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Variability in palaeoclimatic periodicity over 2,500 kyr from magnetic susceptibility of Lake Baikal sediments

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ABSTRACT

Magnetic susceptibility was measured on the sedimentary core, BDP-96-2 (100 m length), drilled at the Academician Ridge of Lake Baikal, central Siberia. The palaeomagnetic study has showed that the sediment core covers the past 2,500 kyr. The magnetic susceptibility of BDP-96-2 showed high value during glacial periods and low value during interglacial periods, therefore, the susceptibility can be considered to be a good proxy for palaeoclimate around Lake Baikal region.

Spectral analysis to the susceptibility showed that principal periodicity well corresponded to the Earth's orbital cycles. Temporal changes in spectral power of principal periodicities showed a dominance of 100 kyr cycle since 1,200 kyr B.P. and an increase of 23 kyr cycle since 400 kyr B.P. The increase of 100 kyr cycle has been observed also in ODP records around 1200~700 kyr B.P. This variability in the periodicity is thought to be a reflection of change in the global climatic system related to the elevation of Himalayan Mountains. This study demonstrates that the signal of this global climatic change was also found in continental-interior region such as Lake Baikal. Whereas, the increase of 23 kyr precession cycle since 400 kyr B.P. is distinctive of Lake Baikal record. This suggests that local climatic system around Lake Baikal became highly sensitive to the solar insolation since 400 kyr B.P.

INTRODUCTION

Lake Baikal, located in eastern Siberia (104°~110°E, 51°~56°N), is one of the deepest (1,643 m), most voluminous (23,000 km^3) and oldest freshwater lakes in the world. It is an important and unique site for palaeoclimatic studies because of its high-latitude, continental-interior setting, and its long, continuous stratigraphic record. Grosswald (1980) suggested that Lake Baikal was not fully glaciated during the last glacial maximum, so that the continuous sedimentary record can be obtained during glacial periods. As the palaeoclimatic record from continental region is much fewer than marine records, the Lake Baikal sediment is particularly valuable and gives the information on continental climate over a long time period.

The purpose of this study is to investigate variability of palaeoclimatic periodicity over 2,500 kyr recorded in the magnetic properties of the sediment sequence. Recent studies show that the change in magnetic susceptibility can be a candidate of palaeoclimate proxy. In hemipelagic calcareous sediments, magnetic susceptibility is generally low in an interglacial period and high in a glacial period (*e.g.* Robinson 1986). This phenomenon is thought to reflect the dilution and concentration of magnetic material due to a change in biogenic sedimentation with climatic change (Thompson and Oldfield 1986). Bloemandal and DeMenocal (1989), for example, used magnetic susceptibility as palaeoclimatic proxy, and applied spectral analysis on the susceptibility data from Arabian Sea. In this study, we tried to extract palaeoclimatic signals from susceptibility data of Lake Baikal.

The Baikal Drilling Project (BDP) running since 1993 is an international project to investigate the palaeoclimatic history and tectonic evolution of this sedimentary basin. In 1996, the drilling of BDP-96-2 core (length of 100 m) was conducted at Academician ridge in the middle of Lake Baikal (Fig. 1). The upper 60 m of the core was obtained by piston corer and the lower portion (60~100 m) was obtained by percussion corer.

The core was divided into sub-cores of 2 m length, and each sub-core was cut in half-length-wise (split). Samples for rock-magnetic study were extracted from the half-length-wise core by plastic cases of 10 cm^3 with the interval of 20 cm and susceptibility of these samples were measured by the Bartington MS-2 meter.

AGE SCALE AND SPECTRAL ANALYSIS METHOD

Variation in inclination with depth and magnetostratigraphy

Fig. 2 shows the inclination change with depth in the discrete samples (Sakai et al. 2000), where the clear polarity reversal pattern was identified. The inclination change was compared with the geomagnetic polarity timescale of Cande

