Climatic Changes and Lacustrine Sediment Information

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I. Introduction

We are in the inter-glacial period of the Quaternary Ice Age. Present inter-glacial period is also called post-glacial period. Almost all human beings live their lives on the earth surface and have been significantly influenced with the earth surface environment, fundamental system of which has been constructed in the late Cenozoic or Quaternary. The beginning of the Quaternary is defined, in the present stage, at about 1.796 Myr B.P., referring to Virica, Italia [1].

A major shift in climatic changes is also found at about 2.8 Myr B.P.[2]. Cooling with large amplitude in the Cenozoic began at this time and a new climatic system (current climatic system) has been established. This major climatic change is assumed to be attribute to the uplift of the Himalayan Tibetan Plateau, southwestern North America, and the opening and closing of the Panama Isthmus [3, 4].

A shift at the mid Pleistocene (a regular cycle with a 10-kyr inter-glacial period per 100 kyr has been shown since then) is also assumed to have a relation with the uplift of the Himalayan Tibetan Plateau [5]. These suggest that tectonic movements, such as changes in land-masses (opening and closing of isthmuses), and uplifts of mountains have been very important for the general circulation of the atmosphere and oceanic general circulation.

II. Paleoclimatic theory for the Quaternary

It has been gradually cool also in the Quaternary as was in the other periods of the Cenozoic. There are some climatic characteristics in this period. One of them is cyclic fluctuation in climate. The theory, which can explain the regular cycle of glacial-interglacial period, has been one of the significant targets to be discussed in Earth Science during these decades [6, 7, 8, 9, 10]. It is closely related to what M. Milankovitch (a Serbian mathematician and geophysicist) established between 1915 and 1940 as an astronomical theory of the Pleistocene [11]. This theory is widely accepted now because it gives a fundamental frame for long-term climatic change in the Quaternary.

It is based on the idea that the distribution of seasonal insolation on the earth surface is determined by the Earth orbital parameters; eccentricity, obliquity and precession. The outline of this theory is as follows [11]; the Earth revolves around the Sun (Fig. 1): point *S* represents the center of the sun, and the ellipse *PIAIIIP* is the annual terrestrial orbit. The angle *VSN* represents the inclination of the rotational axis of the Earth or the obliquity ε of the ecliptic when two lines are drawn; one line *SV*, normal to the Earth's orbital plane, directed to the north and another line *SN* parallel to the rotational axis of the Earth. The plane *E*, defined by the straight lines *SV* and *SN*, is normal to the Earth's orbital plane and intersects it along the straight line *II, IV*. The points *II* and *IV* represent the solstices on the Earth's orbit (winter solstice and summer solstice). If in the orbital plane we draw a straight line through *S*, normal to *II, IV*, this will intersect the orbit at the points *I* and *III*, which represent the two equinoxes of the Earth (autumnal equinoctial point and vernal equinoctial point). The position of these four points on the terrestrial orbit is determined by the angle *IIISP* (=Π_{γ} representing the longitude of the perihelion to the vernal point).

If the planets did not disturb one another in their course and if the rotational axis of the Earth kept its orientation in universal space, then the terrestrial orbit (Fig. 1) would be fixed and its cardinal points *I, II, III, IV* would be fixed. The annual march of the insolation of the Earth would recur without change year after year. However, the precession of the terrestrial axis of rotation would displace *SN* drawn parallel to it in such a way that within about 26 kyr it would describe the circular cone *NSM*. The axis of this cone is *SV*, its vertex angle ε. Owing to this rotation of the terrestrial axis, the plane *E* turns around the straight line *SV* as axis, and the cardinal points *I, II, III, IV* move clockwise along the terrestrial orbit. They would accomplish a complete revolution along this orbit within 26 kyr, if this orbit were fixed. However, due to the mutual perturbations of the planets, the major axis of the orbital ellipse moves toward the cardinal points, and therefore these points perform a full revolution (from perihelion to perihelion) in about 22 kyr.

Owning to the perturbations, the terrestrial orbit gradually changes its shape; although its semi-major axis remains unchanged, the eccentricity *e* is exposed to noticeable secular changes. The plane of this orbit also varies in space, since the astronomical elements, which determine the position of this plane in space, are secularly changeable, affecting the obliquity ε of the rotational axis *SN* of the Earth.

The insolation received by the Earth from the Sun depends only on the shape of the terrestrial orbit and on the orientation of the Earth's axis relative to this orbit, and not on the position of this orbit in universal space. This mutual position of the Sun, the Earth, and the Earth's axis is uniquely defined by the three astronomical parameters; perihelion (Π_{γ}, mainly related to the precession as mentioned above), obliquity (ε) and eccentricity (e), so that only the variations of these three parameters affect the condition of insolation. These parameters have some dominant periods; the precession at about 23-kyr and 19-kyr, as described above, the obliquity at about 41-kyr and the eccentricity at about 410-kyr and 100-kyr, which were very effective for reactivating the theory mentioned below.

