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Onset of current Milankovitch-type climatic oscillations in Lake Baikal sediments at around 4 Ma[☆]

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Abstract

Low summer insolation would increase Northern Hemisphere ice sheets only if winter snow persisted all year. Lake Baikal records reveal that such a climatic threshold may have been reached at around 4.0 Ma. Insolation minima at about 3.9, 3.8 and 3.7 Ma, which were obliquity-related, may have triggered Milankovitch-type climatic oscillations characterized by orbital cycles (with periodic major Northern Hemisphere ice sheets). Intensification of these oscillations at about 2.8 Ma was probably connected to another decrease in insolation (i.e. another obliquity-related insolation minima), and seemingly triggered larger oscillations in the prevailing climatic regime of the late Pliocene and Pleistocene.

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Keywords: Lake Baikal; Insolation; Northern Hemisphere glaciation

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1. Introduction

When was the beginning of the current Milankovitch-type climatic oscillations that are characterized by major Northern Hemisphere glaciations? This has been one of the most important climatic issues to address in recent decades [1,2]. Low summer insolation would increase Northern Hemisphere ice sheets only when climatic conditions (including CO_2 concentration) allowed winter snow to persist all year. Most previous discussions have focused the timing of the shift around 2.8 Ma. Many high-resolution records have been obtained, especially from marine sediments, and models have been proposed to explain the initiation of the shift in climatic regimes [3,4]. Some workers have attributed its main causes to tectonic movements, some to changes in land masses (opening and closing of isthmuses), and some to uplift of the Himalayan Tibetan plateau and southwestern North America [5]. Others have

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studied atmospheric CO_2 concentrations with reference to tectonic movements [6]. Fluctuations in insolation have also been inferred as a trigger for this climatic shift [7].

New information from oceanic and loess records suggests that the initiation of the current climatic regime may have been somewhat older (3.6–4.0 Ma) than previously believed [8–11]. Driscoll and Haug [10] have proposed a plausible scenario in which variations of obliquity in orbital parameters are a trigger for initiating this climatic regime. Unfortunately, there have been few studies on the beginning and early nature of Milankovitch-type cyclic oscillations, which we will address by using long lacustrine records from Lake Baikal.

2. Baikal data and age-scaling

We have previously reported that climatic signals related to orbital movements are imprinted as long records (2.5 Myr, 3.5 Myr and 11.5 Myr) in Lake Baikal sediments [12–14]. Lake Baikal is sensitive to insolation fluctuations because of its geographic location [15], and its sediments are among the highest-resolution and longest known terrestrial records of climatic change. These factors imply that Baikal sediments may record information crucial for studying the beginning of Milankovitch-type cyclic oscillations.

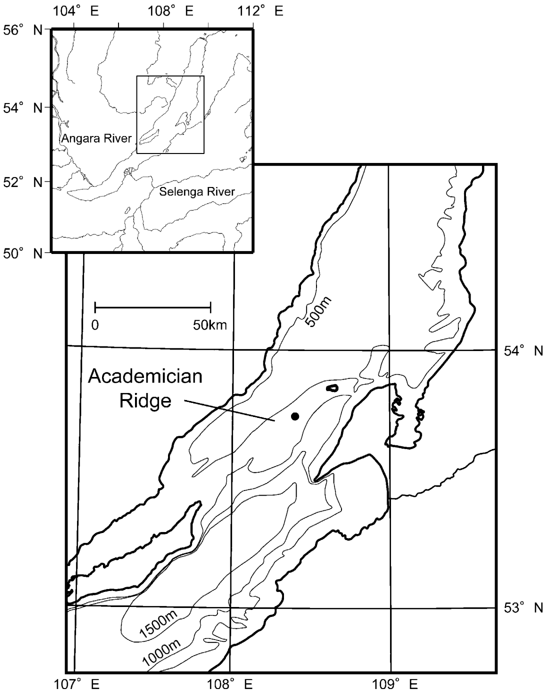

Fig. 1. Location map of BDP98 in Lake Baikal. ●: sampling site.

