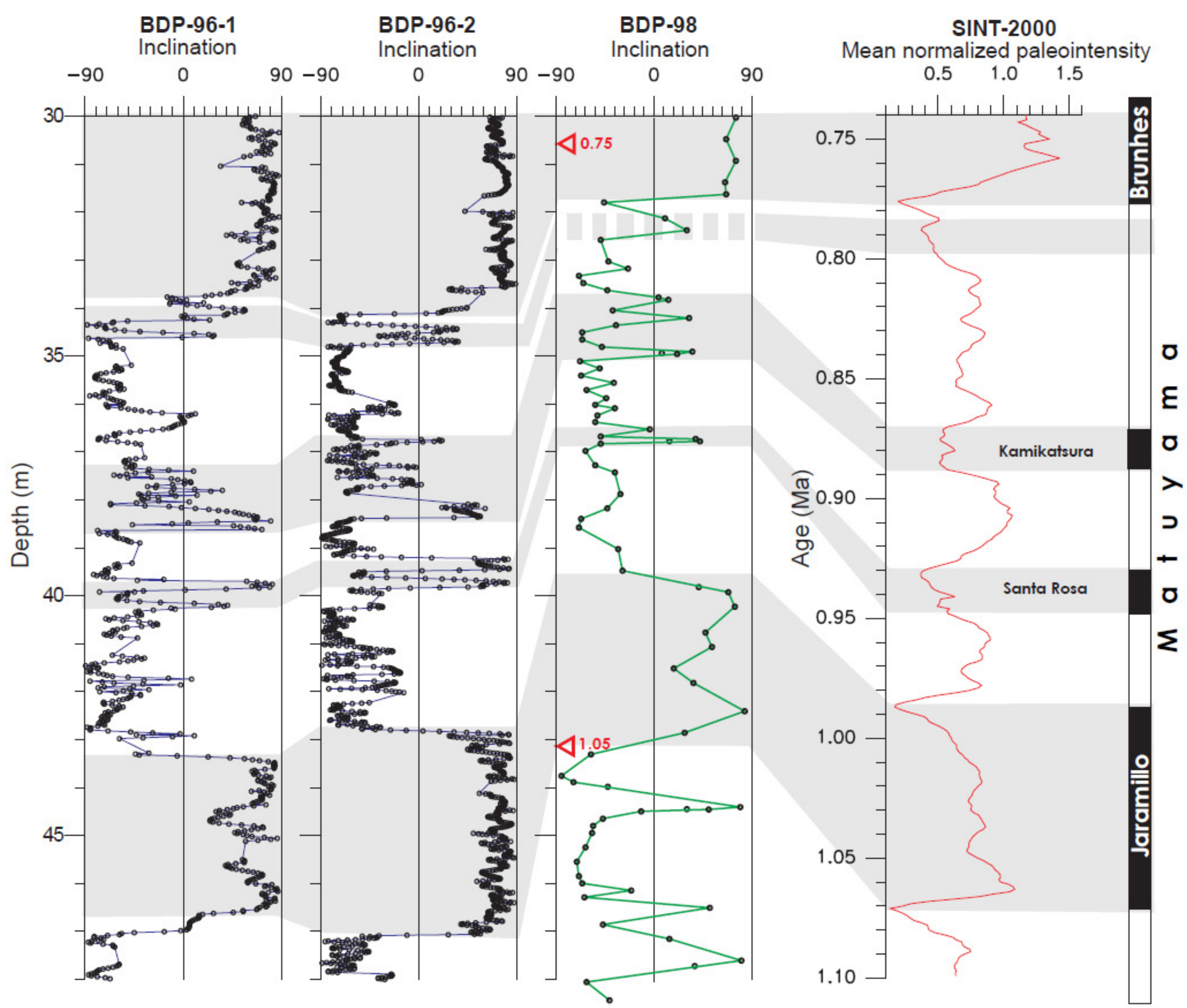

Figure 2-3. Inclination profiles for all BDP cores (after Sakai et al. 2000 and Kravchinsky et al. 2003) matched to the paleointensity reference curve SINT-2000 (Valet et al. 2005). Grey correlation lines correspond to the known geomagnetic normal polarity reversals. The average measurement spacing for the BDP-96 quarter of the core segments was 1 cm whereas for the BDP-98 core single samples it was 30 cm. The inclinations represent characteristic remnant magnetization reconstructed on the basis of multiple alternating field demagnetization step analysis.

of Kravchinsky et al. (2003) who estimated the average depth for the BMB in the middle of the transition from strictly negative to positive directions without considering the precursors. In this paper we rely on the uppermost location of the transition from the positive to the negative inclinations, i.e. above the double peak of the BMB precursor (Figure 2-3). The BMB precursor in the BDP-96 core 1 and 2 is a double peak event. The BDP-98 single sample data set indicates that it is a single event as reported earlier. We consider that the BDP-98 does not resolve the precursor as well (samples were taken approximately every 30 cm) as the BDP-96 where the measurements on the quarter cores were taken every 1 cm using the 2-G cryogenic magnetometer. The quarter core measurements, however, are somewhat smoothed comparing to the single sample measurements because the 2-G magnetometer measuring area was ~5 cm long. Nevertheless both cores BDP-96-1 and 2 demonstrate that the precursor is a double peak. Although the choice of the exact point at the BMB is always somewhat subjective we can report that it does not influence the spectral analysis results presented further in this paper which was verified with a set of additional calculations. Our choice of the BMB position is validated by the beryllium date of ~0.75 Ma at the depth 30.5 m just above the BMB.

The correctness of the BMB assessment was verified with the earlier events illustrated in Figure 2-3. Assessment of the Jaramillo, Kamikatsura, Santa Rosa was done by correlation with SINT-2000 and verified with very similar relative paleointensity and oxygen isotope stack PISO-1500 (Channell et al. 2009).

Kamikatsura is provisionally assigned to the paleointensity minimum at SINT-2000 which seems logical even when slightly contradicts recent $^{40}Ar/^{39}Ar$ ages reported by Coe et al. (2004). The top of Kamikatsura has multiple features which are very short in time and may appear to be a noise taking in account relatively low sedimentation rate (4.0–4.4 cm/kyr). Therefore we used only the bottom of Kamikatsura as a correlation point for our further tuning procedure. Double event of Santa Rosa appears very clearly as a double peak in all records and both top and bottom were used as correlation points. The event was reported earlier as a single peak (Singer and Brown 2002).

The position of the end of the Brunhes chron is additionally confirmed by the presence of magnetic susceptibility minima as well as the maximum of biogenic silica at the boundary in all three BDP records (BDP-96-1, BDP-96-2 and BDP-98). This can be seen in Figure 2-4 by a horizontal light brown line. Other authors such as Ochiai and Kashiwaya (2005) indicated the Brunhes chron boundary for the BDP-98 core at 32 m, however they do not elaborate on that choice.

We used the age-depth control points based on correspondence of the top and bottom of the geomagnetic events BMB, bottom Kamikatsura, Santa Rosa, Jaramillo when building the age model (Table A-1, A-2 and A-3 in Appendix A). We did not use the top of Kamikatsura because we were not sure which event of the multiple short events correctly represented the top of Kamikatsura. The bottom of Kamikatsura, however, is very distinct with a positive inclination event and therefore was used as a control point. Coe et al. (2004) have not reported any positive inclinations only the shallow ones but they studied the lava flows which are not continuous.

The uppermost point of the magnetic susceptibility record was estimated based on the first age point (3.57 m – 56 kyrs) obtained with the software of Paillard et al. (1996) using the solution of Laskar et al. (2004). The software was used to create age-depth control points by visual correlation of extrema between the insolation and susceptibility curves (Table A-1, A-2 and A-3 in Appendix A). Now, assuming the constant sedimentation rate from 0 m–3.57 m, the estimated age of the first susceptibility data point of 0.03 m was calculated to be 0.47 kyr. The value estimated in this way is more accurate than the value that could be calculated based on the first beryllium data point (1.97 m – 50 kyrs) from Sapota et al. (2004). This can be explained as follows, younger sediments are less compressed and thus have larger sedimentation rates than older sediments. The average rate based on the first beryllium point is equal to 3.94 cm/kyr, whereas the mean rate calculated using the first point from visual judgment is equal to 6.38 cm/kyr. Since the average rate for the Brunhes and upper Matuyama part of the core is 4.02 cm/kyr, the first beryllium point is rejected as it implies the compression of sediments that is higher than for much older parts of the BDP-98 core.