The insolation can be calculated for any point on the earth at any moment. Milankovitch started to calculate the insolation for caloric summer half-year, which comprises all the days of stronger insolation at 65° N, where climate was considered to be most sensitive to insolation, suggested by Köppen [cf., 11]. One of the calculated results given by Milankovitch with hand-calculation for caloric summer half-year during the past 600 kyr [11] and recent calculation for the same half-year with new celestial values [12] are shown in Fig. 2, indicating remarkably small difference between them.

III. Discussions on the theory

It was firstly said that the theory had been proved with the geological evidence; the four ice stages found in the Alps by Penk & Brückner (1909) [13] were well corresponded to the four low insolation groups in the insolation curve (Fig. 3). The temporal insolation curve calculated during the past 1.0 Myr was considered to be available for a dating tool [11]. Some geological events were dated on the basis of the curve although they were not appropriate for the insolation dating, which also led to the decline of the theory [8]. It was gradually ignored because of beyond-verification, in addition to the development of radiocarbon dating. However, it has been drastically revived in mid-1970 from the ocean bottom (Hays et al.,

1976) [7]. Periods from the three orbital parameters (eccentricity, obliquity and precession) were found in the oceanic sediments (Fig. 4). Since then, the periods have been found in many oceanic sediments from various areas (Shackleton et al., 1991; 1995) [14, 15], indicating that the Milankovitch theory should be the fundamental concept explaining glacial-interglacial cycles in the Quaternary. The periods were also found in the Antarctic ice cores that could include long-term atmospheric information (Jouzel et al., 1987) [16], suggesting the glacial-interglacial cycles are global fluctuations.

Terrestrial information has been given from lake and loess sediments (cf., Kukula, 1978) [17]. Long-term lake sediment information was firstly given from Lake Biwa Drilling in 1970 (Horie, 1984) [18], which provided much precious long environmental information. However, discussions on the information and comparisons with global changes were limited because the bottom of the sediments did not reach Brunhes-Matuyama boundary and some absolute dates were confusing. Essential discussions based on new age models have started after longer sediment core samples (1400m) were obtained from nearly the same point in 1983 (Kashiwaya et al., 1991; Meyers et al., 1993) [19, 20]. It was also shown that the 200-m core samples span about 350 kyr and the environmental fluctuations were closely related to global changes. The grain size fluctuation shown in Fig.5a is a proxy for hydrological conditions (rainfall), indicating that it was wet in interglacial periods while it was dry in glacial periods. Four distinct periods related to three Milankovitch parameters are clearly seen in the fluctuation (Fig. 5b).

It is not oceans, but terrestrial areas that are calorically sensitive to solar insolation, and the most sensitive area is mid-latitudinal land areas in the northern Hemisphere (around N60º, E100º), which was shown by Short et al. (1991) [23] with a energy balance model in case the obliquity extremes were 24.4º (with summer solstice at the time of perihelion) and 22.1º (with summer solstice at the time of aphelion) (Fig.6). It is mainly related to difference in heat capacity between land and oceanic areas. Altitudinal conditions were ignored in this model because of two-dimensional one. However, if the Himalayan Tibetan Plateau with large heat capacity were considered, the most sensitive area might be a little extended to the southward. In any case, the most sensitive zone can be located around N50-60º, E100º. It is sure that long-term climatic changes due to the solar insolation may have been imprinted in detail in this zone. Then, on what mediums they have been imprinted? At a glance of a map of east Eurasia, we can find Lake Baikal in the middle of the zone and Ghozi desert, Loess Plateau in the southward. Therefore, terrestrial sediments in these areas, especially lake sediments from Lake Baikal, can be targets for long-term insolation-related environmental changes.

Aeolian sediments from Loess Plateau have been connected to global changes in detail since 1980's on the basis of magneto-stratigraphy although they were studied only from geological view points [22]. In the loess sediments here, paleo-soil parts indicate interglacial periods while loess parts glacial ones. It has been also revealed that magnetic susceptibility of the sediments is a good proxy for climatic changes and it can be closely correlated to oceanic $\delta^{18}O$; large susceptibility is corresponded to warm periods while small one cold periods [23]. Recently grain size variation has been studied to examine cyclic periods including the Milankovitch parameters [24], which shows that there were large environmental shifts at about 0.5-0.8 Ma and 1.6-1.7 Ma, 100-kyr period has been dominant since 0.6 Ma and 41-kyr period was dominant in the interval of 0.8-1.6 Ma during the past 2.5 Myr. Recently, older loess sediments were found, which were of great use to reconstruct long-term terrestrial paleo-environment (Ding et al., 1999; Guo et al., 2002) [25, 26]. It is necessary to be careful for analyzing them and comparing them with other temporal proxy data because aeolian sediments, in general, are exposed to air and surface erosion.

