Paleoclimate of Interglacial Marine Isotope Stage 11 (MIS 11) from Strata in the Japanese Islands

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Paleoclimate of interglacial Marine Isotope Stage 11 (MIS 11), about 400 ky ago was estimated using data from shallow-marine to terrestrial strata of the Japanese Islands. The reason of the estimation comes from that the paleoclimate gives analogs for the future climate, because the conditions of Milankovitch forcing of MIS 11 are similar to those of modern Holocene. The results show the MIS 11 of the Japanese Islands was warmer, with a longer interval of highstand, and higher sea levels than the other interglacials. Further investigation for the strata of MIS 11 of the Japanese Island is needed and will give us important information about our future climate.

Keywords : interglacial, Jizodo Formation, MIS 11, paleoclimate, the Japanese Islands, the 9th Marie Clay Bed (Ma 9)

I. Introduction

Over the last 700,000 years, the Earth's climate has oscillated between cold glacial and warm interglacial intervals, mostly in cycles with a period of about 100 ky. The oscillation also includes shorter cycles of 41 ky, 23 ky and 18 ky. We believe that these climatic cycles, known as "Milankovitch cycles", are the result of astronomically induced changes in the distribution of solar energy reaching the Earth (Imbrie *et al.*, 1984 ; Berger *et al.*, 1996). The climatic changes due to Milankovitch cycles, known as, "Milankovitch forcing", are the most important determining factor for climate over the past 700 ky. We are now in a warm interval, the Holocene interglacial of the Marine Isotope Stage 1 (MIS 1). This warm interval has lasted for about 10 ky and is characterized by minimum eccentricity of the Earth's orbit and low amplitude of the precessional cycle. These Milankovitch forcing conditions are similar to those of Marine Isotope Stage 11 (MIS 11), about 400 ky ago (Berger and Loutre, 2003 ; Berger *et al.*, 2003 ;

Droxler *et al.*, 2003). Finding and studying analogs from the MIS 11 interglacial can provide a powerful tool to improve our understanding of our present-day climate and how it might change in the future.

According to Droxler *et al.* (2003), MIS 11 was an unusual and perhaps unique interglacial interval. It exhibited warm interglacial climatic conditions for a period of at least 30 ky, more than twice as long as the modern interglacial stage (MIS 1) ; it was characterized by a warm climatic conditions that were probably warmer than any conditions observed since 2.2 Ma ; and melting of the Greenland and West Antarctic ice sheets contributed to sea levels that were most likely 13 to 20 m higher than current sea levels. Variation of temperature and CO₂ content in the atmosphere during MIS 11 and MIS 1 (Broecker and Stocker, 2006) show a strong correlation. This facts and evidence from analysis of Antarctic ice cores, suggest that the current warm interglacial may continue for some time.

In this study, I used data from shallow-marine

Received December 6, 2006. Accepted January 25, 2007.

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to terrestrial strata of the Japanese Islands to show that the climate of MIS 11 was different from that of other interglacials. In particular, MIS 11 was warmer, with a longer duration, and higher sea levels.

II. Strata of MIS 11

Strata formed by the glacio-eustatic sea level changes of the middle to late Quaternary are present on the Japanese Islands. Plio-Pleistocene to Holocene sequences of several hundred meters thickness are well developed, especially in the Boso Peninsula and Osaka Bay areas of central Japan. Both of these areas were inundated at the interglacial highstand and emergent at the glacial lowstand. These sequences therefore can be clearly correlated with marine oxygen isotope curves from deep sea cores (Fig. 1, Masuda, 1997a ; Masuda and Ito, 1999).

Strata correlated with MIS 11 include the Jizodo Formation of the Shimosa Group on the Boso Peninsula (Machida *et al.*, 1980), and the 9th Marine Clay Bed (so-called "Ma 9") of the Osaka Group in Osaka Bay area (Yokoyama *et al.*, 1980). The Jizodo Formation is a forearc basin deposit and the 9th Marine Clay Bed is an intra-arc basin deposit.

In this paper, I discuss mainly paleoclimatic information obtained from the Jizodo Formation and 9th Marine Clay Bed (Ma 9), but also briefly discuss MIS 11 deposits from other areas.