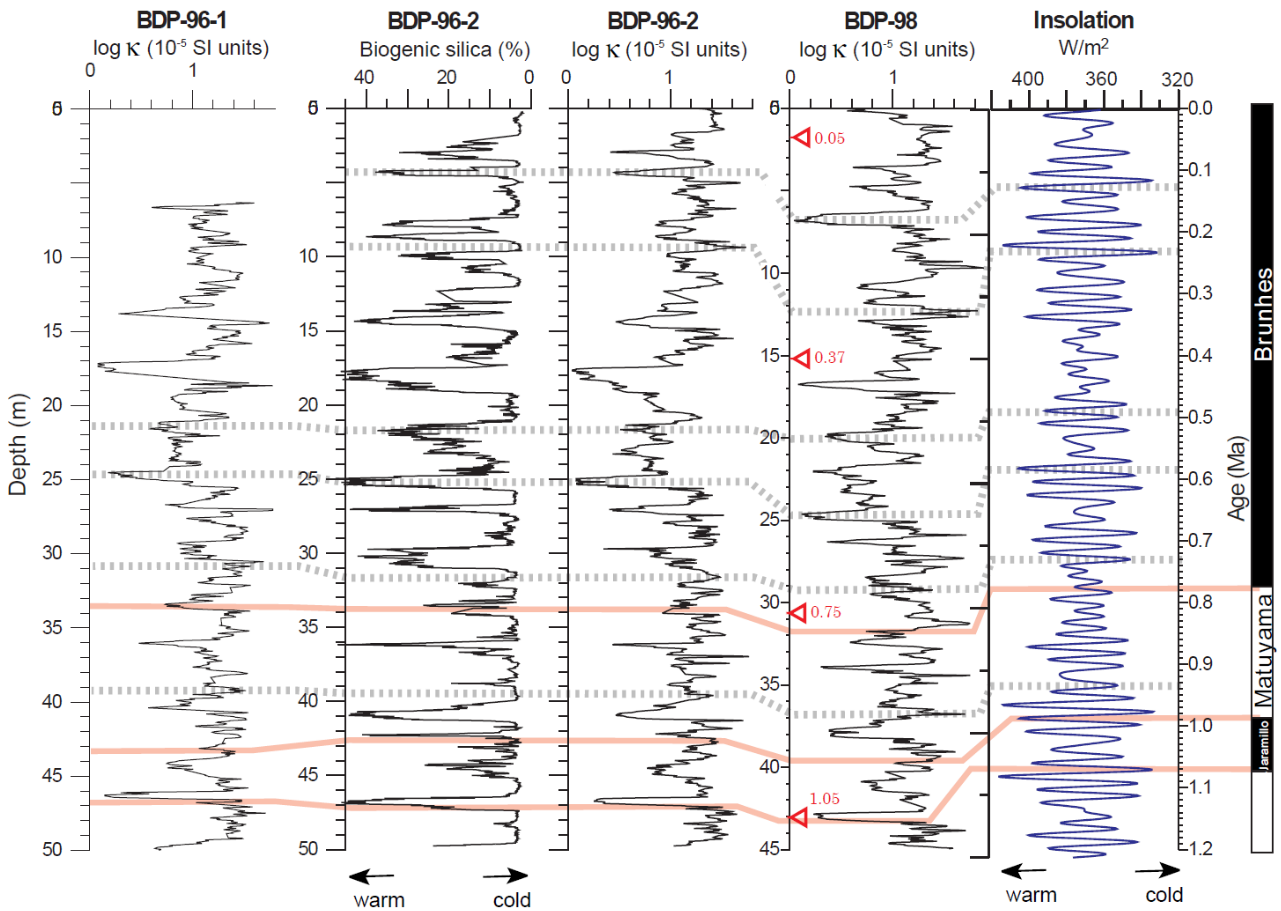

Figure 2-4. Magnetic susceptibility records for all three BDP cores (after Antipin et al. 1998 and Kravchinsky et al. 2003) and biogenic silica (after Williams et al. 1997) matched to the theoretical insolation (calculated with the software of Paillard et al. 1996 using the solution of Laskar et al. 2004) and the geomagnetic polarity scale. Light brown lines correspond to known geomagnetic polarity reversals and dashed grey lines shows representative control points that were obtained by visual matching between extrema of the data.

In the present study the volume normalized magnetic susceptibility κ will be tuned to insolation. King et al. (1993), Peck et al. (1994), Kravchinsky et al. (2003, 2007) showed that there exists a correlation between κ, the concentration of biogenic silica in the Lake Baikal sediments and the solar irradiation. The correlation was already briefly explained in Chapter 1 and a very detailed description of it the can be found in the papers of Prokopenko et al. (2001) and Kravchinsky et al. (2003). The theoretical solar insolation was computed by the software of Paillard et al. (1996) using the solution of Laskar et al. (2004). The mean insolation was calculated at the standard latitude of 65°N and for the period between June 21 and September 21. According to Short et al. (1991), the seasonal surface temperature precession effect in north central Eurasia is around three times larger than that of obliquity effect. Following this reasoning we chose the standard latitude of 65°N at which the precession dominates over obliquity which is not the case at the latitude of the drilling location (53°N). The summer months were chosen since in the Siberian region summer temperatures have a significant impact on the Lake Baikal water heat balance and therefore on the diatom production (Prokopenko et al. 2001, Short et al. 1991) which dilutes magnetic susceptibility record. Kravchinsky et al. (2003, 2007) and Prokopenko et al. (2006) showed that tuning to the oxygen isotope curve from the marine sediments destroys the precession frequency. Prokopenko et al. (2006) suggested to tune directly to the precession component of the insolation and compared their record to the ETP (eccentricity–tilt–precession theoretical curve) frequency spectra. Following their suggestion we chose to tune to the total insolation signal because it contains all Milankovitch frequencies and we avoid destroying any of the orbital periods.

The age-depth control points together with the ^{10}Be dating from Sapota et al. (2004) are given in Table A-3 in Appendix A and will be used in tuning to create an initial time scale (Figure 2-5). The data of Sapota et al. (2004) was used since it is the only beryllium data available for the Brunhes chron for the BDP-98 core. Horiuchi et al. (2003, 2004) also performed beryllium analysis, but their dating corresponds to depths below 200 m. The mentioned datings are the only absolute

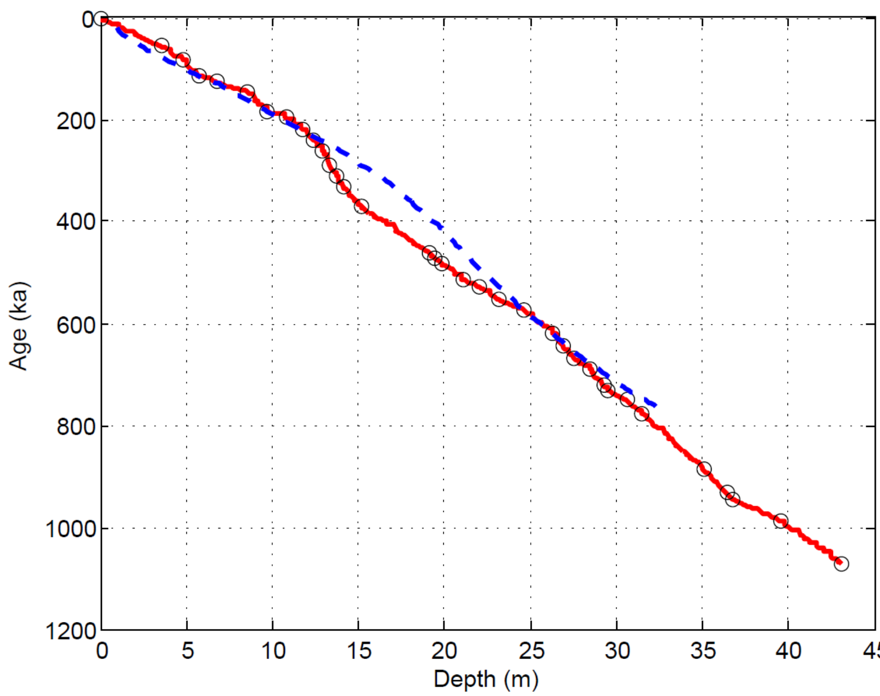

Figure 2-5. Black circles represent initial low resolution scale obtained by visual correlation of extrema between the insolation and magnetic susceptibility curves using the software of Paillard et al. (1996) and by using beryllium ages from Sapota et al. (2004) as well as the paleointensity ages. Red curve shows tuned age model for the BDP-98 core obtained in the present study. Blue curve represents an age model for the same core produced by Ochiai and Kashiwaya (2005) but for a shorter time interval.

datings currently available for the BDP-98 core. After the construction of the first order age model we applied the technique of Yu and Ding (1998) to further improve the resolution of the timescale.

Since the magnetic susceptibility record has some intervals with small and large amplitude oscillations, the tuning is done to log(κ) in order to stabilize the data variance. This procedure will change the distribution of power in spectral domain but at the same it will eliminate high power jumps caused by data intervals with large variance (Weedon 2003). The logarithmic transformation will also change the probability density function of the time series to be closer to Gaussian. Normally distributed data is often the main assumption in most of statistical tests. The statistical method of Grinsted et al. (2004) that will be used for spectral analysis assumes the distribution of data should not deviate much from Gaussian.

2.3 Tuning Procedure

First, let's consider two known data series, one of which depends on time t i.e. A(t) and the other depends on depth x i.e. B(x). If the correlation exists between both series, then the climate record that is present in B(x) can be transformed into the function B[t(x)]. This can be done by stretching or squeezing of the depth–dependent curve until the best matching with the time–dependent series is achieved. The best matching can be obtained by maximizing the correlation coefficient between both data sets and is given by the following formula

$$R = \frac{\sum_{j=1}^{M}(A(t_j) - \langle A(t_j)\rangle)(B[t_j(x)] - \langle B[t_j(x)]\rangle)}{\sqrt{\sum_{j=1}^{M}(A(t_j) - \langle A(t_j)\rangle)^2 (B[t_j(x)] - \langle B[t_j(x)]\rangle)^2}}, \quad (1)$$

where $A(t_j)$ and $B[t_j(x)]$ correspond to the two series with length M where j corresponds to the j-th element of the series and $\langle \dots \rangle$ denotes the mean value of the data set. The above formula is the standard correlation coefficient formula (for instance from Rodgers and Nicewander 1988). It was chosen instead of the one from Yu and Ding (1998) since it is additionally normalized to one. The normalization allows better understanding of the correlation between two data sets. For $|R| = 1$ both curves have exactly the same shapes, whereas $|R| = 0$ means that there is no correlation between both series. Since both curves are somehow correlated, we want to adjust the shape of $B[t(x)]$ such that the correlation coefficient is maximized. This can be done by changing the timescale $t(x)$ in $B[t(x)]$. The scale that corresponds to maximum value of R will be the optimal age model that we are looking for.