Lacustrine sediments are often disturbed by turbidity currents and then continuous records included are lost. Therefore, it is essential to select suitable sampling points without direct tubidity currents and riverine influence. Then, how about Lake Baikal sediments? There are various kinds of sediments, with and without significant influence from turbidity currents. The first long cores were BDP93, which was obtained from the Buguldeika Saddle of Lake Baikal in 1993. Baikal Drilling Project (BDP) was organized by Russia, USA, Japan and Germany in the first stage and several long cores were obtained (Minoura, 2000; Kashiwaya, 2003) [27, 28]. Here, we will introduce some results from BDP96 obtained in 1996, which was analyzed comparatively in detail [29, 30]. Two long cores (BDP96-1 and BDP96-2) were drilled in the Academician Ridge without direct turbidity influence. BDP96-1 was 200 m long and spans about 5 Myr, and BDP96-2 was 100 m and about 2.5 Myr. There are some lacks in the lower part of the BDP96-1, on the other hand few lacks in the BDP96-2. Continuous detailed information during the past 2.5 Myr was recorded in the BDP96-2 sediments. Fig. 7 shows analytical results for grain size, indicating that there were major environmental shifts at about 0.7-0.8 Ma and 1.6 Ma, and 100-kyr period was dominant since 0.7-0.8 Ma and 41-kyr period was dominant before then, which are closely corresponded to global changes. One of the most important facts revealed in these records is the 410-kyr period, the largest period in the eccentricity (Fig. 7b), which was not so clear until now, suggesting that Baikal records are so sensitive to the insolation. A temporal change in grain size during the past 0.25 Ma for a short core (10 m), obtained from nearly the same point, shows that there are deep depressions in 5d (115 Ka) and 7d (205 Ka), which are more corresponded to the insolation than any other dataset in various areas (Fig. 8).

In 1998, the longest cores, BDP98 (ca. 600 m) were obtained from the Academician Ridge (close to the BDP96), which spans around 10 Myr (Kashiwaya et al., 2001; Horiuchi et al., 2003) [31]. Some new findings have been reported although all the analyses are not yet completed; the existence of larger periods around 2 Myr and 1 Myr related to the eccentricity in addition to well known periods, the initiation of the major northern Hemisphere glaciation at about 4.0 Ma, etc. (Kashiwaya et al., 2003a; 2003b) [33, 34].

IV. Some problems

Several models on climatic changes have been proposed on the basis of the Milankovitch theory (e.g., Crowley and North, 1991) [35]. On the other hand, some problems have been indicated since the beginning. One of them is the 100-kyr periods, which are related to the eccentricity. The periods are so small, compared with other ones. They can be also synthesized with main precessional periods (Berger, 1978) [13]. However, it is this period that have been largest during these 0.7-0.8 Myr. Recently, it is reported that this period was not related to the eccentricity but the inclination of the Earth orbitary plane (Mullar and Gordon; 1997) [36]. However, it is not necessary that the period is only connected to the inclination because 124-kyr and 95-kyr periods, which have been combined as a 100-kyr one, as well as the 410-kyr one have been found in the same datasets (Clements and Tiedemann, 1997; Kashiwaya et al., 2000) [37, 38].

Another one discussed widely is MIS (marine isotope stage) 11 problem; super interglacial period at about 400 kyr before (Imbrie et al., 1993) [39]. In this period glacial volume on the Earth largely decreased although local maximum insolation was not so high. In addition, there was no interstadial corresponded to low insolation in the marine sediments records (Fig. 9). The main point of the problem is the cause of prolonged interglacial period.

Recently, a model considering changes in insolation and CO_2 concentration has been proposed to explain the phenomena (Loutre, 2003) [40]. However, the debate on this problem will continue because we are facing to global warming problem.

V. Beyond Quaternary

The initiation or establishment of the northern Hemisphere glaciation at about 2.6 – 2.8 ma has been widely discussed and there have been many opinions proposed to explain it; increase in volcanic activity in the late Cenozoic (Kennett and Thunell, 1975) [41], the deepening of the Bering Strait (Einarsson et al., 1967) [42], the emergence of the Panama Isthmus (Keigwin, 1978; 1982) [43, 44], etc. The uplift of the Himalayan Tibetan Plateau has been also a target of discussion (cf. Ruddiman and Kutzbach, 1991) [45]. However, these tectonic-related models cannot explain abrupt cooling at the time (Maslin et al., 1998) [46]. Hence, some models considering insolation (especially, obliquity parameter) and CO_2 concentration have been proposed (Li et al, 1998; Berger et al., 1999) [47, 48]. Recently, some ideas that the beginning of the extension of the glaciation may be around 4.0 Ma have been reported; it may be attributed to the closure of the Panama Isthmus and insolation fluctuation (Haug and Tiedemann, 1998) [49], the closure of the Indonesian seaway due to tectonic movement (Cane and Molnar, 2001) [50], and to insolation (eccentricity-related period, obliquity related period) and CO_2 concentration (Kashiwaya et al., 2003) [34]. These remain to be thoroughly discussed.