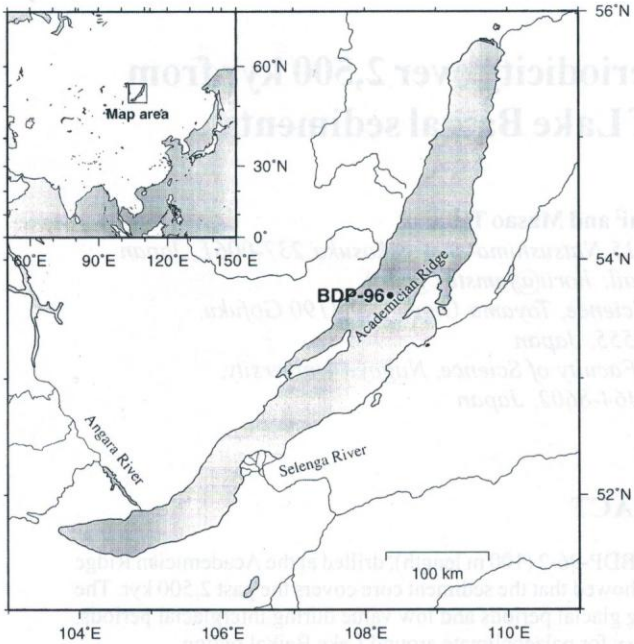

Fig. 1: Location map of BDP-96 drilling site (closed circle; 53°41'48"N, 108°21'06"E), Lake Baikal. Inset is the map of Eurasia continent.

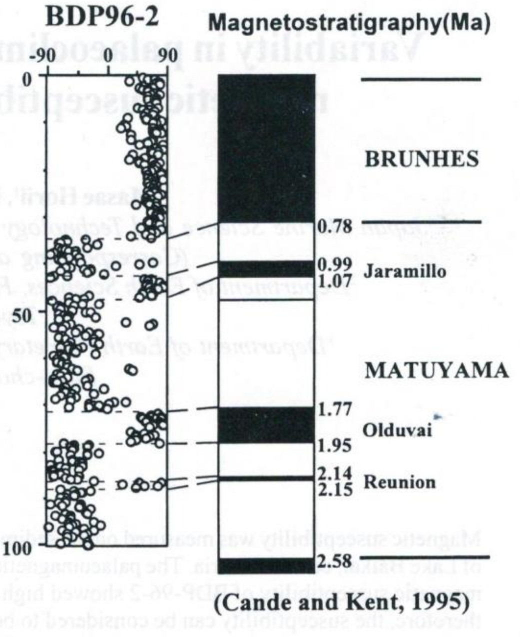

Fig. 2: Palaeomagnetic inclination of BDP-96-2 core with depth after AF demagnetization to 20 mT (open circles in the left graph). The geomagnetic polarity time scale by Cande and Kent (1995) is shown on the right for reference.

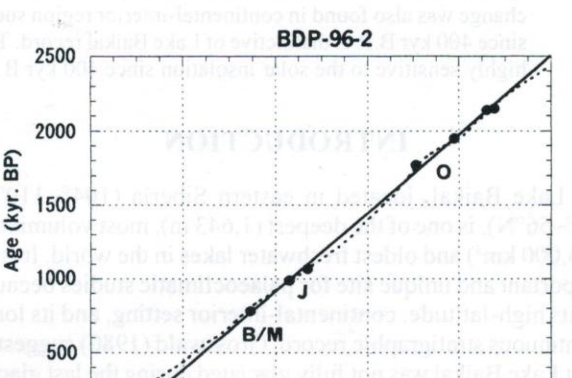

Fig. 3: Depth-age diagram of the polarity boundaries of geomagnetic chron and subchron for BDP-96-2. The characters of B/M, J, O mean Burnhes-Matuyama boundary, Jaramillo Subchron and Olduvai Subchron, respectively. Solid line is drawn by the least squares method on the plots in the diagram. Broken line expresses depth-age relation after orbital tuning.

and Kent (1995). The inclination sequence included the Brunhes normal Chron and Matuyama reversed Chron, and most of the geomagnetic subchrons (*e.g.* Jaramillo Subchron) were identified. The comparison showed that the BDP-96-2 covered the past 2,500 kyr.

Fig. 3 shows the correlation between depth and age for the assigned geomagnetic polarity boundary in Fig. 2. Solid line is drawn by the least squares method on the plots in the diagram. Broken line expresses depth-age relation after an orbital tuning. Through the linear relation in the figure, we can estimate the average sedimentation rate as 3.8 cm/kyr. The correlation coefficient of linearity is 0.999, which suggests that the sedimentation at Academician Ridge has not suffered large disturbances such as long hiatus or very large turbidity current during the past 2,500 kyr. Therefore, this site (core) is quite suitable for palaeoclimatic study.