Yu and Ding (1998) suggested the Dynamic Optimization method of Råde and Westergren (1995) for changing the timescale and finding the maximal correlation coefficient. First a linear timescale is constructed for the data series B and initial value of R is calculated. Then each point in the timescale is shifted between neighbouring points until the largest value of R is found. In this way, by shifting each time point, the correlation coefficient is increased step by step until it reaches maximal value. When treating paleoclimate records the knowledge of several well–dated points is required. These points can be obtained from the identification of normal/reverse polarity chrons or absolute dating (radiocarbon, beryllium etc.). At least two such well–dated points should be known in order to properly identify the boundaries of the tuning curves between these points. Otherwise it would not be possible to uniquely identify which parts of the curves should be tuned to each other.

Often curves that are tuned have different shapes which makes tuning somewhat difficult. This is due to the presence of noise. To remove this problem the signals that are tuned can be first filtered for specific frequencies. This approach was suggested by Yu and Ding (1998). The authors tuned obliquity and precession curves to the paleoclimate record that was filtered around the central frequencies of 41 kyr and 21 kyr, respectively. Additionally, the authors assume sedimentation rates to oscillate around their average values between two control points. By repeating the tuning algorithm several times, more freedom to sedimentation rates can be given resulting in the calculated timescale to be more accurate.

2.4 Results and Discussion

We have applied tuning to the data from all three Lake Baikal drilling cores, i.e. magnetic susceptibility that varies with depth and insolation that varies with time. The former curve was additionally filtered (Butterworth bandpass filter of order three) for all the frequencies that are present in the insolation (Figure 2-2) after every new and improved timescale was built in the dynamic optimization algorithm. Tuning to precession and obliquity only, as Yu and Ding (1998) suggested, assumes a linear relationship between the paleoclimatic record and the irradiation curve. Such assumption can introduce errors in the tuned age model as the relationship is not that straightforward (Rial and Anaclerio 2000) and will be described later in the text. That is why we decided tuning to the susceptibility record that was filtered for all the frequencies present in the insolation in order to avoid removal (or lowering the significance) of prospective non Milankovitch cycles. An example of the tuned time-age scale for the BDP-98 core for the Brunhes and upper Matuyama chrons is shown in Figure 2-5. The age models for the two remaining cores as well as the control points that were used in tuning can be found in Appendix A. The points were obtained independently for each magnetic susceptibility curve to avoid possible bias when choosing correlation extrema. The obtained age model is different than the one produced by Ochiai and Kashiwaya (2005) given in Figure 2-5. Our model additionally utilizes well dated control points from the beryllium based chronology by Sapota et al. (2004) which were adjusted by the visual correlation of the insolation and magnetic susceptibility peaks and control points for the top and bottom of the geomagnetic events in upper Matuyama.

The stack i.e. the average of the separately tuned susceptibility data sets from BDP-96-1, BDP-96-2 and BDP-98 records, has been calculated and the results are shown in Figure 2-6. The standard deviation, denoted in the figure by the blue

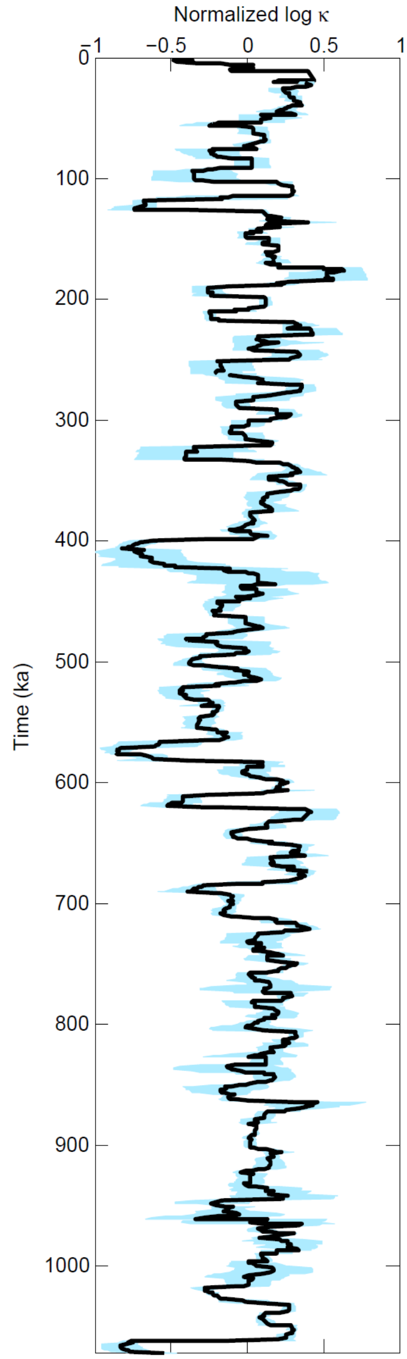

Figure 2-6. Stacked and normalized magnetic susceptibility record from the Lake Baikal BDP-98, BDP-96-1 and BDP-96-2 drilling cores for the Brunhes and upper Matuyama chrons (black line). The blue area represents standard deviation from the mean value of the series.

area, has also been computed for each stacked data point. For the deviation calculation, data from two or three cores have been taken depending on the part of the core due to their different lengths. No deviation was computed for the time interval for which there was data from only one core. Although the recovery rate for cores is exceptionally high (93–98%) the stacking procedure eliminated the gaps as well as any inaccuracies during core sampling or individual core age model imperfections.

In order to check the validity of the model, spectral analysis of the tuned susceptibility record has been performed. Climatic records are often unequally sampled. Such records are usually interpolated to obtain equal spacing and then Fourier Transform is used for spectral analysis. The results obtained in such way are often unreliable as the interpolation may cause smearing effect between spectral numerical artifacts and true periodicities in the data (MacDonald 1989). To eliminate these problems we apply spectral analysis of data with unequal spacing (method of Lomb-Scargle). First, Lomb-Scargle (Lomb 1976, Scargle 1982) normalized periodogram of the stacked magnetic susceptibility record has been calculated and the results are shown in Figure 2-7a. Since the periodogram does not estimate the power spectral density in a consistent manner, it was additionally smoothed with the Tukey-Hanning discrete spectral window. In this way erratic fluctuations of the periodogram and the data variance can be reduced (Weedon 2003). From Figure 2-7a one can notice that Milankovitch periodicities are indeed present in the signal i.e. eccentricity at 100 kyr, obliquity at 41 kyr and

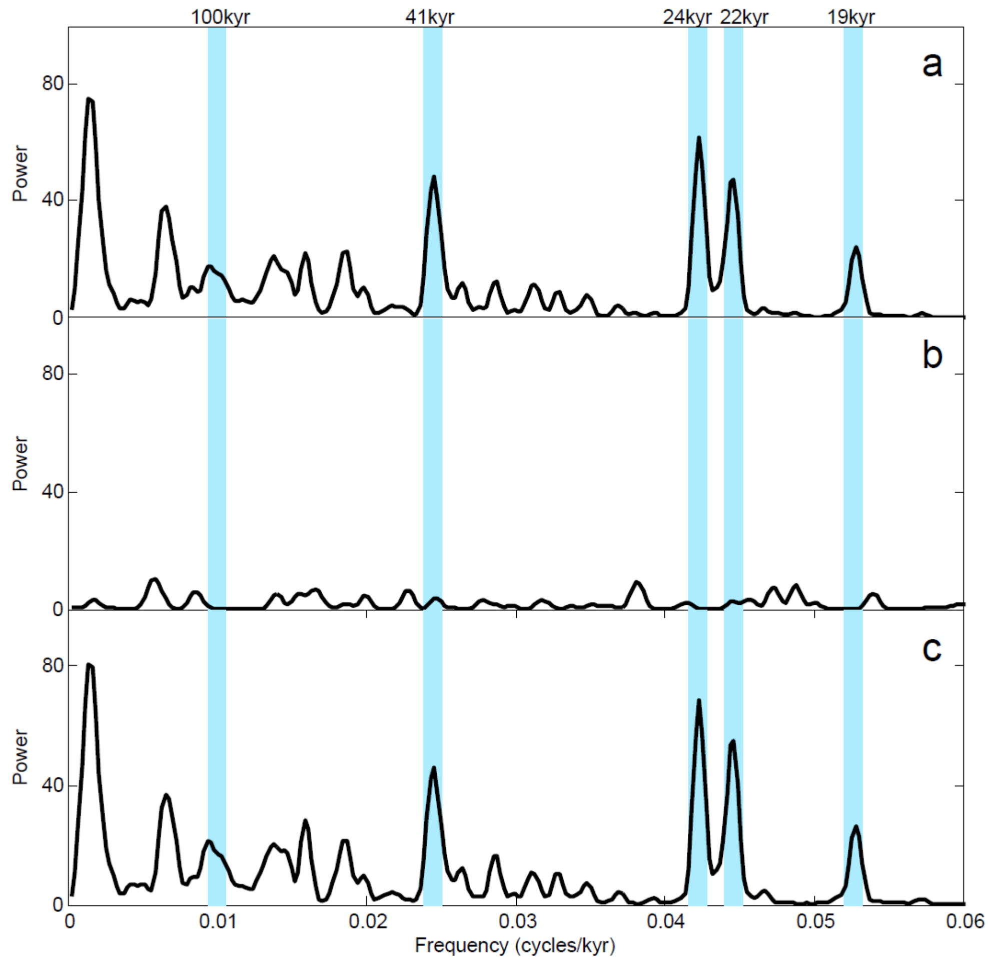

Figure 2-7. Smoothed periodogram of: (a) the magnetic susceptibility stack built based on the tuned timescales of the BDP-98, BDP-96-1 and BDP-96-2 drilling cores, (b) the noise and (c) the true signal (after noise removal) from the magnetic susceptibility spectrum (Figure 2-7a) based on the method of MacDonald (1989). Known Milankovitch periodicities are denoted by vertical blue lines.