III. The Jizodo Formation of the Shimosa Group

The Jizodo Formation, a sequence correlated with MIS 11, is consistently thicker than its overlying and underlying sequences. In ascending order, it is composed of a sequence of thin gravely sand and mud, which together represent lowstand fluvial deposits, transgressive estuary bay-floor mud, and thicker sand of highstand delta or shoreface deposits. The Jizodo Formation in Kisarazu area is 74–85 m thick, which is thicker than other formations deposited during the interglacial that were reported to be 15–65 m thick by Tokuhashi and Kondo (1989), and Okazaki (1996). The thicker sequence, however, cannot be solely attributed to a longer interglacial interval because other factors, such as tectonic activity, eustasy, and sediment sup-

ply (flux), also contribute to sequence thickness.

Sea level during MIS 11 may have been higher than that of the modern interglacial (MIS 1). The height of foresets in fluvio-deltaic deposits in the Jizodo Formation is about 23 m. The height of these structures, which are formed by delta progradation, shows the paleodepth of the delta front at the time of their deposition. Their height in the Jizodo Formation is greater than in modern deltas in these area (the Koito River delta, 12–18 m ; the Obitsu River delta, 8–16 m), and greater than the deltaic succession of MIS 7, reported as about 15–18 (?) m by Okazaki *et al.* (2000). This suggests that the sea level during MIS 11 was 5–7 m higher than those of MIS 7 and the present-day (MIS 1).

The Jizodo Formation contains abundant shallow-marine fossil shells. A warm- and deep-water shell assemblage, including *Glycymeris pilsbryi*, *Cryptopecten vesiculosus*, and *Nemocardium samarangae* of the "Jizodo fossil bed", was reported from the middle of the formation (Aoki and Baba, 1971, 1973 ; Tokuhashi and Kondo, 1989). This assemblage indicates water depths from 50–60 to 100–120 m (O'Hara, 1973 ; Kondo, 1989 ; Okazaki, 1996). No other horizon in the Shimosa Group contains such a deep-water assemblage, with the exception of a thin bed within MIS 9 that also includes some shells from a shallow-water assemblage.

Relatively high paleotemperatures and paleosalinities were calculated by Masuda (1977b, c) based on analyses of oxygen and carbon isotopes and strontium content from the fossil molluscan shells of the upper part of the Jizodo Formation. These results strongly suggest that sea level during MIS 11 in this area was higher, and sea temperature was warmer, than in other interglacial periods.

Although the Jizodo Formation was deposited during the MIS 11 interglacial, it includes a few micro-sequences that show small changes of relative sea level (Kamataki and Kondo, 1997 ; Nishikawa and Ito, 1997). There are several possible explanations for these micro-sequences, and their existence is corroborated by some small fluctuations of relative sea level shown in the curves of ice-core record.

IV. The 9th Marine Clay Bed of the Osaka Group

The 9th Marine Clay Bed (Ma 9), which is correlated to MIS 11 is within the fill deposits of an active subsiding basin represented by the Osaka Group (Itihara, 1993). The fill deposits are characterized by alternations of coarse-grained non-marine fluvial deposits and marine bay-floor muddy deposits (Ikebe *et al.*, 1970). There are 15 layers of marine bay-floor mud intercalated in the upper Osaka Group and the 9th Marine Clay Bed is one of them (Marine Clay, No. 9 in Fig. 1).

The 9th Marine Clay Bed is a homogenous bed with 26–43 m thick. It is thicker than the other marine bay-floor mud layers in the sequence, and is easily traced throughout the basin (Furutani, 1993). It is also thicker than the interglacial Marine Clay Beds of other marine

isotope stage sequences (Osakawan–Kibanjoho–Kenkyu–Kyogikai, 2002). For example, the marine clay of MIS 5 is 12–30 m thick. The thicker bay-floor mud may be indicative of a longer duration of deposition, and hence a longer warm interglacial period for MIS 11.