Insolation can be calculated for fairly long time and several calculations have been made with some modified parameters since Milankovitch (1941) [11]. Hays et al. (1976) [7] used calculations given by Vernekar (1972) [51]. Then, calculated results with some modifications by Berger (1978) [13], and Berger and Loutre (1991) [52] have been used. Recently, those by Lasker et al. (1993) [53] have been used, especially, for longer than 10 Myr (e.g., Hilgen et al., 1995) [54].

Insolation curves have been used again to tune age models since the Milankovitch cycles were found in the ocean bottom as was used “Milankovitch calendar”. The boundary between Brunhes and Matuyama chrons has been moved from 0.73 Ma to 0.78 Ma and the upper end of Gauss chron from 2.47 Ma to 2.60 Ma (Shackleton et al., 1990) [16]. The insolation calendar has been used to date some chemical and physical parameters for long oceanic records (10 Ma, Shackleton et al., 1995) [55]. Age models based on the insolation may be of use for further long intervals with parameters modified in detail.

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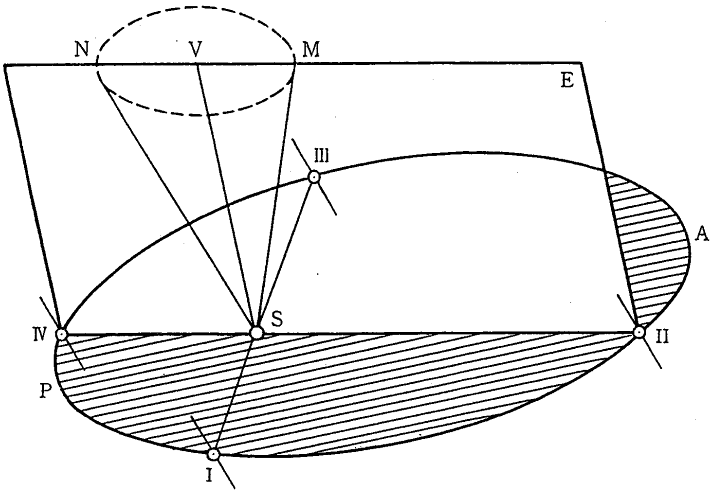


Fig. 1 The orbit of the Earth. S: Sun, A: aphelion, P: perihelion, I: autumnal equinox, III: vernal equinox, II: winter solstice, IV: summer solstice (Milankovitch, 1941) [11].

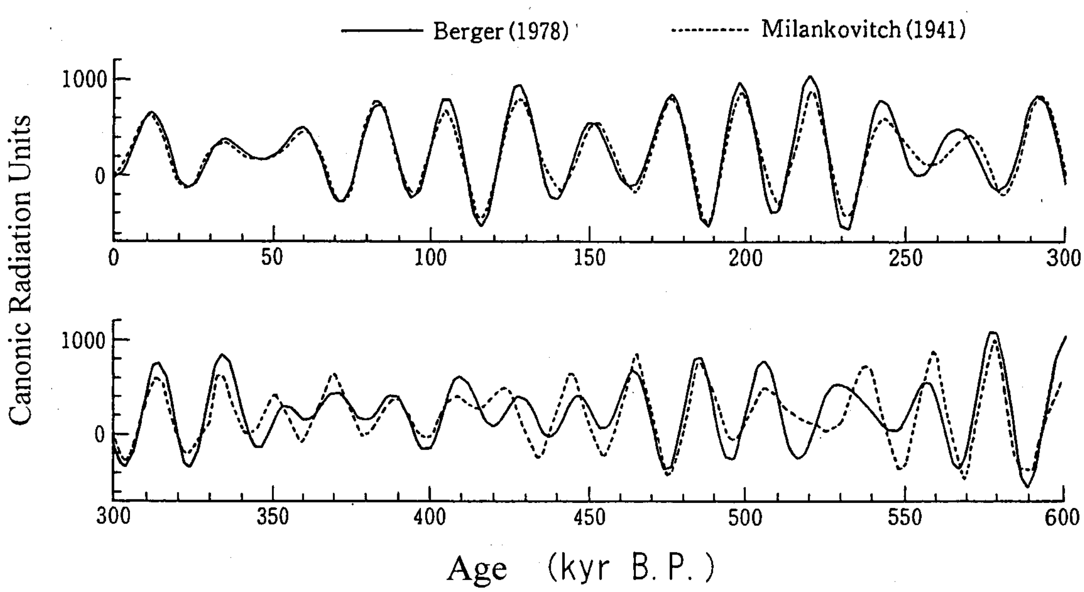


Fig. 2 Insolation during the past 600 kyr. Solid line after Berger (1978) [12] and dotted line from Milankovitch (1941) [11].