precession at 19 kyr, 22.4 kyr and 23.7 kyr. The latter two cycles are usually denoted in the literature by one frequency at 23 kyr, since both peaks lie very closely to each other and are often indistinguishable. In this paper we follow the literature terminology though we will distinguish both peaks in periodograms when possible. To investigate the statistical validity of spectral peaks from Figure

2-7a the method of MacDonald (1989) was used. The main advantage of this method is the possibility of investigation of unequally sampled data. This is especially important as recent studies of Rial and Anaclerio (2000) showed the existence of nonlinearities in climatic records. The technique of MacDonald (1989) is as follows, the maximum peak in the normalized Lomb-Scargle periodogram is found and tested against false alarm probability which denotes the statistical chances of misidentifying a noise peak as a true peak. If the peak passes the false alarm test, the amplitude and phase that correspond to the sinusoid at peak frequency is calculated. Subsequently, the sinusoid is subtracted (together with its side lobes) from the time series what results in the decrease of the variance of the data. In the next steps further maximal peaks are found and removed from the spectrum until they fail to pass the false alarm test. The residual part of the spectrum is a noise of the original time series. In the present study the false alarm rate was set to 0.01 which means that there is 1% of chances to falsely identify a noise peak as a true peak (under the assumption that noise is normally distributed). The detailed theoretical analysis of the procedure outlined above is described in MacDonald (1989). The results of the statistical analysis are given in Table 2-1 and also in Figure 2-7b and 2-7c. The table contains ten the most significant peaks in the spectrum, whereas the figures show smoothed spectra of noise and of true signal (after noise removal), respectively. Figure 2-7c and Table 2-1 confirm the existence of main Milankovitch cycles in the magnetic susceptibility record i.e. precession around 22, 24 kyr and obliquity around 41 kyr. These are the same periodicities as the ones in the insolation spectrum in

Peak number	Frequency (cyc/kyr)	Period (kyr)	Contribution to total variance (%)
1	0.0016	611.6	12.4
2	0.0423	23.7	10.7
3	0.0245	40.8	7.8
4	0.0446	22.4	6.4
5	0.0065	152.9	5.9
6	0.0528	18.9	4.0
7	0.0028	356.7	3.6
8	0.0159	63.0	3.6
9	0.0135	73.8	3.4
10	0.0187	53.5	2.9

Table 2-1. Significant peaks in the magnetic susceptibility periodogram of the stacked data.

Figure 2-2. Apart from these cycles one can observe spectral peaks that are not present in the solar irradiation curve (non Milankovitch periodicities). Rial and Anaclerio (2000) and references therein, indicate nonlinear response of the climate to solar forcing as a reason for the extra peaks in the power spectra. The nonlinear behaviour is not understood at the present time. However, researchers try to explain the peaks as harmonics and/or combination tones of the orbital cycles (Rial and Anaclerio 2000). Such extra frequencies have often been found in climatic records. Many other authors reported similar peaks as the ones found in the present study. Phedorin and Goldberg (2008) mentioned the presence of ~70 kyr and ~30 kyr in the Vostok polar temperature signal. Hinnov (2000) showed in her calculations the presence of ~29 kyr and ~54 kyr peaks in the insolation. Rial and Anaclerio (2000) found ~29 kyr and ~69 kyr in the Vostok ice core data as well as ~148 kyr and ~65 kyr in the oxygen isotope data.

Goldberg et al. (2000) discussed ~54 kyr and ~72 kyr in the geochemical signals of Lake Baikal. Kravchinsky et al. (2003, 2007) showed the presence of ~35 kyr and 72 kyr in their Lake Baikal magnetic susceptibility data. Additionally frequency decomposition of the eccentricity and obliquity on Earth performed by Laskar et al. (2004) resulted in cycles around 346 kyr, 103 kyr, and 52 kyr.

Further analysis of the tuned records is done using the software of Grinsted et al. (2004). Most researchers (Prokopenko et al. 2001, 2006, Kravchinsky 2003, Ochiai and Kashiwaya 2005 and others) when treating climatic records only analyze common powers between two time series. Grinsted et al. (2004) proposed wavelet analysis not only to investigate common powers, but also phases in order to gain confidence in common periodicities. Additional phase investigation is of importance since it is statistically possible for two series to have a common peak but not be related. Figure 2-8a and b, obtained using the software of Grinsted et al. (2004), show continuous wavelet transforms (CWT) of the magnetic susceptibility and insolation data sets. The thick black contour represents the area with 5% significance level against red noise. Red noise i.e. the sloping of the spectrum especially at low frequencies has been often found in climatic records (Schulz and Mudelsee 2002). The thin black line denotes the cone of influence i.e. the area where the power of the edge discontinuities decreased to e^{-2} of its value at the edge (Grinsted et al. 2004). Edge effects are due to a wavelet being not completely localized in time and may cause problems in the interpretation of results outside the cone of influence since found peaks maybe either true peaks or

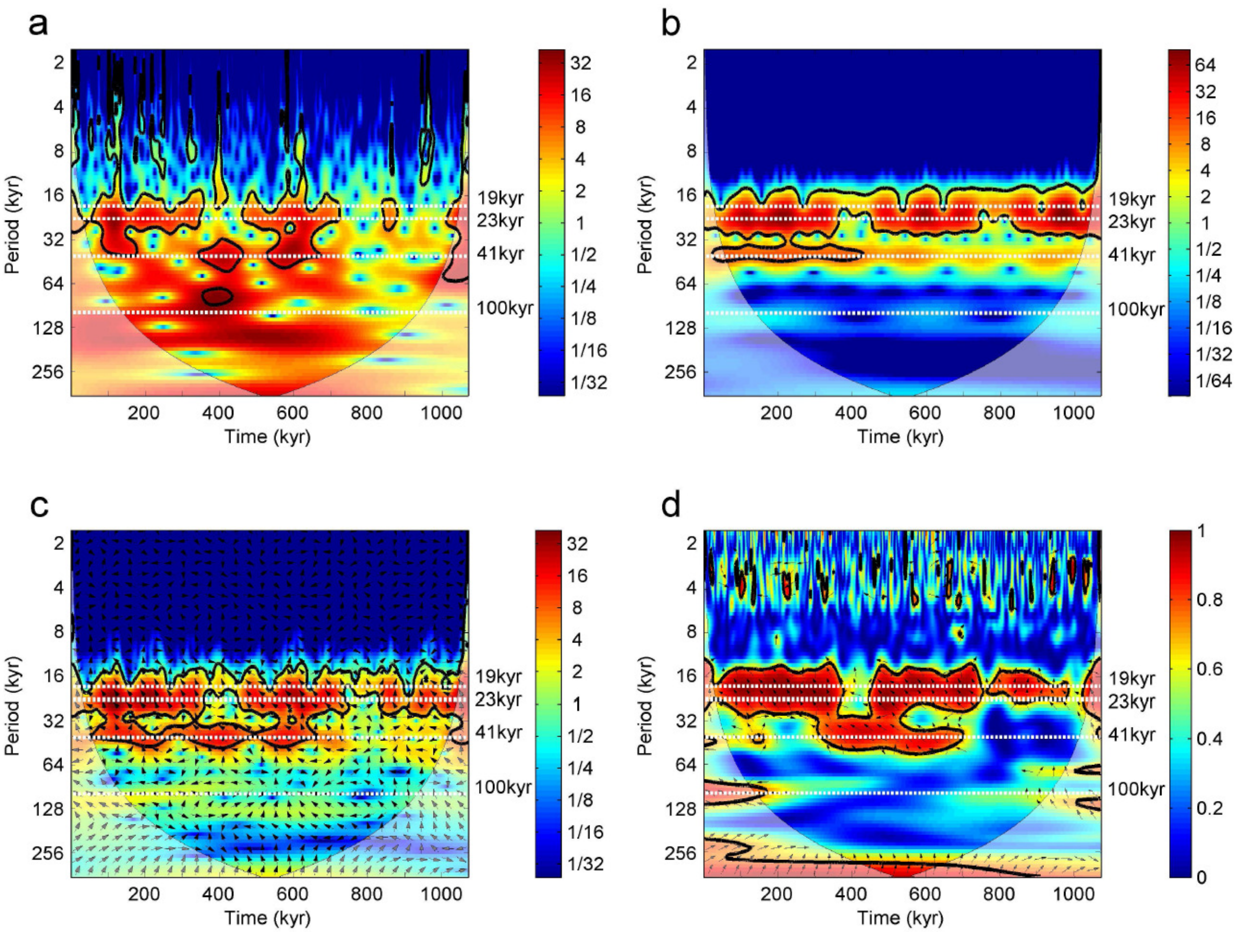

Figure 2-8. Continuous wavelet power spectra of the stacked magnetic susceptibility (a) and insolation (b). The color bars correspond to wavelet power. Cross wavelet transform and squared wavelet coherence of the stacked magnetic susceptibility and insolation time sets are given in (c) and (d), respectively. The phase relationship between series is shown by arrows. The color bars corresponds to cross wavelet power (c) and to the magnitude of coherence (d). The thick black line denotes the 5% significance level, the thin black contour shows the cone of influence and white dashed lines represent known Milankovitch periodicities.

artifacts of signal processing (Torrence and Compo 1998). From Figure 2-8a and b one can clearly see high powers that correspond to Milankovitch periodicities (i.e. precession and obliquity) which are denoted by dashed white lines. In the insolation spectrum Milankovitch cycles are visible for almost the entire time period whereas in the susceptibility spectrum there are noticeable only for specific time intervals. Grinsted et al. (2004) applied subsequently, the cross wavelet transform (XWT) to investigate common powers and relative phase relationship between series, and wavelet coherence (WTC) to check the local correlation between the curves. The authors explain that if the series are related then the phase should be either constant or vary very slowly i.e. phenomena should be phase locked. Figure 2-8c and d show XWT and WTC of the input series, respectively. From both figures one can see substantial common power and correlation at the obliquity and precession frequencies. Also, phases which are denoted by the black arrows (arrows pointing right correspond to the two series being in-phase whereas arrows pointing left correspond to anti-phase) vary slowly in the area with 5% significance level. This means that the main periods for the stacked records are obliquity and precession.

