Reconstruction of sea-surface temperatures in Suruga Bay (central Japan) during oxygen isotope 6.5, using planktonic foraminiferal transfer functions

Akihisa Kitamura*1, a, Eiji Tominaga*2, Motoyoshi Oda*3 and Ayumi Takemoto*4

We reconstruct both summer and winter sea surface temperatures (SSTs) at around 177 ka (marine isotope stage 6.5) from planktonic foraminiferal assemblages in the Kunosan Formation in the Udo Hills along Suruga Bay, central Japan. The results show that the SSTs were 2–3°C colder than today and are comparable to those at Kashimanada today. This may imply that the subtropical Kuroshio Front was located off Suruga Bay during MIS 6.5.

Keywords: Kunosan Formation, marine isotope stage 6.5, planktonic foraminifer, transfer functions, SSTs, Suruga Bay

I. Introduction

Several paleoenvironmental studies have documented exceptional phenomena in marine isotope stage (MIS) 6.5. The isotopic ratio of atmospheric O$_2$, $\delta^{18}$Oatm in the Vostok data, displays variations similar to those of mean ocean water ($\delta^{18}$Osw) over the last 135 ka (Sowers et al., 1993; Bender et al., 1994a). However, there was a major discrepancy between these two signals in MIS 6.5 (Bender et al., 1994b) (Fig. 1). The high and nearly constant value of $\delta^{18}$Osw in MIS 6.5 implies a glacial climate, whereas the $\delta^{18}$Oatm has the strong variation and conspicuous minimum of an interglacial stage.

Sapropel S6 was deposited in the Mediterranean Sea during MIS 6.5 (Fig. 1). Sapropels, organic-rich black sediment layers formed under anoxic conditions, were deposited basin-wide in eastern Mediterranean Sea sediments at intermittent intervals throughout the Quaternary (Olausson, 1961; Kidd et al., 1978). Most sapropel deposits (termed S1, S3, S4, S5 and S7) formed during interglacial or interstadial stages (i.e. climatic warm phases) (Cita et al., 1977; Vergnaud-Graziini and Cita, 1977). In contrast, pollen and foraminiferal records indicate that glacial conditions prevailed in the Mediterranean region during the deposition of sapropel S6 (Cita et al., 1977; Thunell et al., 1983; Mélières et al., 1997; Eméis et al., 2003).

Many workers have observed that these unusual paleoenvironmental changes were related to strong boreal summer insolation under glacial conditions. For example, Mélières et al. (1997), Ayalon et al. (2002) and Bard et al. (2002) inferred that the deposition of sapropel S6 may have been caused by increased precipitation

Received November 12, 2007. Accepted March 1, 2008.
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Fig. 1 A comparison of boreal summer insolation and four paleoenvironmental data during 300–100 ka

The vertical grey bands represent the timing for MIS 6.5. These are compared with, from the top: 65°N July insolation (Berger, 1992); a stack of 57 benthic δ18O record (Lisiecki and Raymo, 2005); atmospheric δ18O record from Vostok ice core (Jouzel et al., 2002); sea-level curve based on open-system coral ages from Barbados (Thompson and Goldstein, 2005); horizons of sapropel deposits based on sediment lightness (Emeis et al., 2003).

below the Mediterranean region that was linked to increased monsoon activity associated with the summer insolation maximum at 65°N (Fig. 1). This interpretation is also supported by Emeis et al. (2003). Masson et al. (2000) used an atmospheric general circulation model (GCM simulation) to demonstrate the possible coexistence of glacial conditions in the middle and high latitudes, plus strong African and Asian monsoons.

To examine details of the climate changes during MIS 6.5 requires numerically dated climate records from many regions. Although many radiometric ages have been reported from corals on uplifted terraces since MIS 9 (Thurber et al., 1965; Broecker et al., 1968; Chappell, 1974; Chen et al., 1991; Gallup et al., 1994; Edwards et al., 1996; Esat et al., 1999; Stirling et al., 2001), numerical ages for MIS 6.5 are reported only from marine terraces in Barbados (Gallup et al., 2002; Thompson and Goldstein, 2005). This near-absence of radiometric ages is due to sea level during MIS 6.5 having been about 40 m below present sea level (Thompson and Goldstein, 2005) (Fig. 1), so that the ancient near-shore deposits are now mostly under water, except in a tectonically uplifting area such as Barbados. Kitamura et al. (2005) recently reported a U–Th ages of 176.5 ± 3.7 ka (error is 1σ) for a solitary coral from emerged marine strata of the Kunosan Formation in the Udo Hills, central Japan (Fig. 2). In the present study, we in-
fer the sea surface temperatures (SSTs) during deposition of these sediments, using the planktonic foraminiferal transfer function (PFJ-125) presented by Takemoto and Oda (1997).