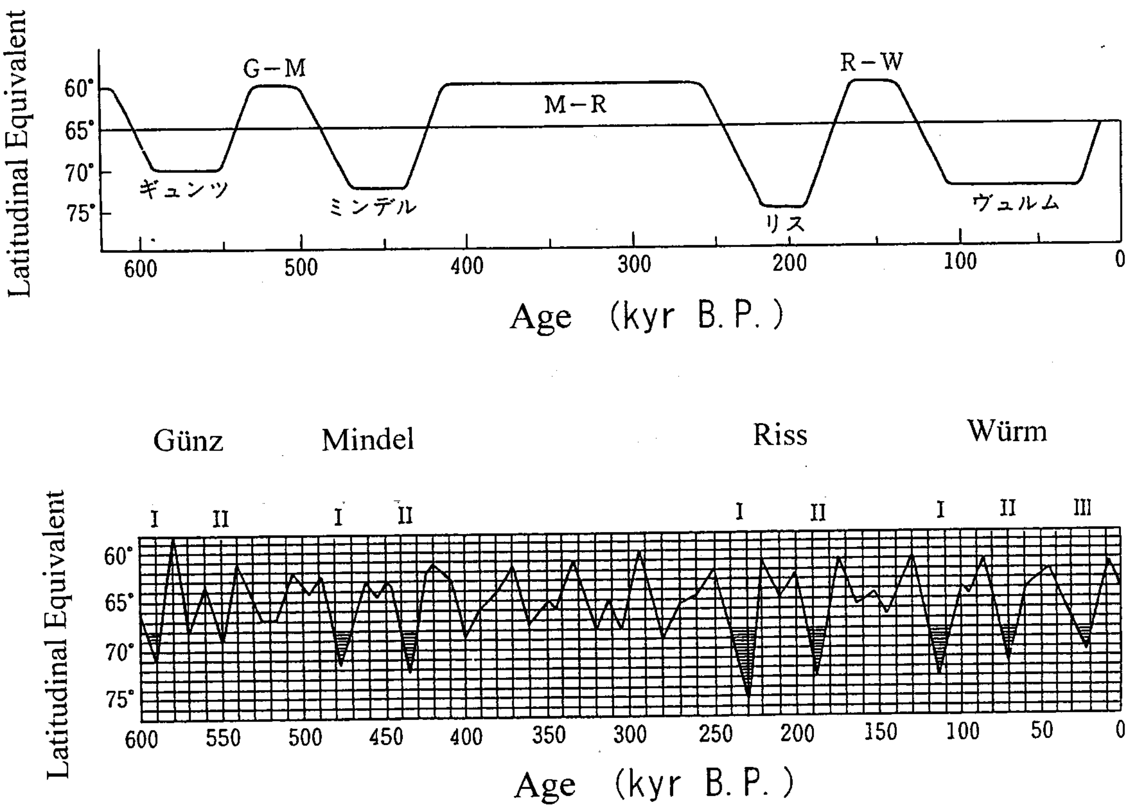


Fig. 3 a) Theoretical succession of European ice periods suggested by Penk & Brückner (1909) [13], b) the Milankovitch insolation curve for 65° N [11].