The investigation of the spectrum of the stacked magnetic susceptibility data (Figure 2-7c or Figure 2-9a) reveals that the precession is resolved much better than in any previous publications. This is definitely a difficult task because of the nonlinearities in the sedimentation rates that, as our study demonstrates, have important damaging influence particularly on high frequencies. Our tuning

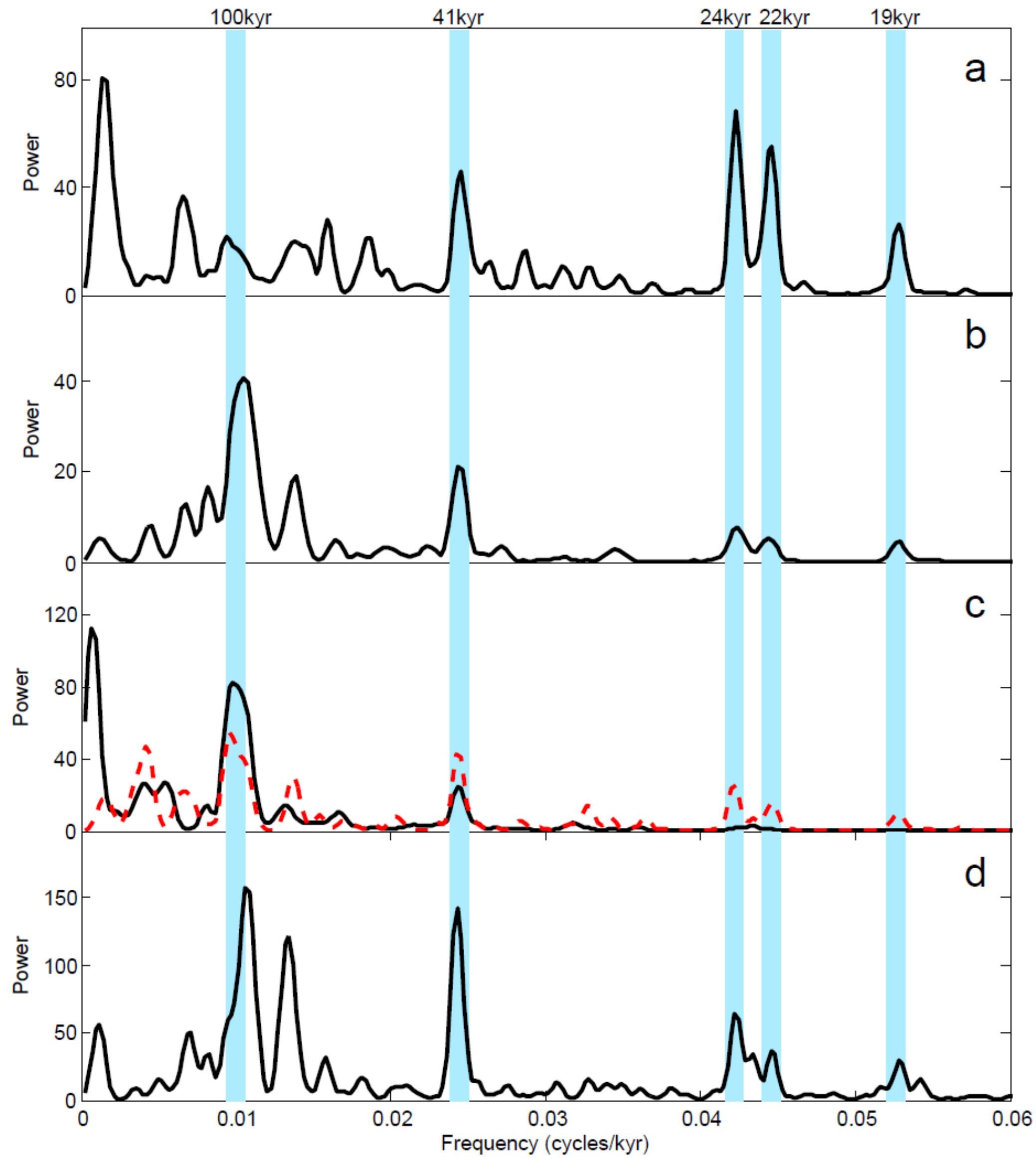

Figure 2-9. Smoothed periodogram of: (a) the magnetic susceptibility stack after noise removal (the same as Figure 2-7c), (b) the oxygen isotope record based on the data given in Bassinot et al. (1994), (c) Chinese Loess Plateau grain size (red dashed line) and magnetic susceptibility data (black line) from Sun et al. (2006), (d) Lake Baikal composite BDP-96 Pleistocene biogenic silica data from Prokopenko et al. (2007). Known Milankovitch periodicities are denoted by vertical blue lines.

methodology does not destroy high frequency orbital periodicities. Our control points were constructed not only by visual correlation between the susceptibility data and insolation but also are backed up with magnetostratigraphy and beryllium dating. The automatic orbital tuning technique implied in our study demonstrates effective correction for the non-linearity of the sedimentation rate and shows that any other age model that accounts for the linear changes between control points destroy the short frequencies at different degree.

Strong precession peaks observed in the Lake Baikal magnetic susceptibility record are in agreement with the theoretical insolation power spectrum which predicts such peaks to be stronger than others (Laskar et al., 2004) (Figure 2-2). We consider that the previous works on the Lake Baikal climatic proxy records did not succeed in extracting the precession peaks because they did not take in account non-linear variations of the sedimentation rate. Our record also eliminates most of the white noise errors during the stacking procedure. Short et al. (1991) developed a theoretical model that demonstrates that 19 kyr and a double 23 kyr peak are expected to be the strongest in the continental interior whereas eccentricity should appear as a weak peak. They concluded that precession must influence the climatic changes in the continent in a much larger degree than eccentricity. An example of marine spectrum is given in Figure 2-9b (based on the data from Bassinot et al. 1994). The spectrum clearly shows high amplitude peak at 100 kyr. This is in agreement with Short et al. (1991) who explained that the ocean damps obliquity and precession responses resulting in 100 kyr peak becoming more evident in marine records. The Chinese loess magnetic susceptibility and sedimentary grain size power spectra from Sun at el.

(2006) (Figure 2-9c) are similar to the oceanic ones. The Chinese loess is situated very close to the ocean and is under the strong influence of the ocean caused summer monsoon. Lake Baikal is one of the most remote from the oceanic influence locations on Earth and therefore we consider that its climatic record could be driven by the precession climatic cyclicity. At the same time previous publications showed that climatic proxy records from the Lake Baikal correspond better to the oceanic record because the oceanic record was taken as a reference curve for dating. Only very careful correlation of Prokopenko et al. (2006) was able to highlight an importance of the precession cycles in the Lake Baikal diatomaceous record for the first time (Figure 2-9d). Nevertheless, the resulting power spectra were still analogous to the oceanic spectra probably because the rate of sedimentation was considered linear between the correlation points.

Our study demonstrates that the eccentricity cycles could be the leading climatic change factor at the center of the Eurasian continent. The correctness of such presupposition is additionally confirmed by an independent dataset from the continental West Siberian loess/paleosol record in which spectra the precession cycles dominate (Kravchinsky et al. 2008). This is especially important as Kravchinsky et al. (2008) did not apply any tuning to obtain an age model but used numerous thermoluminescence absolute dates to construct their age model. On the basis of our Baikal result we predict the continental records from other lakes and loess deposits from the deep continental interior should show stronger precession peaks when non-linearity of the sedimentation rate is taken into account.

Our stack can be used as a reference curve for dating paleoclimatic data from the continental interior. Dating using our reference curve might be preferred than using insolation directly because in the stack we preserved other than orbital cycles. Some of the cycles might be destroyed or shifted when tuning data from only one drilled core to insolation. Stacking of the data from three cores that were extracted from almost the same location is not often the case in paleoclimatic studies.

2.5 Conclusions

The Lake Baikal magnetic susceptibility signal contains the information about climatic response to orbital forcing. Based on this knowledge new age models were constructed for the Brunhes and upper Matuyama chrons for the BDP-98, BDP-96-1 and BDP-96-2 cores. The magnetic susceptibility records from all three cores were also stacked. The tuned age model is a definite improvement to the previously constructed timescales. Our timescale is in agreement with recently published beryllium dating. Also, spectral analysis confirmed the presence of Milankovitch periodicities and showed that their significance is in accordance with the expected theoretical model.

The high frequencies in our power spectra of the magnetic susceptibility stack were resolved better than in any previous work. This is definitely a challenging task due to nonlinearities in the sedimentation rates that have important destructing effect especially on short periods. Since the non-orbital periods were preserved in the stack, our composite can be used as a reference when dating sedimentary sequences in the deep continental interior.

Precession and obliquity responses are the most profound out of all Milankovitch cycles whereas eccentricity signal is small. The results serve as a confirmation that climatic response in the continental interior is different from the one over ocean where the eccentricity signal is the most prominent. Spectral analysis also showed the presence of non-Milankovitch cycles. This is definitely an important observation that was already previously reported in literature but may help in the understanding of climatic nonlinear behaviour.