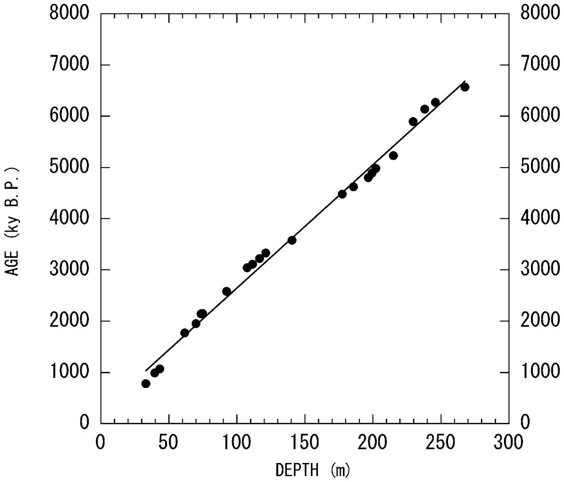

Fig. 2. Tentative age model based on paleomagnetic records ([14]).

Lake Baikal data presented here are mainly from a long core (BDP98, 600 m long) that was obtained from Academician Ridge in central Lake Baikal (Fig. 1; 53°44′40″N, 108°24′30″E). Academician Ridge is conveniently located for obtaining a continuous record of lake sedimentation, because it is topographically isolated, with little influence from fluvial input or turbidity flows. The age range of core BDP98 is inferred to be approximately 12.0 million years [14], based on paleomagnetic correlations. However, there is an alternative age estimate for the lower part of the core [16]. The core segment between subchrons C3An.2n and C3Bn (6.567–6.935 Ma) exhibits an abnormally high sedimentation rate, based on paleomagnetic correlations [17]. The structure of this core segment is distinctive, as shown by spectral analysis that implies an anomalous mix of climatic periods [18]. We have excluded this segment from statistical analyses to avoid data distortion [14], since we cannot yet explain this phys-

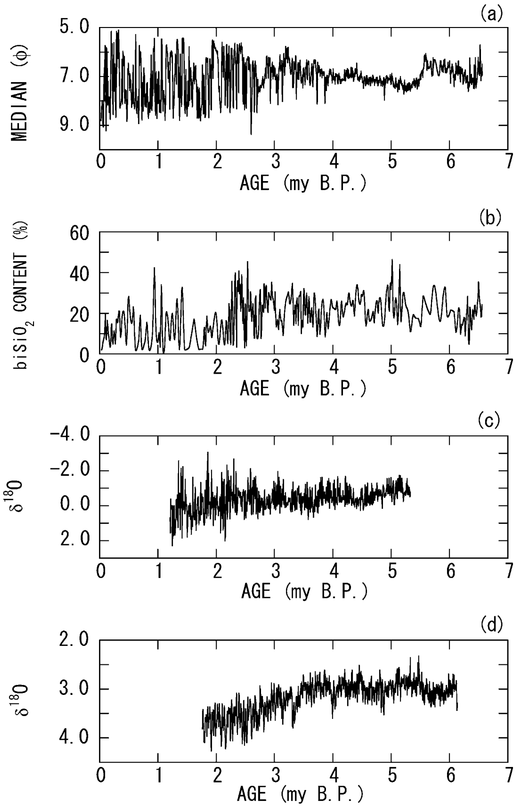

Fig. 3. (a) Mean grain size of BDP98, (b) BiSiO$_2$ content of BDP98, (c) oceanic δ^{18}O records from Mediterranean [18], and (d) oceanic δ^{18}O records from ODP (site 846) [17].

ical anomaly. The tentative age scale discussed here is based on geomagnetic polarity reversals and linear interpolations between them (Fig. 2).