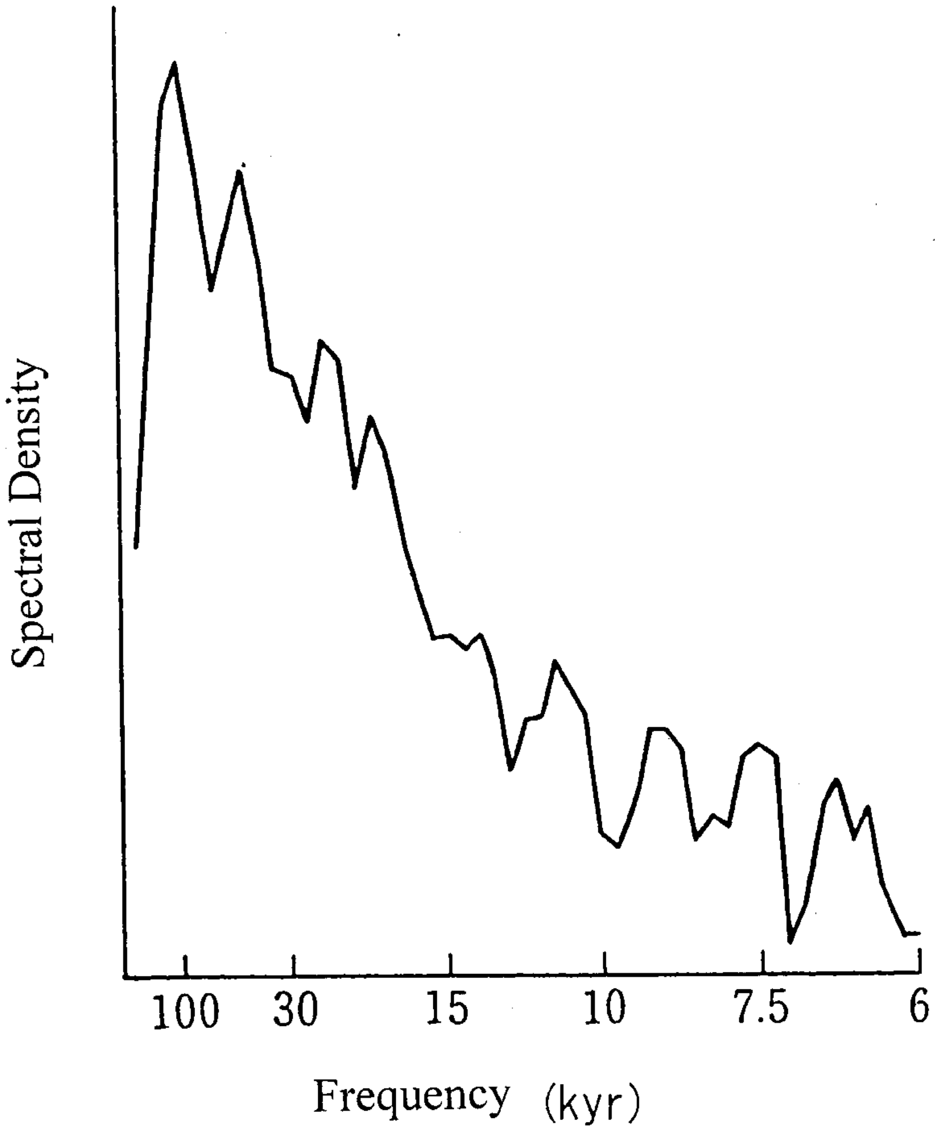
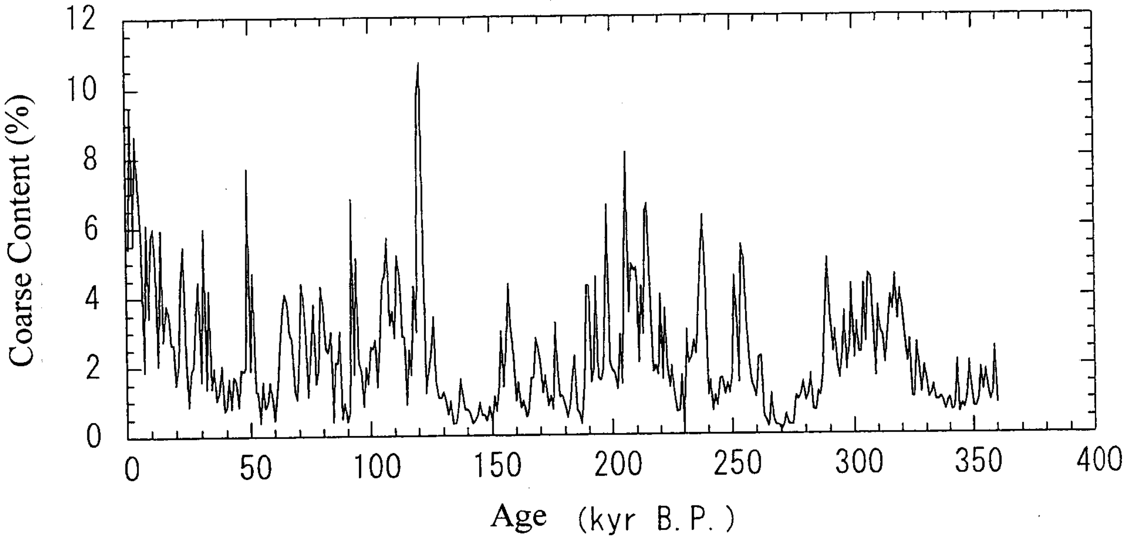


Fig. 4 Spectrun of climatic oscillation from oceanic records (Hays et al, 1976) [7]

(a)



(b)

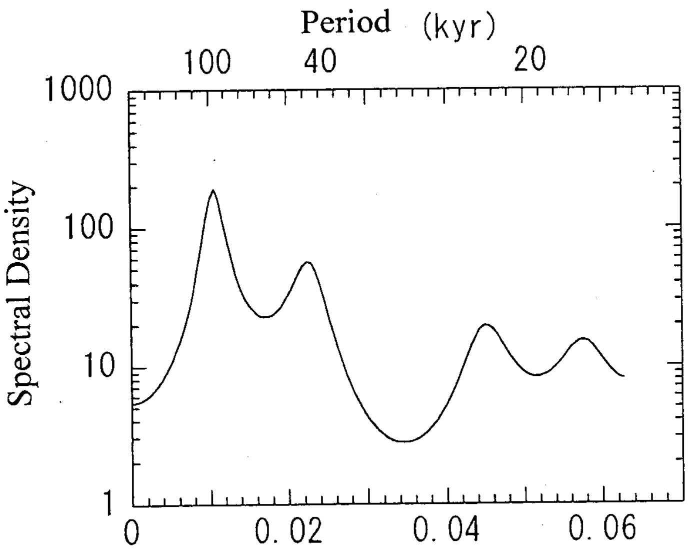


Fig. 5 a) Climatic oscillation (grain size) from Lake Biwa and b) dominant periods included.