Spectral analysis method on the susceptibility time series

In the analysis on susceptibility, three points of extremely high value (over 1000 x 10^{-6} SI) were omitted from time series data for spectral analysis, because they were considered to express extraordinary events such as turbidite or ice rafted sand. Although these episodic events are also important for palaeoclimatic study, we paid attention only to rhythmic variation in palaeoclimate here.

Time scale used in this study was based on the magnetostratigraphic data (Sakai et al. 2000), with orbital tuning by means of Kashiwaya et al. (1998). Also, by applying the interpolation on the susceptibility data, we obtained equally spaced data points for spectral analyses (1kyr intervals). Before spectral analysis, 10~238 kyr period band pass filter was imposed on the data. Analysis was done through the Discrete Fourier Transform method (DFT) on the whole 2500 kyr data, and then applied 4-points running mean to the power spectra on frequency domain.

Further we applied DFT to the 500 kyr segments data with stepped every 100 kyr interval (1~500 kyr B.P., 101~600 kyr B.P., 201~700kyr B.P., ---, and 1501~2,500 kyr B.P.).

Furthermore, filter analyses (80~150 kyr, 35~50 kyr and 18~25 kyr periods band pass filters) were used to check temporal changes in the amplitude of each orbital cycle (100 kyr eccentricity, 41kyr obliquity, 23 kyr and 19 kyr precession).

For comparison, we applied the same analyses to 65°N summer insolation data (Berger and Loutre 1991) and $\delta^{18}O$ data for ODP 677 (0°N, 84°W) (Imbrie et al. 1992, 1993). Glacial-interglacial cycle has been thought to be concerned with the change in summer insolation on high-latitude area of northern hemisphere. Relative changes in $\delta^{18}O$ record in Plio-Pleistocene mainly express change in global ice volume rather than change in local water temperature and do not depend on the site location. The SPECMAP stack (Imbrie et al. 1992, 1993), that is the synthesis of some $\delta^{18}O$ records, is frequently used as an index of Plio-Pleistocene climate, however, SPECMAP only span 700 kyr. We referred $\delta^{18}O$ for ODP 677, which is long-term record and is commonly used.

RESULTS

Change in magnetic susceptibility as a palaeo-environmental parameter

Fig. 4 shows the variation in magnetic susceptibility and the change in content of biogenic silica (Williams et al. 1997) with age. The susceptibility showed high value during glacial periods and low value during interglacial periods, whereas biogenic silica content was high during interglacials and was low during glacials. The same tendency has been observed in 10 m length short core sampled near the BDP-96 site (Sakai et al. 1997). The primary mechanism for the relation between susceptibility and palaeoclimate is considered as follows. During interglacial periods, the dilution of magnetic minerals due to the increase of biogenic material (mainly diatom frustule in Lake Baikal) leads to low susceptibility, while during glacial periods, the increase of terrigenous flux with low biogenic mineral causes high susceptibility (Sakai et al. 2000).

As a palaeoclimate proxy, biogenic silica is thought to be more direct than magnetic susceptibility. However, the content of biogenic silica showed extremely low value and little fluctuation in glacials, whereas magnetic susceptibility showed some fluctuation in glacials. Therefore, magnetic susceptibility of the sediments can be used as a good proxy for palaeoclimatic fluctuations in Lake Baikal.

Results of spectral analyses on the magnetic susceptibility

Fig. 5(a) is the susceptibility record for BDP-96-2 and Fig. 5(b) is the result of the spectral analysis (DFT) on susceptibility record for BDP-96-2. For comparison, the time series of the 65°N summer insolation (Berger and Loutre 1991) and oxygen isotopic ratio from ODP 677 (Imbrie et al. 1993) are shown in Fig. 5(c) and (e) with spectra (d) and (f), respectively. The spectrum of magnetic susceptibility for BDP-96-2 (Fig. 5 b) shows distinct Earth's orbital cycles (23, 41 kyr) and 100 kyr of major glacial-interglacial cycle. The 100 kyr cycle cannot be directly connected with orbital eccentricity (see Fig. 5 c). The characteristic feature of the spectrum of BDP-96-2 (Fig. 5 b) is similar to that of ODP 677 (Fig. 5 f). This correspondence shows that BDP-96-2 climatic data reflect global palaeoclimatic changes. However, the power of 23 kyr precession period of BDP-96-2 is significantly larger than that of ODP 677.