Here we use data sets for grain size and biogenic SiO$_2$ content from the upper 6.5 Myr of the core for statistical analyses, in order to deal with an undoubted continuous record. We compare our results from Lake Baikal with oceanic records from ODP846 [19] (1.8–6.2 Ma) and onshore marine records from the Mediterranean area [20] (1.2–5.4 Ma). The data sets we discuss are shown in Fig. 3 (Table 1[1] for the biogenic SiO$_2$ data set). These exhibit shifts at about 2.7–3.0 Ma in most data sets, which would include the ca. 2.8-Ma shift noted above, and shifts at about 3.5 and 4.0 Ma. We must clearly define these shifts in order to further discuss the initiation of the current cyclical climatic oscillations. Hence, we include detailed statistical analyses in the present study.

4. Analyses and discussions

As stated above, we have detected long-term, orbit-related signals (ca. 1000-kyr, ca. 600-kyr and ca. 400-kyr periods) in the Baikal record, and these imply that long-term global fluctuations were influenced by solar insolation [14]. In the present study, we focus on comparatively small signals in the data sets. Fig. 4 shows filtered fluctuations for each data set. The numerical filters

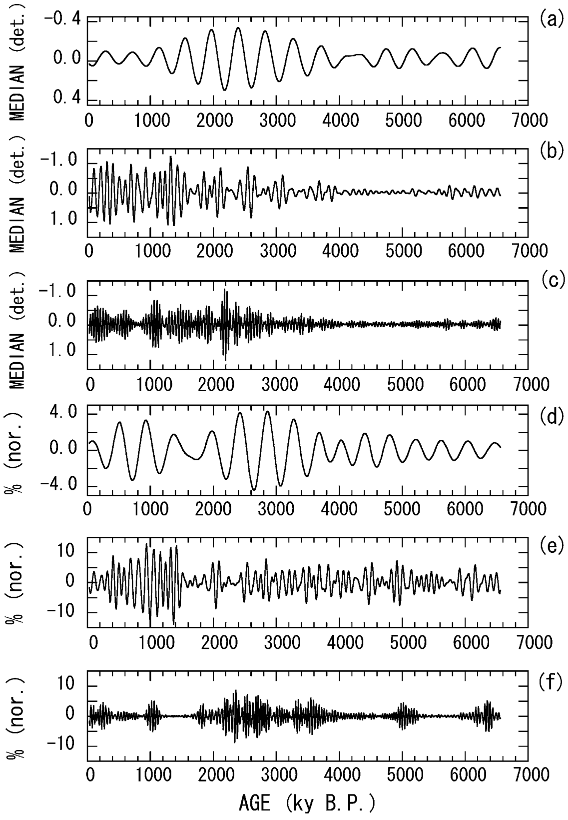

Fig. 4. Filtered curves for mean grain size: (a) 500–350 kyr, (b) 150–80 kyr, and (c) 50–35 kyr, and for BiSiO$_2$ content: (d) 500–350 kyr, (e) 150–80 kyr, and (f) 50–35 kyr band-pass filter.

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[1] See online version of this paper.

used here are the 500–350-kyr, 150–80-kyr and 50–35-kyr band-pass filters [21]. The 500–350-kyr and 150–80-kyr band-pass filters address periods of around 400 kyr and 100 kyr, respectively, which are major eccentricity parameters, whereas the 50–35-kyr band-pass filter addresses the obliquity period around 40 kyr. Most filtered fluctuations imply that an increase in the amplitude of fluctuations began at about 4.0 Ma, although there were lesser changes at about 3.5 Ma, plus further intensification at about 2.8 Ma. The Baikal records support onset of the current climatic oscillations at about 4.0 Ma.

In order to consider in detail the timing of these climatic changes, we have applied the filtering mentioned above to the data-sets from other areas of the world [19,20]. The results are shown in Fig. 5. Equatorial Pacific and Mediterranean records of the 500–350-kyr filtered fluctuations clearly show an intensification of amplitude at about 4.0 Ma. A climatic shift at about 2.8–3.0 Ma is also shown by fluctuations of around 100 kyr and 400 kyr that are related to eccentricity and obliquity parameters (the 3.4–3.6-Ma shift is also present in the curves but is less distinct). These data suggest that initiation of the current climatic oscillations occurred at around 4.0 Ma (Fig. 6), and that the Baikal region truly is extremely sensitive to climatic fluctuations, as suggested by Short et al. [15].