Tuning was done to the solar irradiation curve as it directly influences the surface temperature and therefore, the deposition of terrigenous minerals as well as the diatom production. Some authors in their tuning methods use an oceanic oxygen isotope record as a correlation target. This approach is flawed when dealing with continental data and such analyses should be corrected. This is due to different climatic responses between continental and non-continental environments, as it was proven in the current study.

Inclination record demonstrates a few geomagnetic polarity events resolved in the BDP cores in details. We demonstrate the Brunhes Matuyama Boundary precursor which may be a double peak event, Kamikatsura, Santa Rosa and Jaramillo. Santa Rosa appears as a double event, Kamikatsura's bottom can be easily identified, the top of the event is not well resolved in the Baikal record. We dated the top and bottom of the events using the correlation with SINT-2000 paleointensity minimums. The obtained ages compare with published dates favourably and could be used as the reference dates in the future.

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3. Novel automatic orbital tuning methodology[3]

3.1 Introduction

Numerous studies in the last decades have shown that various properties of sediments in the oceanic and continental records (grain sizes, concentration of the oxygen isotope, biogenic silica content, magnetic susceptibility, etc.) are influenced by orbital changes of Earth i.e. Milankovitch cycles (Imbrie et al. 1984; Shackleton et al. 1990; Kravchinsky et al. 2003; Ochiai and Kashiwaya 2005). This climatic forcing enables the creation of age models for sedimentary sequences from drilled boreholes with the technique called orbital tuning. There exists a wide range of tuning methods. Most of them employ a comparison between theoretical curve that represents orbital variations and the paleoclimatic data set. The comparison can be made by quasi-visual analysis (Kravchinsky et al. 2003), maximization of the correlation coefficients (Yu and Ding 1998) or construction of additional mapping or intermediary functions (Martinson et al. 1982; Brüggemann 1992; Ochiai and Kashiwaya 2005). A common problem in most of the tuning techniques is related to the presence of noise in the paleoclimatic data. Tuning to noise will introduce errors in the built timescale. Many of the tuning methods utilize some form of filtering of the input data to overcome these problems. Care has to be taken when applying filters since one can eliminate frequencies that are in non-Milankovitch bands. Such frequencies do exist and are the result of the climate responding in a nonlinear way to orbital forcing (Rial and Anaclerio 2000).

[3] A version of this chapter together with Chapter 1.2 is in the stage of submission for publication. Rohraff, Kravchinsky, Sacchi 2011. Geophysical Research Letters.

One of the biggest challenges in orbital tuning is connected with resolving high frequency components. These components are of significant importance when studying paleoclimatic data, especially from deep continental interiors where climatic response to precession should be dominant (Short et al. 1991 and Chapter 2). Even small errors in the tuned timescales can completely destroy short periodicities. In Figure 3-1 we present how the spectral response of a simple sinusoidal signal with two dominant periods (100 kyr and 19 kyr) changes after adding random errors to the signal's timescale. Introducing the error of several kyrs causes the power of the 19 kyr peak to be substantially diminished and shifted towards other frequencies. On the other hand, the 100 kyr peak has been preserved even when the large error of about 10 kyrs was introduced. This toy example shows how sensitive the high frequency components are to the potential errors in the built timescales.

Considering the importance of the accuracy of the tuned age models and the influence of errors on the spectrum we are presenting a novel automatic orbital tuning technique that eliminates the need of filtering of the paleoclimatic records. The technique will be applied after the initial and low resolution age model has been constructed to improve its resolution. The control points used for the creation of the initial timescale are described in large detail in Chapter 2 and are based on beryllium dating, magnetostratigraphy and visual inspection. The magnetic susceptibility data that is used in the study was obtained from the cores from Lake Baikal and their description with the explanation about the connection to orbital forcing can be found in Kravchinsky et al. (2003) and in Chapter 2.

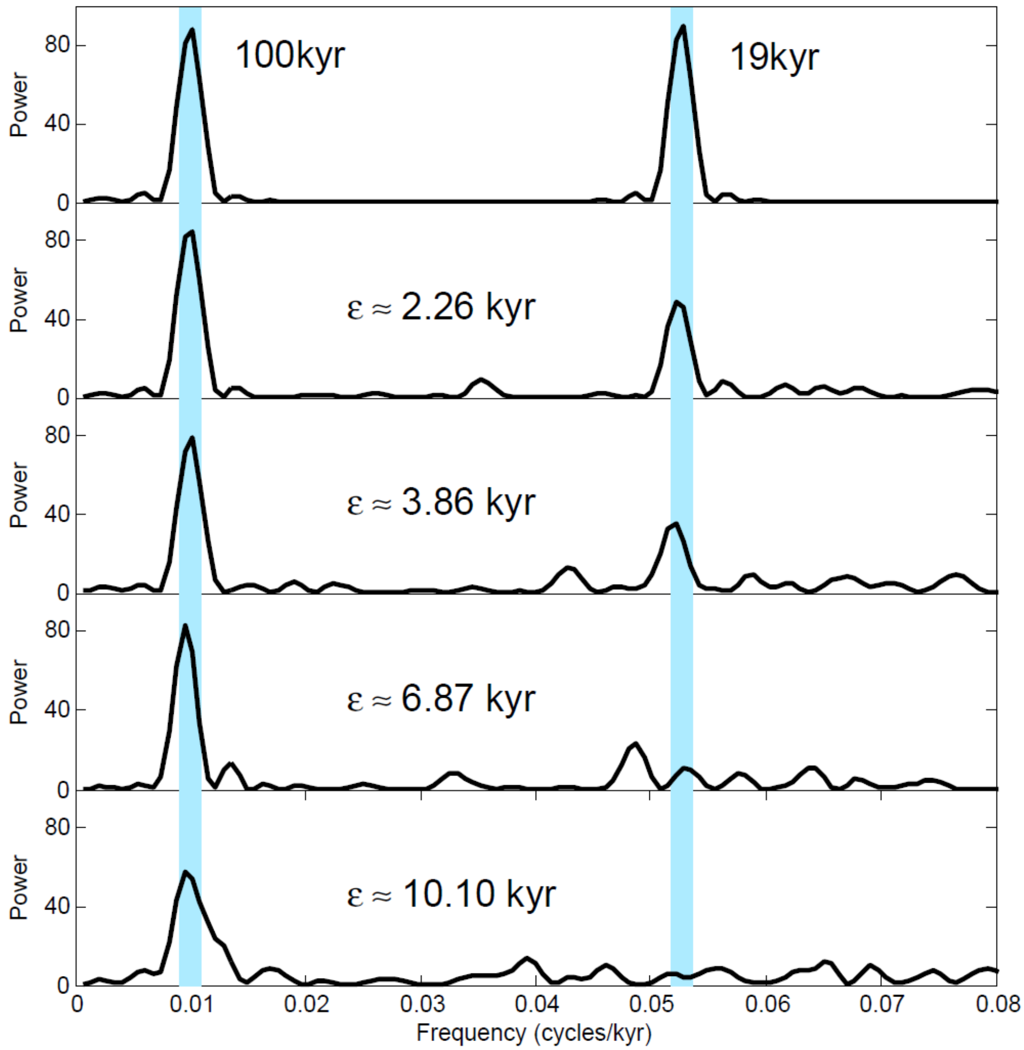

Figure 3-1. Periodogram of a simple sinusoidal signal with two dominant frequencies (100 kyr and 19 kyr) is shown in the upper plot. The remaining figures represent how the spectrum changes after introducing random errors to the timescale. The ε parameter denotes the average random error that was added to the timescale.

3.2 Tuning Methodology

Paleoclimatic data set B, obtained from sediment analysis, is always a function of depth x. A common procedure in tuning is the comparison of B(x) with a time dependent curve A(t) that contains Milankovitch periodicities. The A(t) function can be either theoretically calculated insolation or some other previously tuned paleoclimatic record such as oxygen isotope. From the comparison of the two curves a new function B[t(x)] can be constructed, where the t(x) is the sought age model. In the present study we are not using the reference curve A(t) in tuning but only the Milankovitch periods that the curve contains. The tuning procedure consists of the following steps:

1. A randomly sampled timescale is constructed between two control points. The length of the sampled data should be the same as of the original paleoclimatic record unless interpolation of the record is desired.
2. Using Lomb periodogram the value of power at one chosen Milankovitch frequency is recorded. The Lomb method is used since it allows the estimation of the power spectrum from unequally sampled data.
3. Step 1-2 is repeated N times and the random timescale is chosen for which the value of power at the desired frequency is maximal. The number N is chosen such as to guarantee the stability of the solution. The lager the number the more stable result can be found. For our purposes we found that $5x10^4$ is a good compromise between stability and the computational time. Additionally, the more control points are used, i.e. the shorter time interval for which the timescale is built, the lower value of N is required to guarantee the stability of the solution.
4. Steps 1-3 are done again M-1 times, where M is the number of control points from the initial age model. In this way the optimal timescale is created between all control points.

5. Steps 1-4 are repeated for all Milankovitch periodicities of interest and thus the optimal timescale for each cycle is produced.

6. The constructed timescales are then stacked to produce the final age model.

In the procedure described above we do not put any restraints on the maximal powers sought between different Milankovitch cycles. It is because the importance (in terms of numerical values) of the periodicities with respect to each other is not understood at the present state of knowledge. We also found that tuning to separate peaks and then stacking gives better results than tuning to all peaks at the same time. This is due to the former method having slightly less shifts of power to non-Milankovitch bands. Thus this method assumes that the main driving force in climatic changes are orbital periodicities however it does not eliminate other cycles that could be used for understanding climatic nonlinear behaviour. Our tuning methodology allows tuning a paleoclimatic signal to specific frequencies. This is very advantageous since climate in various regions in the world exhibits sensitivity to different periodicities.