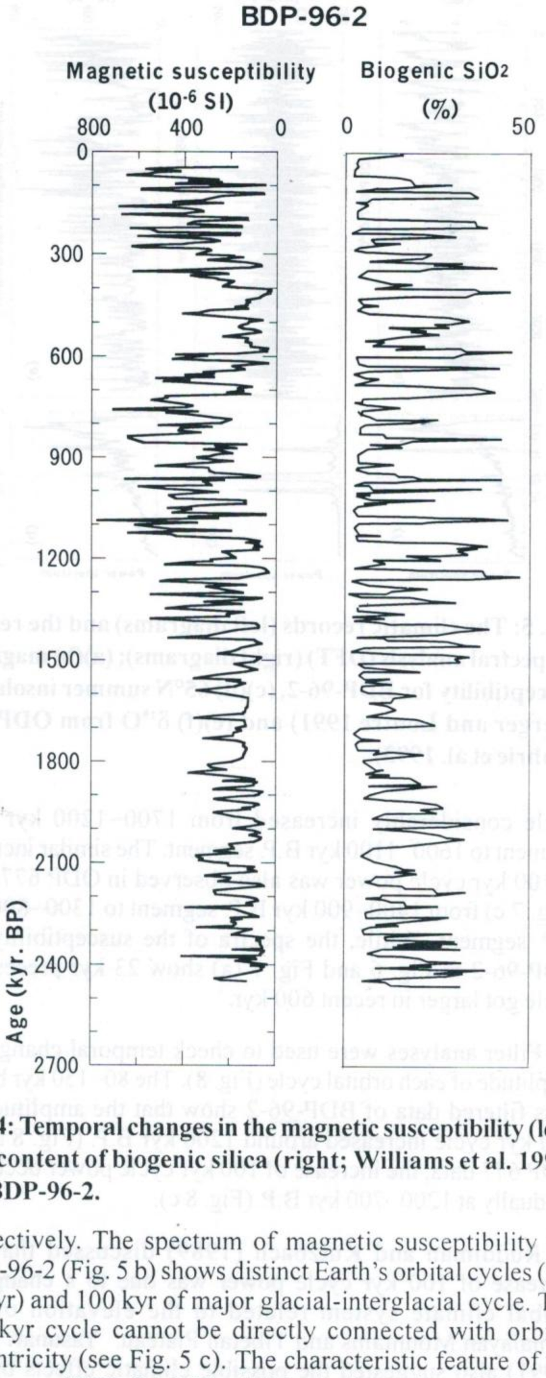

Fig. 4: Temporal changes in the magnetic susceptibility (left) and content of biogenic silica (right; Williams et al. 1997) for BDP-96-2.

Fig. 6 shows the series of power spectra on susceptibility record of BDP-96-2 for the past 2500 kyr in 500 kyr segments stepped every 100 kyr intervals. In Fig. 7 spectral densities for each orbital cycle bands (18~25 kyr, 35~50 kyr and 80~150 kyr) were plotted against median ages of the data segments. Fig. 6 and Fig. 7 (a) shows the spectral power of 100 kyr

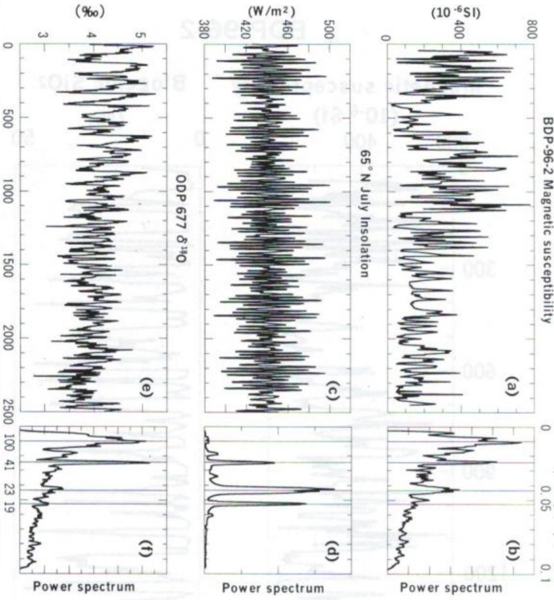

Fig. 5: The climatic records (left diagrams) and the results of spectral analysis (DFT) (right diagrams); (a)(b) magnetic susceptibility for BDP-96-2, (c)(d) 65°N summer insolation (Berger and Loutre 1991) and (e)(f) $\delta^{18}O$ from ODP 677 (Imbrie et al. 1993).