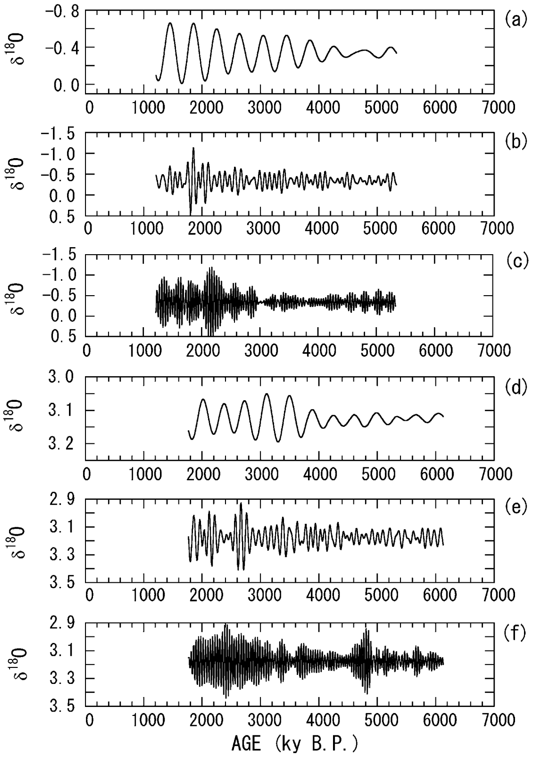

Fig. 5. Filtered curves for oceanic $\delta^{18}O$ records from Mediterranean: (a) 500–350 kyr, (b) 150–80 kyr, and (c) 50–35 kyr, and for oceanic $\delta^{18}O$ records from ODP (site 846): (d) 500–350 kyr, (e) 150–80 kyr, and (f) 50–35 kyr band-pass filter.

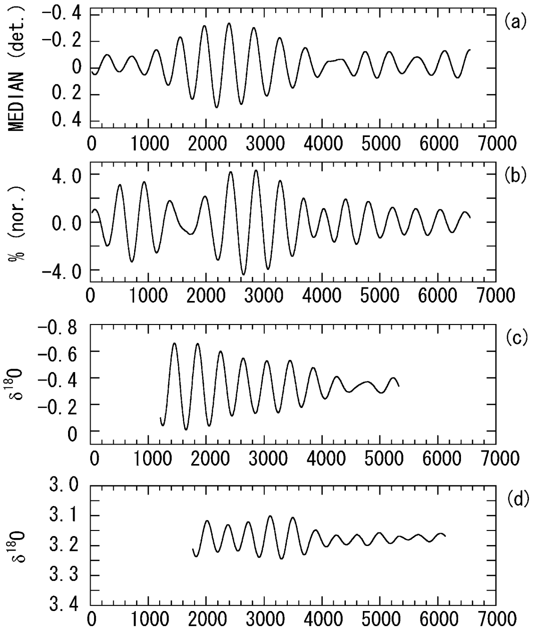

Fig. 6. Filtered curves (500–350 kyr band-pass filter) for (a) mean grain size, (b) BiSiO$_2$ content, (c) oceanic $\delta^{18}O$ records from Mediterranean, and (d) oceanic $\delta^{18}O$ records from ODP (site 846).