3.3 Results and Discussion

We have applied our new tuning methodology to three cores from Lake Baikal i.e. BDP-96-1, BDP-96-2 and BDP-98. The timescale for each core was constructed by tuning to precession peaks. Tuning to 19, 22 and 24 kyrs was chosen as these are the Milankovitch frequencies that have the most significant influence on the Lake Baikal climate (Short et al. 1991 and Chapter 2). The constructed timescales were subsequently stacked to reduce white noise and produce the final age model for the magnetic susceptibility signal. The result is presented in Figure 3-2 together with similar stack developed in Chapter 2 using the same data sets but employing classical tuning to the insolation curve. Both stacks are very similar and show the same general features with the exception that some of the peaks are slightly stretched or squeezed.

In order to investigate the accuracy of the model, the spectral analysis using the method of MacDonald (1989) was performed. This method was chosen as it enables the analysis of the irregularly sampled data and estimation and removal of Gaussian noise from the input signal. The obtained result is given in Figure 3-3 which shows the power spectra of the stacks from Figure 3-2. Both spectra are very similar with precession peaks being most profound out of all Milankovitch cycles. This implies the correctness of our new tuning methodology. The main advantages of our approach compared to the classical tuning is no need for filtering of the input data, simplicity of tuning to chosen frequencies and possibility of enhancing short Milankovitch periods. The latter may be of special importance as different regions of the world record orbital cycles in a different way.

The analysis of the stacked magnetic susceptibility spectrum from Figure 3-3a demonstrates that precession peaks are resolved much better than in many other publications. The difficulty of this task is partially due to nonlinear sedimentation

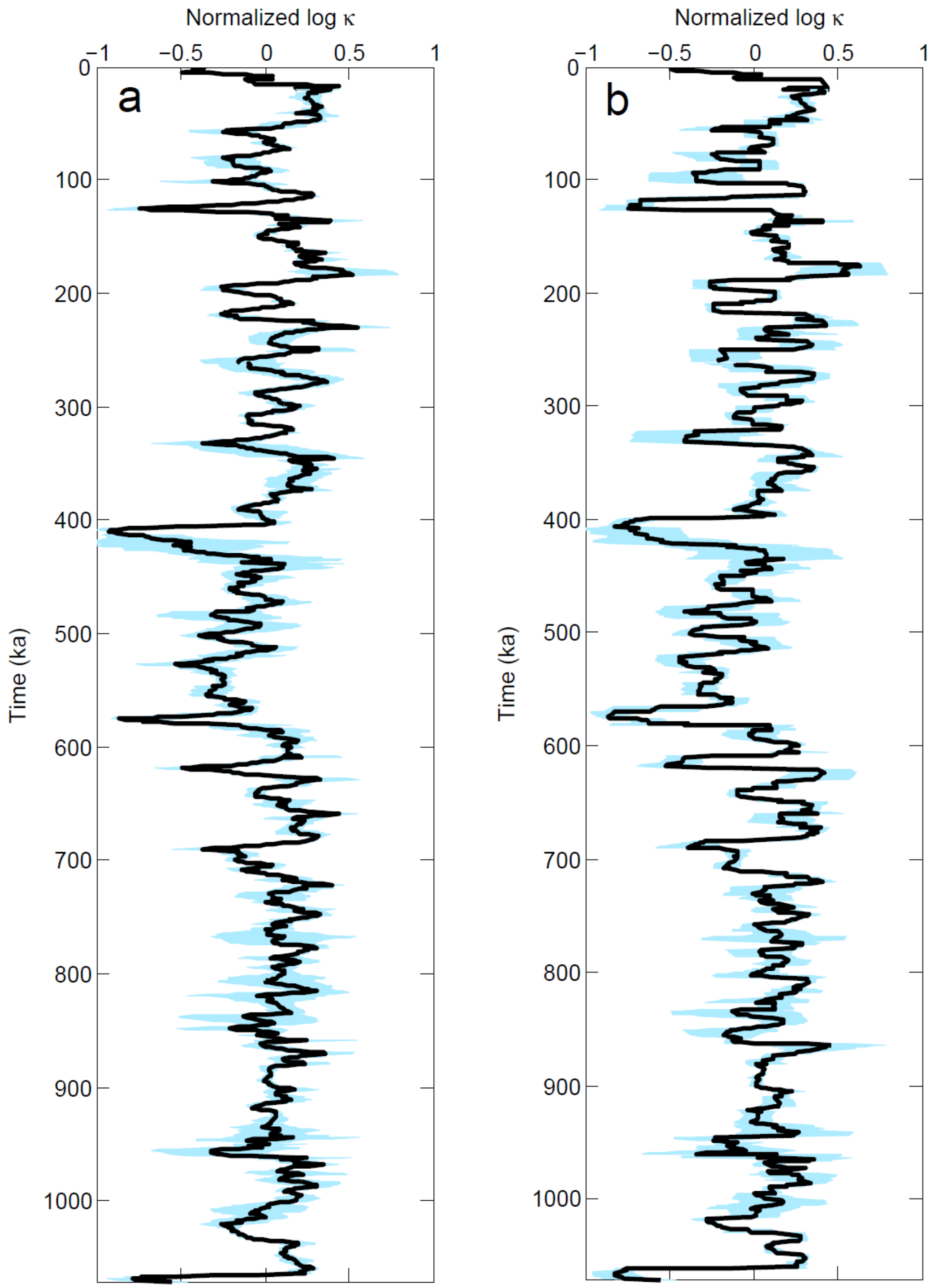

Figure 3-2. (a) Stacked and normalized magnetic susceptibility (κ) signal from Lake Baikal for the Brunhes and upper Matuyama chrons (black line) using tuning methodology developed in the present study and (b) similar stack developed in Chapter 2. The blue area represents standard deviation from the mean value of the series.

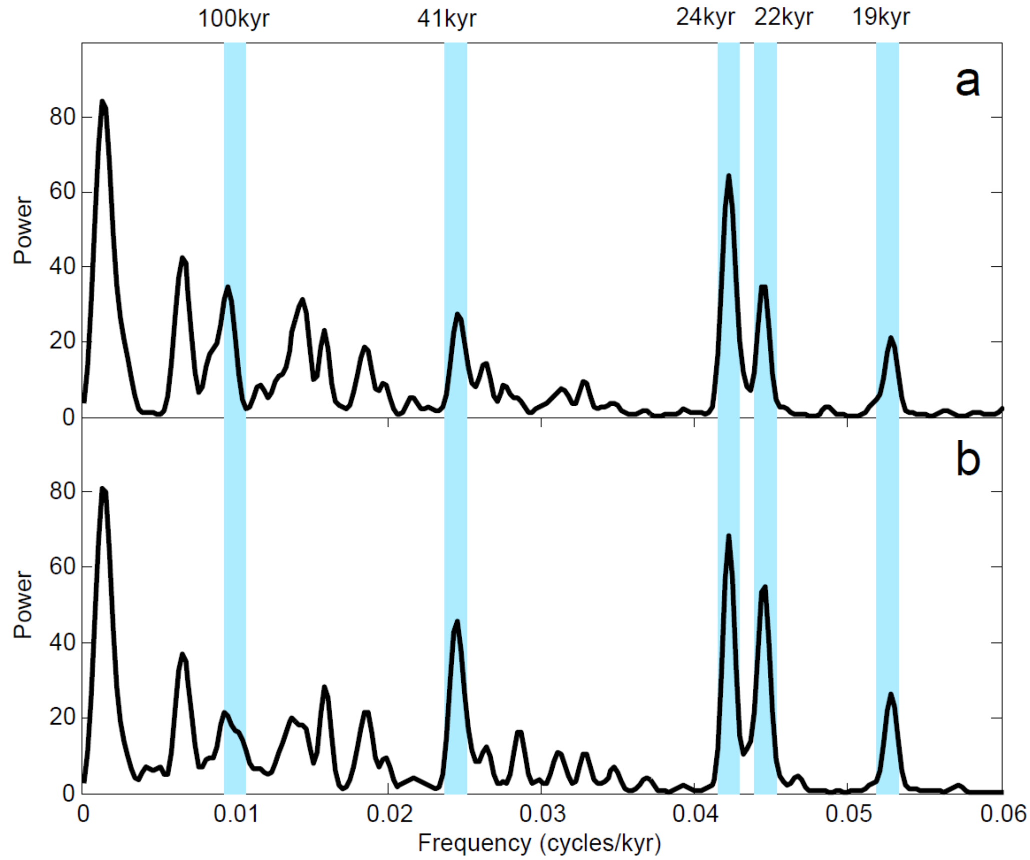

Figure 3-3. Smoothed periodogram of: (a) the magnetic susceptibility stack after noise removal based on the method of MacDonald (1989) and (b) similar stack developed in Chapter 2. Known Milankovitch periodicities are denoted by vertical blue lines.

which has a damaging effect especially on high frequencies. Our new tuning approach does not destroy short Milankovitch cycles. The automatic tuning method presented in this paper is able to account for a nonlinear sedimentation rate. Any other timescale that assumes linear sedimentation between control points, destroys high frequencies at various degrees.

3.4 Conclusions

The construction of age models for drilled boreholes is of primary importance in paleoclimatic studies that focus on the investigation of the past climate. High accuracy of the timescales is needed to properly date climatic changes with the passage of time. Most of the orbital tuning methods have difficulties with resolving short periodicities. It is because even small errors in the tuned timescales shift the power in the spectrum from high frequencies to other periods. The method developed in the present study aims to improve the high frequency response by accounting for nonlinearity in sedimentation rates and thus providing a more accurate age model. This can be achieved through the maximization of the spectral response at orbital frequencies. Our methodology also allows tuning of the paleoclimatic record to specific periods which can be very useful as the different regions in the world respond to orbital cycles in a different way. Additionally, the method enables the construction of high resolution timescale since each of the measured data points is assigned an age individually and thus eliminating the need for linear interpolation between control points.