II. Geological setting and chronology

The Udo Hills (35°N latitude) are situated along the coast of Suruga Bay (Fig. 2–b, c) and have been tectonically uplifted about 300 m during the past 100,000 years or so (Tsuchi, 1970). They comprise a 500-m-thick sequence of alternating fan-deltas and shallow-marine sediments that were deposited during the middle to late Pleistocene (Tsuchi, 1960; Kondo, 1985). This sequence has been divided into the Negoya, Kunosan, Kusanagi, Oshika and Kuniyoshida formations, in ascending order (Figs. 2–c and 3).

The Negoya Formation consists mainly of marine mudstone and contains three gravel wedges (Ago, Furuyado and Nakahiramatsu Gravel members, in ascending order) (Kondo, 1985). The gravel wedges have thicknesses less than 70 m, pinch out eastward and are bounded by marine mudstone. Three tuff beds, Ng–1, Ng–2 and Ng–4, are readily identified by their lithological characteristics and are used as marker horizons within the Negoya Formation (Kondo, 1985) (Fig. 3). The first occurrence (FO) of the nannofossil *Emiliania huxleyi*, which first appeared late in MIS 8.0 (Thierstein *et al.*, 1977), is in a marine mudstone just above the top of the Ago Gravel Member (Okada, 1987) (Fig. 3). Based on the pollen analysis and biostratigraphic data, Sugiyama (1991) inferred that the mudstone containing tuff beds Ng–2 and Ng–4 was deposited during MIS 7.3 (ca. 220 ka).

The Kunosan Formation unconformably overlies the Negoya Formation, and is in turn conformably overlain by the Kusanagi Formation that was deposited during the last interglacial stage (Kondo, 1985). In the eastern Udo Hills, the Kunosan Formation is up to 80 m thick and divided into lower and upper parts in the study area (Figs. 2 and 4). The lower part consists of an alternation of stratified conglomerate (average 1 m thick) and well-sorted sand (beds average 0.2 m thick) (Kitamura *et al.*, 2005). The clasts in many conglomerate beds are mostly pebble-sized and clast-supported, and long-axis-parallel imbricated. The sand beds yield well-preserved specimens of the trace fossil *Rosselia socialis* which occurs in shallow-marine (only locally continental-slope) deposits (Nara, 1995, 2000; Nara *et al.*, 2004). The clast-supported and imbricated fabric in the conglomerate beds implies that the stratified conglomerates represent high-density turbidity currents (Lowe, 1982). The overlying sand beds are interpreted as resulting from low-density turbidity currents.

![Fig. 2 Simplified location map of the Udo Hills, Shizuoka Prefecture, Japan and schematic geological map](image-url)

Geological map is modified from Kondo (1985).
The upper part of the Kunosan Formation consists of alternating beds of conglomerate and siltstone (Fig. 4). The conglomerate beds have erosional bases and show inverse-to-normal grading, and change upward into a graded sand unit with parallel laminations. The clasts are long-axis-parallel imbricated and support each other. These features imply that the conglomerate beds resulted from the combined processes of cohesion-less debris flows and turbidity currents (Nemec, 1990; Walker and Plint, 1992). Siltstone represents massive and yields many well-preserved and articulated shells of *Limopsis belcheri*, *Acila divaricata* and *Keenaea samarangae* (Kitamura et al., 2005). Based on their modern occurrences around Japanese Islands (Higo et al., 1999; Nobuhara et al., 2005), these bivalves imply upper water-depth limits of 100 m.

Kitamura et al. (2005) collected the solitary coral *Flabellum transversale* from silt in the lowest portion of the upper part of the Kunosan Formation. The thorium-230 age of a specimen is $176.5^{+3.7}_{-3.5}$ ka (error is 1σ) (Kitamura et al., 2005) (Figs. 3 and 4). This age range is generally consistent with the age of MIS 6.5 inferred from the δ¹⁸O record in marine sediments (175 ka) (Martinson et al., 1987) and atmospheric oxygen trapped in Antarctic ice (178 ka) (Shackleton, 2000).