Until now, major shifts in climatic oscillation, such as the one at around 2.8 Ma [3,4], have been attributed to tectonic movements. However, other causes have been proposed, since rapid climatic changes cannot be explained solely by the slow pace of tectonic movements. For example, Li et al. [22] proposed fluctuations in insolation, especially the obliquity component, and a decrease in atmospheric CO$_2$ as major factors for intensifying Northern Hemisphere glaciation at 2.8 Ma against a background of tectonic influence. Driscoll and Haug [10] also indicated an obliquity-related contribution as well as the Atlantic Ocean thermohaline circulation due to tectonic movements and ensuing atmospheric circulation. Hence, we will address fluctuations in some components of insolation using the same filtering mentioned above. The insolation curve (65°N July) we use here was calculated by Laskar et al. [23]. Our results (Fig. 7) indicate that the increase in amplitude of the 400-kyr filtered (eccentricity component) insolation began at about 4.0 Ma, and that the amplitude of the 40-kyr filtered (obliquity component) insolation increased at around 4.0 Ma as well as at 3.0 Ma. In contrast, there was no large fluctuation in the 100-kyr filtered insolation. These observations suggest that the climatic shift at about 4.0 Ma was closely related to changes in insolation, especially the obliquity component and the 400-kyr eccentricity component.

These data suggest that the onset of the current climatic oscillations began at about 4.0 Ma, and evidently was related to an increase in the amplitudes of insolation variables. This conclusion is supported by a numerical simulation [22] in which ice sheet volume in the Northern Hemisphere began a pulsed increase after 4.0 Ma (and more frequently after 2.8 Ma), for a gradual decrease in atmospheric CO_2 concentration; in contrast, such an ice sheet increase began at about 2.8 Ma for a comparatively rapid CO_2 decrease. These changes led to initiation of the present cyclical climatic oscillations at around 4.0 Ma, and to intensification of these cyclical oscillations at about 2.8 Ma. Both changes are closely related to fluctuations of insolation. The 400-kyr eccentricity parameter and the obliquity parameter were significantly involved in the climatic shift at about 4.0 Ma, whereas mainly the obliquity parameter caused the shift at 2.8 Ma.

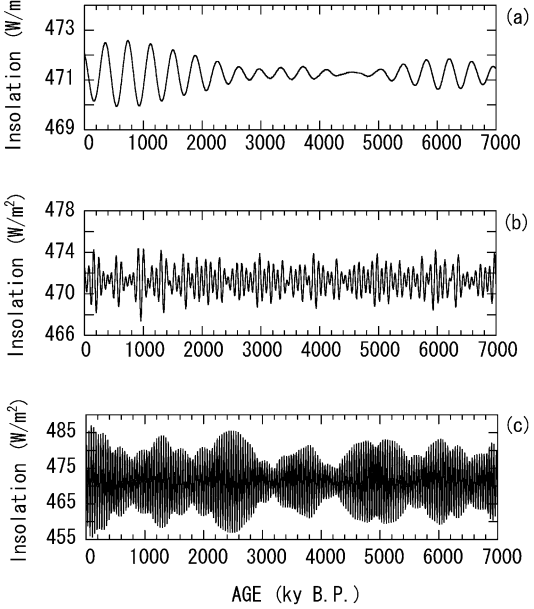

Fig. 7. Filtered curves for N65° July: (a) 500–350 kyr, (b) 150–80 kyr, and (c) 50–35 kyr.

5. Conclusions

The ideas presented here are a possible explanation for the appearance of the prevailing cyclical climatic oscillations, as follows. Gradual Northern Hemisphere cooling has taken place over the past 6–7 Ma, due to tectonic movements and/or a possibly related, gradual decrease in CO_2 concentration, without detectable Milankovitch-type cyclical oscillations. Low summer insolation would have increased Northern Hemisphere ice sheets only when climatic conditions (including CO_2 concentration) allowed winter snow to persist all year. This climatic threshold was possibly reached around 4.0 Ma. Insolation minima at about 3.9, 3.8 and 3.7 Ma, which were obliquity-related, may have triggered the prevailing climatic oscillations (which are related to the major Northern Hemisphere ice sheets). A rapid increase in dust deposition in the North Pacific and loess deposition in the Loess Plateau [10,11] at about 3.6 Ma may have been closely related to initiation of these climatic oscillations. Intensification of the major oscillations at about 2.8 Ma was probably connected to an additional decrease in obliquity minima at 2.9–2.6 Ma [22]. This intensification seems to have triggered larger oscillations, characterized by Milankovitch-type cycles, in the climatic regime that prevails today.

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