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4. General Conclusions

All goals of the thesis have been achieved.

- The magnetic susceptibility stack and its timescale have been developed based on three cores from Lake Baikal. The obtained new timescale is in compliance with previously published absolute ages and improved already published age models for last 1.1 Myrs considerably.
- Spectral analysis of the composite magnetic susceptibility record clearly demonstrates that precession has been resolved much better than in any other studies. This is in agreement with the expected theoretical models of Short et al. (1991) and Laskar et al. (2004). Since non-Milankovitch cycles have also been preserved in the composite record, the developed stack can be used as a future reference curve for dating and comparison with other sedimentary records in the continental environment of Eurasia.
- It was shown that inland and marine climatic responses differ which implies that using the oceanic reference curves for dating of the continental sedimentary records may produce biased results and inaccurate age models. Consequently, previous studies in the continental interior that built the age models using the correlation with oceanic ones should be regarded with precaution.
- A new tuning methodology has been developed to improve the resolution of short periods by maximizing spectral response at particular frequencies. The technique was tested and deemed very successful by the

usage of the same data set as in the first part of the research. Results of the both techniques coincide.

4.1 Bibliography

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5. Future Work

The location of Lake Baikal in the central Asia not only ensures high climatic sensitivity to the changes in Earth's orbital parameters, but also gives a unique opportunity to evaluate the longest continuous continental record ever. It would be advantageous to construct an age model for the entire dataset of 8.2 Myrs and compare it with the longest possible records coming from different regions of the world in order to asses the regional and global climate changes in the past. Additionally, by analyzing the complete susceptibility record, more understanding about non-Milankovitch or very long-period Milankovitch cycles could be gained, especially since the nature of these cycles is still subject to a scientific discussion.

Appendix A[4]

A.1 Tuning of the BDP-96-1, BDP-96-2 and BDP-98 cores

Control points that were acquired for BDP-96-1, BDP-96-2 as well as for BDP-98 were obtained independently to avoid possible bias when choosing correlation extrema. In order to obtain the best fit between curves, we sometimes tuned to minima and sometimes to maxima. This is why the control points for all cores (Table A-1, A-2 and A-3 in the Appendix A) have different ages.

Depth (m)	Time (ka)
10.20	261
11.10	276
13.27	321
13.79	332
14.41	345
16.72	395
17.13	408
18.48	435
20.84	494
22.06	513
23.94	564
24.49	575
26.73	618
27.63	643
28.98	679
30.53	722
33.80*	776
38.63*	885
39.75*	932
40.30*	945
43.34*	987
46.50*	1071

Table A-1. Age-depth control points for the Lake Baikal BDP-96-1 core.

Note: The control points given in the table were obtained from visual correlation of extrema between insolation and magnetic susceptibility curves. The points

[4]A version of this chapter together with Chapter 2 has been submitted for publication. Rohraff, Kravchinsky, Sacchi, Sakai 2011. Geochemistry, Geophysics, Geosystems.

denoted with an asterisk correspond to chron boundaries found by comparison of inclination records with the SINT-2000 paleointensity data from Valet et al. (2005).

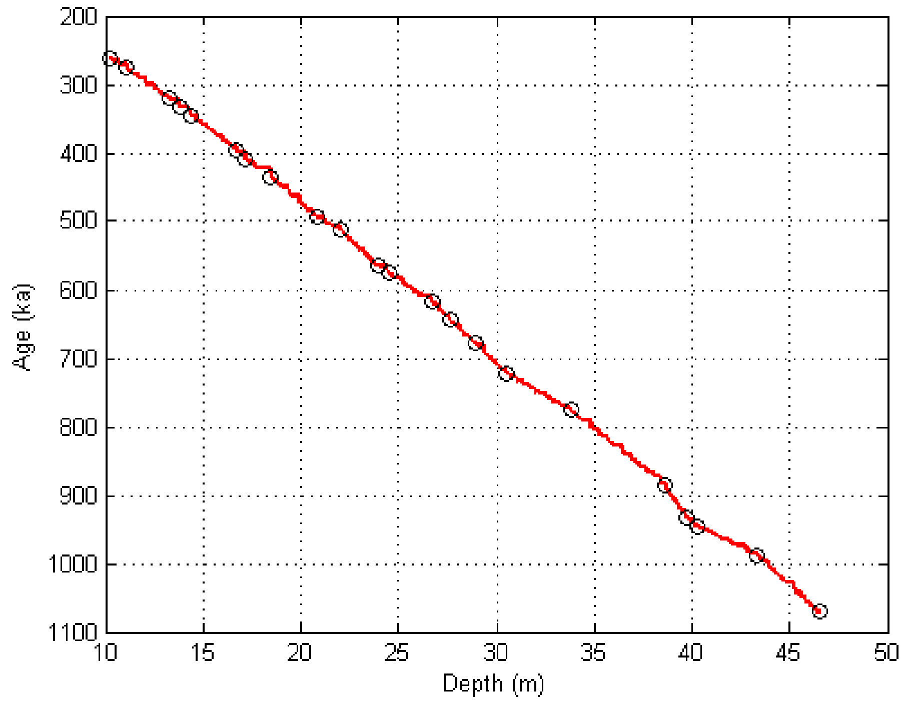

Figure A-1. The tuned time scale for the BDP-96-1 core based on the control points from Table A-1.

Depth (m)	Time (ka)
0.21	20
1.76	55
2.96	101
4.36	126
9.38	229
9.85	240
11.75	276
14.38	333
17.68	409
20.87	472
21.37	483
21.68	502
23.05	524
24.64	565
25.34	575
27.06	619
29.71	691
31.57	722
34.20*	776
38.38**	-
39.21*	932
39.84*	945
42.82*	987
46.95*	1071

Table A-2. Age-depth control points for the Lake Baikal BDP-96-2 core.

Note: The control points given in the table were obtained from visual correlation of extrema between insolation and magnetic susceptibility curves. The points denoted with an asterisk correspond to chron boundaries found by comparison of inclination records with the SINT-2000 paleointensity data from Valet et al. (2005). The point with double asterisk represents the bottom of Kamikatsura chron that was not used in tuning. We rejected this point as it did not correlate well with the extrema of the tuning curves.

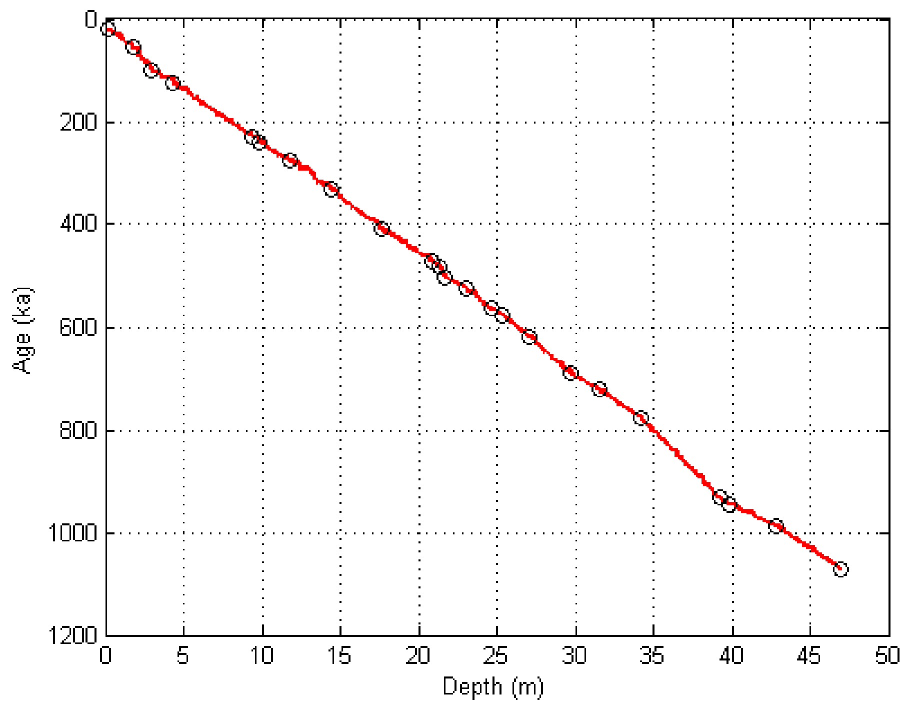

Figure A-2. The tuned time scale for the BDP-96-2 core based on the control points from Table A-2.

Depth (m)	Time (ka)
0.03	0.76
3.57	56
4.80	82
5.72	113
6.77	126
8.59	147
9.68	184
10.82	195
11.77	218
12.43	240
12.91	261
13.30	288
13.75	310
14.17	332
15.145	370
19.12	461
19.39	472
19.87	483
21.10	514
22.08	528
23.22	553
24.67	575
26.32	619
26.92	644
27.55	668
28.47	691
29.28	722
29.52	732
30.59	750
31.50*	776
35.05*	885
36.40*	932
36.80*	945
39.55*	987
43.10*	1071

Table A-3. Age-depth control points for the Lake Baikal BDP-98 core.

Note: The control points given in the table were obtained from visual correlation of extrema between insolation and magnetic susceptibility curves and by checking the results with beryllium dating. The points denoted with an asterisk correspond to chron boundaries found by comparison of inclination records with the SINT-2000 paleointensity data from Valet et al. (2005).