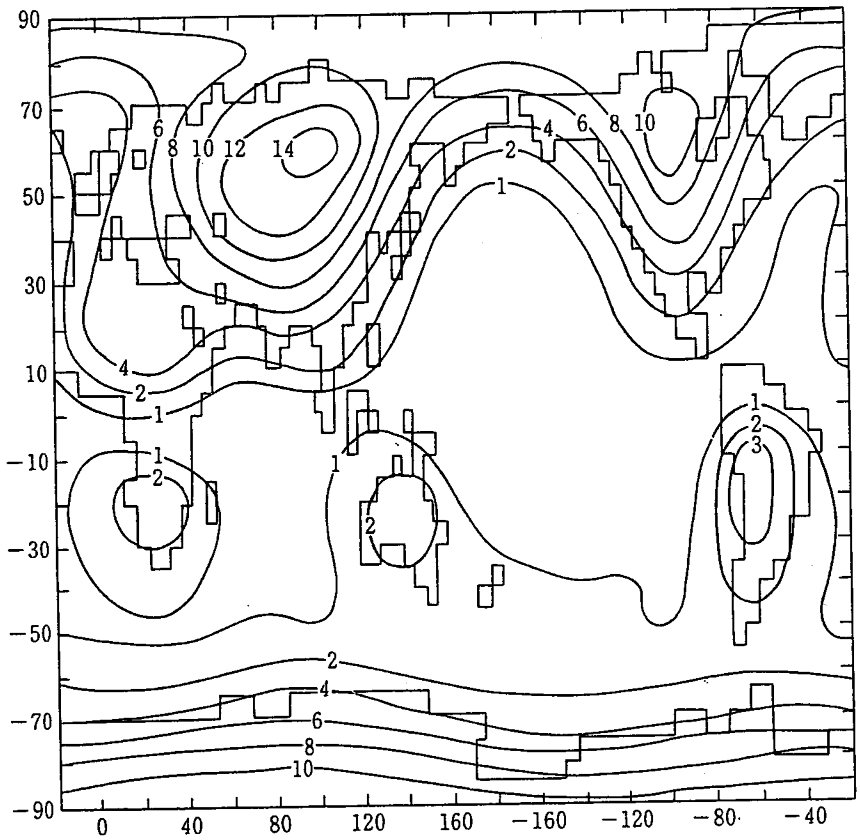
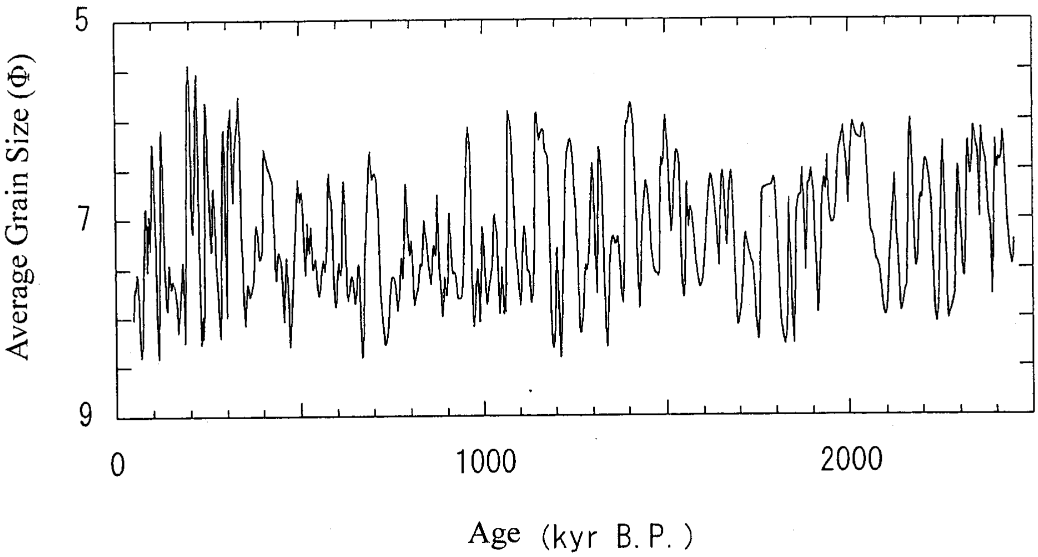


Fig. 6 Geographic pattern of the change in maximum summer temperature (Short et al., 1991) [21].