The 9th Marine Clay Bed is more widely distributed than other marine clays, such as the 7th, 8th, 10th, 11th, 12th and 13th. Its presence has been reported in the adjacent Kyoto Basin, about 20–30 km upper stream area (Kansai–Jibanjohokatuyo–Kyogikai, 2002). However, this correlation needs to be reinvestigated and confirmed.

On the basis of pollen analysis, the interglacial period of the 9th Marine Clay Bed had the warmest climate of all interglacial periods in the last 700 ky (Furutani, 1991; Yoshikawa, 1999). The *Syzygium* flora assemblage, which requires a warm environment, is included in this hori-

Fig. 1 Correlation of oxygen isotopic curves and orbital templates between the typical late Quaternary successions of the Boso and Osaka areas, Japan

Orbital templates are from Imbrie *et al.* (1984) and oxygen isotope curves of ODP Site 849 are from Mix *et al.* (1995). Black parts in the Osaka column represent marine clay beds. In the Boso column, H: Holocene, Ko: Kioroshi, Ky: Kiyokawa, Kz: Kamiizumi, Y: Yabu (Semata), J: Jizodo, Ks: Kasamori, C: Chonan, K: Kakinokidai, and Ku: Kokumoto Formations. Note the horizon of the Jizodo Formation (J) and the 9th Marine Clay Bed correlated to MIS 11 of about 400 ky ago characterized by minimum eccentricity of the Earth's orbit and low amplitude of the precession.

zon of the Osaka Group (Furutani, 1991). Marine diatoms are also abundant in the bed (Noguchi, 1993). Nannofossils of outer sea organisms are abundant in this bed (Okamura and Yamauchi, 1984; Yoshikawa, 1999). These fossil records show that the 9th Marine Clay Bed was deposited under warm climatic conditions at a time of highstand. Sugiyama and Mizuno (1991) proposed that the 9th Marine Clay Bed indicates a notably warm climate at the time of its deposition in central and southwestern Japan.

V. Other MIS 11 deposits

A large gravelly spit deposit (the Higashi Kanbe Gravel) is well developed in the transgressive systems tract of MIS 11 observed in the Atsumi Group on the Pacific coast of the Atsumi Peninsula (Hiroki and Masuda, 2000). This deposit might have been formed during a long period of transgression between MIS 12 (the most severe glacial period, along with MIS 6) and MIS 11, which was the first strong interglacial of the middle to late Quaternary. Droxler *et al.* (2003) pointed out the difficulty of determining what was a unique glacial to interglacial transition due to the extreme amplitude of the temperature curve.

Dry climatic conditions can be inferred from a long cored sequence from Lake Biwa (Hayashi *et al.*, 1999) that correlates with MIS 11. Within this core, coarser materials in general represent interglacial deposits. However, the MIS 11 sequence of this core is characterized by finer materials, mainly silt, and is poor in hyperpycnal-flow flood deposits, "hyperpycnite" (Mulder *et al.*, 2003; Saito *et al.*, 2005). This shows that the climate during MIS 11 was dry in the intra-arc area of Japan.

VI. Conclusions and future investigation

Deposits formed during MIS 11 have different features compared to other interglacial deposits of the Japanese Islands.

It is possible that the MIS 11 of the Japanese Islands was a warmer and longer interval of highstand than elsewhere.

Further investigation of the strata of MIS 11 of the Japanese Islands is needed, and should consider not only the MIS 11 sequence, but also

the transition from glacial MIS 12 (the most severe glacial, along with MIS 16) to interglacial MIS 11 (the first strong interglacial of the middle to late Quaternary).

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- (J) in Japanese, (J+E) in Japanese with English abstract.

日本列島の地層からみた同位体ステージ 11 の古気候

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〔要 旨〕

日本列島の地層の情報は、約 40 万年前の同位体ステージ 11 の間氷期が他の間氷期より温暖で長く、しかも海面も高かったことを示しているようだ。この時期の

古気候の復元は、この時期が現在の完新世の間氷期とミランコビッチ・フォーシングの要素が似ていることから、将来の気候を予測する上で重要である。

キーワード：第 9 海成粘土層 (Ma 9)，同位体ステージ 11 (MIS 11)，地藏堂層，間氷期，古気候

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