cycle considerably increased from 1700~1200 kyr B.P. segment to 1600 1100 kyr B.P. segment. The similar increase in 100 kyr cycle power was also observed in ODP 677 data (Fig. 7 c) from 1400~900 kyr B.P. segment to 1300~800 kyr B.P. segment. While, the spectra of the susceptibility for BDP-96-2 in Fig. 6 and Fig. 7 (a) show 23 kyr precession cycle got larger in recent 600 kyr.

Filter analyses were used to check temporal changes in amplitude of each orbital cycle (Fig. 8). The 80~150 kyr band-pass filtered data of BDP-96-2 show that the amplitude of 100 kyr cycle increased around 1200 kyr B.P. (Fig. 8 a). In ODP 677 data, the increase of 100 kyr cycle power occurred gradually at 1200~700 kyr B.P. (Fig. 8 c).

Ruddiman and Kutzbach (1989) discussed that the increase of 100 kyr cycle power was due to a change in global climate system related to the elevation of the Himalayan Mountains and Tibetan Plateau. Yasunari et al. (1991) also suggested the possible climatic effects by the elevation of Himalayan Mountains and Tibetan Plateau.

The spectral analysis for the susceptibility of Lake Baikal core suggested that this change in global climate system is also recorded in the continental interior site such as Lake Baikal.

The 18~25 kyr band pass filtered data of BDP-96-2 susceptibility showed that 23 kyr precession cycle was larger in recent 400 kyr (Fig. 8 g). The amplitude of 23 kyr cycle was small in ODP record (Fig. 8 i). For this band, the curve of BDP-96-2 was rather similar to that of 65°N insolation during the past 400 kyr (Fig. 8 h). Fig. 9 shows susceptibility record

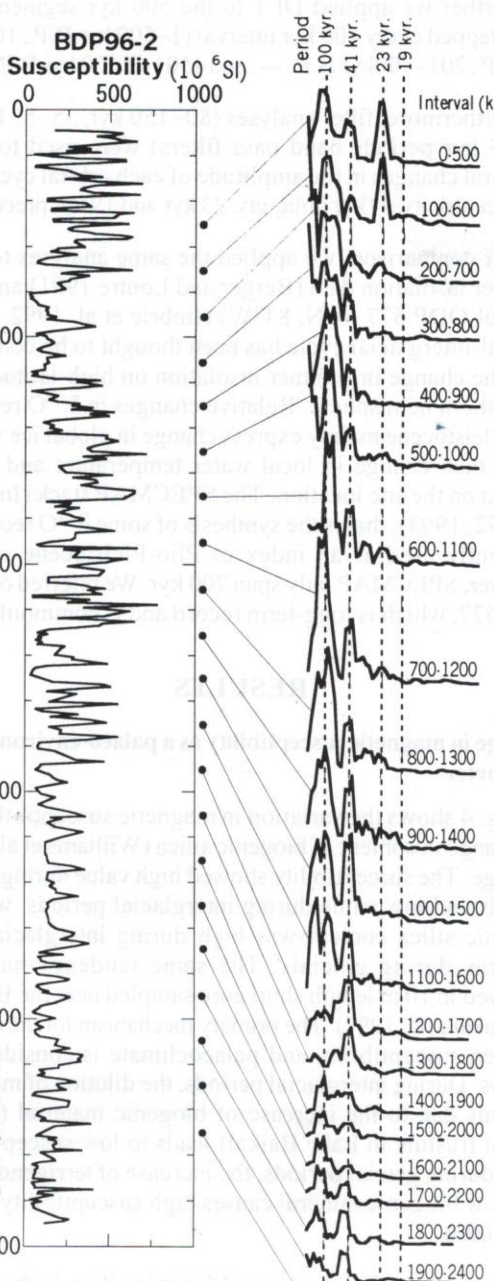

Fig. 6: Temporal change in magnetic susceptibility for BDP-96-2 and the spectrums for past 2500 kyr in 500 kyr segments stepped every 100 kyr.

from Baikal, summer insolation record on 65°N (Berger and Loutre 1991) and oxygen isotopic ratio from ODP 677 (Imbrie et al. 1993) during the past 300 kyr. In this time segment, the climatic record from Baikal showed high sensitivity to 23 kyr precession cycle of insolation. This was not the case for ODP data. This characteristic is, therefore, considered to be local climatic feature around Lake Baikal region.