(a)



(b)

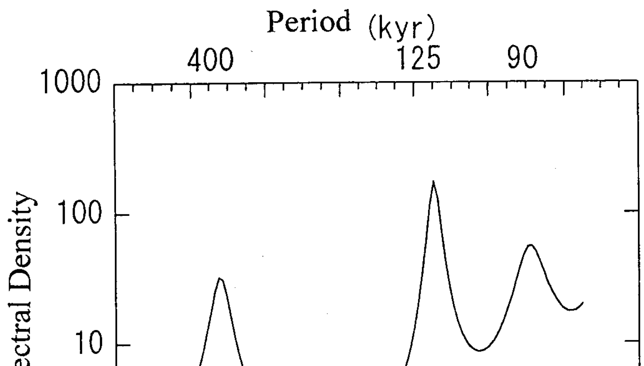


Fig. 7 a) Climatic oscillation (grain size) from Lake Baikal (BDP96-2) and b) eccentricity-related long periods.

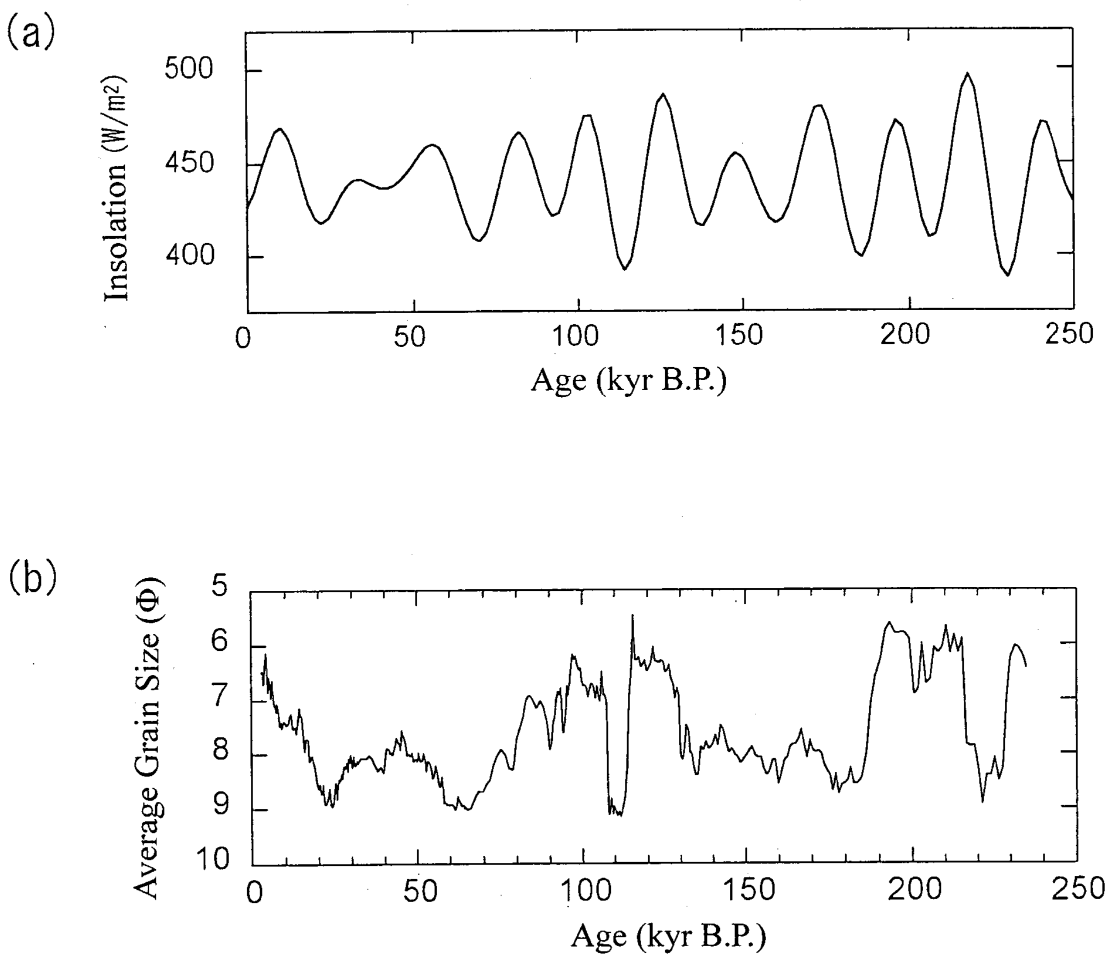


Fig. 8 a) Insolation curve for 65° N at mid July (Berger, 1978) [12] and b) grain size variation in Lake Baikal during the past 250 kyr.