### III. Methods

The planktonic foraminiferal assemblages occur in two samples (sample numbers 1–2) from a mudstone that contains tuff bed Ng–2 of the Negoya Formation (MIS 7.3), and four samples (numbers 3–6) from the upper part of the Kuno-san Formation (Fig. 4). Sample 4 corresponds to the horizon that contains the radiometrically dated coral specimen noted above. All samples were soaked in hot water for 1 hour and washed using a 125–μm diameter sieve. The samples were then split into aliquots containing approximately 200 specimens, and all planktonic foraminifers were picked and identified (Table 1). Given their excellent preservation, we consider that few planktonic foraminifers were derived from older deposits. Foraminiferal census data were translated into both summer and winter sea-surface temperatures (SSTs) using the following transfer functions (PFJ–125) based on foraminiferal assemblages in 81 surface sediments collected from areas in the Pacific offshore from Japanese Islands.

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1. **N.:** Nakahiratsuru Gravel Member
2. **F.:** Furuyado Gravel Member
3. **A.:** Aso Gravel Member
4. **M.:** Muramatsu Gravel-Silt Member
5. **Ng1, 2, 4:** pyroclastic marker b
6. **Ng2:** pyroclastic marker a

**Fig. 3** Summary stratigraphic column of upper Pleistocene deposits in the Udo Hills (Kondo, 1985) and chronologic data

The age of the first occurrence of *E. huxleyi* is based on Thierstein et al. (1977).
Fig. Columnar section of the Negoya and Kunosan formations in the study area, showing stratigraphic distribution of planktonic foraminifera and temporal changes in SSTs. Arrows show sampling horizons for planktonic foraminifera.

IV. Results and discussion

Planktonic foraminiferal assemblages in the Negoya Formation are dominated by *Globigerina bulloides* and contain *Gna. falconensis* and *Globigerinoides ruber*, while those in the Kunosan Formation are dominated by *Gna. bulloides*, *Gna. quinqueloba* and *Neogloboquadridina incompeta* and contain *Globorotalia inflata* (Fig. 4, Table 1).

We tested in two ways whether the foraminiferal transfer function is applied to SSTs during MIS 6.5. First, we estimated the summer and winter SSTs for site 37 (KH74–3; water depth : 1,423 m, Fig. 2–b), the site located nearest to Suruga Bay (surface sediment samples from the bay were not included in Takemoto and Oda (1997)). The resulting summer and winter SSTs are 25.5 and 15.1°C, respectively. Based on Japan Oceanographic Data Center (2007) (1° × 1° grid cells, 34–35°N latitude and 138–139°E longitude, 0 m depth), the modern mean SSTs of the area during summer and
winter are 25.4±0.9°C and 15.5±0.6°C, respectively (mean and standard deviations for July—September and January—March, respectively; data from the period 1906—2003). This strong degree of similarity between the estimated and observed values supports the proposal that the transfer function PFJ-125 is useful in reconstructing SSTs in the area within Suruga Bay.

Second, we estimated the SSTs in MIS 7.3, based on planktonic foraminiferal assemblages in the Negoya Formation. Although the climate during MIS 7.3 has not been examined quantitatively in central Japan, the climatic conditions may have been the same as today’s, since there is no significant difference in sea level (continental ice volume) between the two ages (Chappell, 1994; Bard et al., 2002; Thompson and Goldstein, 2005) (Fig. 1). Our result shows that summer and winter SSTs of the Negoya Formation are inferred to be 25.5—25.6°C and 15.5—15.7°C, respectively (Fig. 4, Table 2). On the other hand, the modern mean SSTs during summer and winter are 25.4±1.3°C, and 14.4±0.7°C in the study area (Suruga Bay), respectively (mean and standard deviations for July—September and January—March, respectively; data from the period 1906—2003) (Japan Oceanographic Data Center, 2007; 35—36°N latitude and 138—139°E longitude, 0 m depth) (Fig. 5). Both summer and winter SSTs at MIS 7.1 were similar to the present day values. This result also supports that our

Table 1  Planktonic foraminifera identified from the study section of the Negoya and Kusunan formations