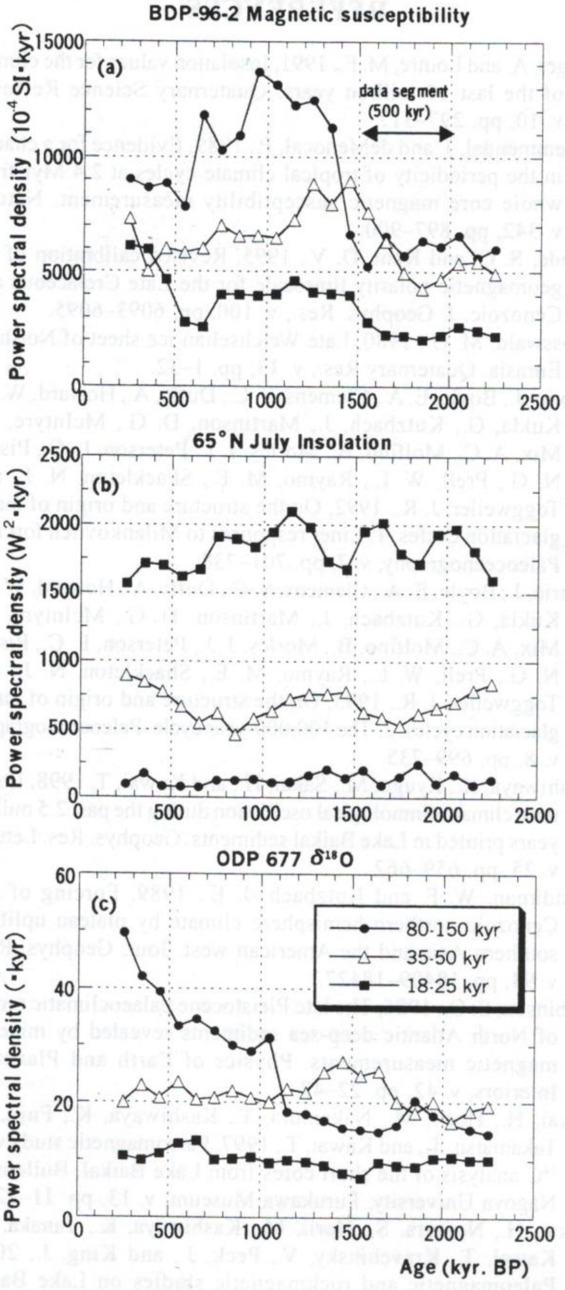

Fig. 7: Temporal changes in spectral power of each orbital period; 23 kyr (closed squares), 41 kyr (open triangles) and 100 kyr (closed circles). (a) magnetic susceptibility for BDP-96-2, (b) 65°N summer insolation (Berger and Loutre, 1991) and (c) $\delta^{18}O$ from ODP 677 (Imbrie et al. 1993).

CONCLUSIONS

BDP-96-2 sediment core showed clear inclination reversals with depth. Through the comparison with the geomagnetic polarity timescale, sedimentary sequence of the 100 m length core was assigned to the geomagnetic polarity chron during the past 2,500 kyr; Brunhes and Matuyama Chron. The average sedimentation rate was estimated to be 3.8 cm/kyr by the least square method on the depth-age relation. The fairly high correlation coefficient (0.999) in the depth-age relation indicated that the sedimentation at Academician ridge had been continuous under the quiet environment.

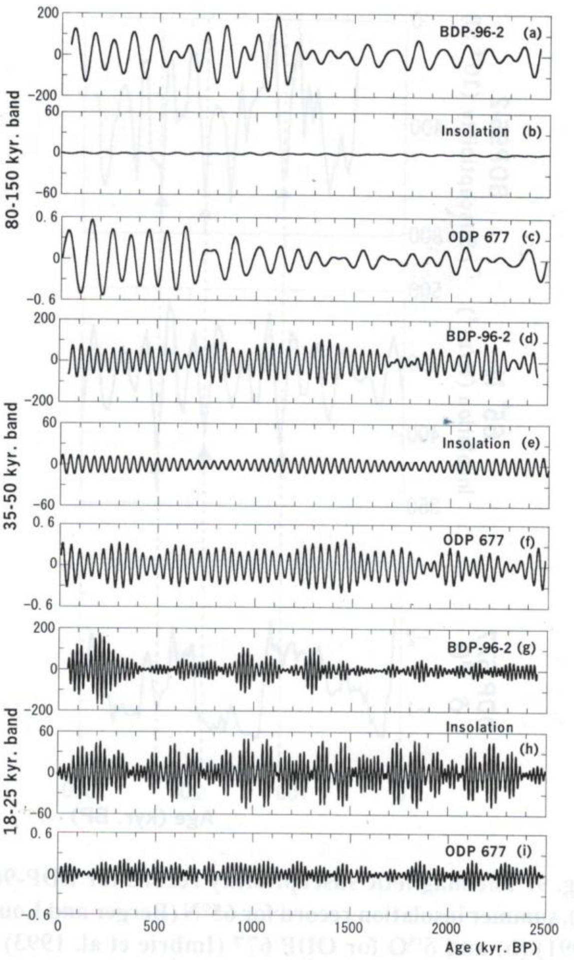

Fig. 8: The 80-150 kyr band pass filtered curves for magnetic susceptibility of BDP-96-2 (a), 65°N summer insolation (Berger and Loutre 1991) (b) and $\delta^{18}O$ from ODP 677 (Imbrie et al. 1993) (c). The 35-50 band pass filtered curves for magnetic susceptibility of BDP-96-2 (d), 65°N summer insolation (Berger and Loutre 1991) (e) and $\delta^{18}O$ from ODP 677 (Imbrie et al. 1993) (f). The 18-25 kyr band pass filtered curves for magnetic susceptibility of BDP-96-2 (g), 65°N summer insolation (Berger and Loutre 1991) (h) and $\delta^{18}O$ from ODP 677 (Imbrie et al. 1993) (i).

The temporal change in magnetic susceptibility showed the inverse tendency with the change in the content of biogenic silica. The susceptibility showed high value during glacial periods and low value during interglacial periods, so the susceptibility can be considered to be a good proxy for palaeoclimate around Lake Baikal region.

The spectral analysis extracted clear orbital cycles in the variation of susceptibility. The spectra showed considerable

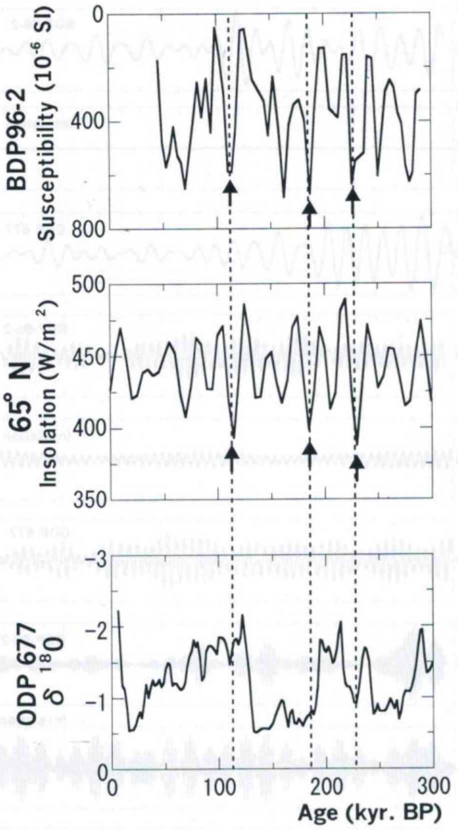

Fig. 9: The magnetic susceptibility record for BDP-96-2 (a), summer insolation record for 65°N (Berger and Loutre 1991) (b) and $\delta^{18}O$ for ODP 677 (Imbrie et al. 1993) (c) during the past 300 kyr.

increase in the power of 100 kyr cycle around 1,200 kyr B.P.. The signal of the global climatic system change at 700~1,200 kyr was also found in continental-interior region such as the Lake Baikal.

Furthermore, the spectra for magnetic susceptibility from the Lake Baikal sediments suggest that 23 kyr precession cycle became larger in recent 400 kyr. This change in amplitude of 23 kyr cycle is distinctive of the Lake Baikal. The local climatic system around the Lake Baikal seemed to get high sensitivity to the insolation directly in this time segment.

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