<table>
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<th>species</th>
<th>sample No.</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>Globigerina bulloides d’Orbigny</td>
<td>272</td>
<td>121</td>
<td>144</td>
<td>57</td>
<td>57</td>
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<td></td>
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<tr>
<td>Gna. falconensis Blow</td>
<td>62</td>
<td>9</td>
<td>50</td>
<td>21</td>
<td>27</td>
<td>13</td>
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<td>Gna. rubescens Hörké</td>
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<td>145</td>
<td>58</td>
<td>72</td>
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<td>Gryt. calida (Parker)</td>
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<td>0</td>
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<td>Gds. ruber (d’Orbigny)</td>
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<td>15</td>
<td>46</td>
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<td>Gds. sacculifer (Brady)</td>
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<td>Gds. innelliis Parker</td>
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<td>Globorotalia bermudezi Rögl and Bolli</td>
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<td>9</td>
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<td>0</td>
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<td>total</td>
<td>522</td>
<td>214</td>
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<td>206</td>
<td>294</td>
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Table 2  The varimax factor loading matrix, communalities and estimated summer and winter SSTs for six samples from the Negoya and Kusunan formations

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<td>0.590</td>
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<tr>
<td>3rd</td>
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<tr>
<td>4th</td>
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<td>0.155</td>
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<tr>
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<td>-0.030</td>
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<td>0.398</td>
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<td>summer SST (°C)</td>
<td>25.6</td>
<td>25.5</td>
<td>22.8</td>
<td>23.5</td>
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<tr>
<td>winter SST (°C)</td>
<td>15.7</td>
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<td>11.3</td>
<td>12.6</td>
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<td>communality</td>
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<td>0.86</td>
<td>0.72</td>
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This study was funded by Grants-in-Aid 08454150 and 10304040 from the Ministry of Education, Science and Culture of Japan. We thank Dr. H. Takata and the editor Dr. S. Sato for comments that improved the manuscript.

Acknowledgments

Fig. 5 Monthly mean sea-surface temperatures in Suruga Bay (35°–36°N latitude and 138°–139°E longitude, 0 m depth) and at Kashimanada (36°–37°N latitude, 140°–141°E longitude, 0 m depth)

Data are from JODC Data On-line Service System. Localities are shown in Fig. 2.

approach is a valid way of reconstructing sea-surface temperatures in Suruga Bay during MIS 6.5.

The estimated summer and winter SSTs of the Kunosan Formation are 22.6°–23.5°C and 10.8°–12.6°C, respectively (Fig. 4, Table 2). The 2–3°C differences in both SSTs between MIS 6.5 and the modern sea (summer and winter are 25.4°±1.3°C and 14.4°±0.7°C, respectively) are significantly greater than the above-noted standard errors for our reconstructed SSTs (1.17°C for summer and 1.75°C for winter). The SSTS at MIS 6.5 (around 177 ka) are comparable to those at present-day Kashimanada (Japan Oceanographic Data Center, 2007; 36°–37°N latitude, 140°–141°E longitude, 0 m depth, data from the period 1906–2003) (Fig. 5). The subtropical Kuroshio Current comes off the Japanese Islands around Kashimanada area at present-day (Fig. 2–a). It is therefore likely that the Kuroshio Front was located off Suruga Bay during MIS 6.5. The climate simulation presented by Masson et al. (2000) predicts that the summer surface air temperature around Japan at 175 ka was 1–2°C warmer than today. Our result implies that the effect of high insolation to the area surrounding Japan was weaker than that predicted in the climate simulations.

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浮遊性有孔虫群集を用いた変換関数による酸素同位体ステージ6.5の駿河湾表層水温の復元

北村晃寿*1,a・富永英治*2・尾田太良*3・嶽本あゆみ*4

[要旨]
静岡県静岡市有度丘陵東縁に分布する中部更新統生産化石層帯を対象に、久能山層から産出した浮遊性有孔虫化石群集に基づき、Takemoto and Oda (1997) の開発した変換関数 PFJ-125 を適用した結果、酸素同位体重手ステージ6.5では夏季・冬季の表層水温がともに現在より2~3℃低かったことが判明した。

キーワード：久能山層、海洋酸素同位体重手ステージ6.5、浮遊性有孔虫、変換関数、海面表層水温、駿河湾

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