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Diatom records in the Quaternary marine sequences around the Japanese Islands

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ABSTRACT

Understanding the Quaternary is a key to estimating what the Earth's climate will be like in the future. Such studies demand high-resolution analyses based on paleoclimatic proxy records of changing Earth's orbital forcing and solar insolation that affect the climate system. Quaternary diatom biostratigraphy and paleoceanography have been well established based on the Quaternary marine sequences obtained by piston coring and deep-sea drilling around the Japanese Islands. This paper firstly reviews the Quaternary diatom datum levels that are directly tied to magnetic polarity, and then the late Pleistocene and Holocene rhythmic fluctuations in *Td'*-derived SSTs (°C) which correlate with the Earth's orbital parameters, and finally reveals the large and abrupt climatic changes that have occurred around the Japanese Islands on centennial to millennial time scales.

The main aim is to provide the results of *Td'*-SSTs (°C) based on the late Pliocene to Pleistocene sequences from three holes obtained by deep-sea drilling (DSDP-ODP). The main difference between *Td'* and *Twt* is that *Twt* gives 0.5 values to *Xt* (warm transitional taxa). *Thalassiosira oestrupii* is grouped with *Xt* in *Twt* but with warm-water species in *Td'*. Differences between the *Twt* and *Td'*-SSTs (°C) curves at Hole 436 are unremarkable. The remarkable variations of paleo-temperatures based on *Td'*-SSTs (°C) show four conspicuous episodes which correspond to the double precession cycle of MIS 11. In the Japan Sea, the *Twt* ratio remarkably decreases at 2.6 Ma due to a large increase in cold-water taxa, and indicates the beginning of the glacial age defined as the Pliocene/Pleistocene boundary. Both *Twt* and *Td'*-SSTs (°C) increase at 2.60–2.0 Ma, and coincide with the lithologic change from diatom-bearing clay with few dark-colored layers to fine-grained sediments with distinct dark–light colored cycles. Wavelet analysis of *Td'*-SSTs (C) at Site 798 indicates a reversed saw-tooth pattern of 48 to 24-ky periods during 1.2–0.7 Ma, and 24 to 12-ky periods during 0.7–0 Ma, resulting in a change from longer to shorter cycles. These fluctuations correlate with the Earth's orbital parameters and climatic changes on a millennial time scale.

1. Introduction

Diatom fossils occur more frequently in sediments of the northwest Pacific than other microfossils, and with a greater diversity of species. Diatom biostratigraphy and paleoceanography have been established for the marine Quaternary around the Japanese Islands during the past 10 years (Fig. 1). The Quaternary diatom datum levels (bio-horizons) were directly tied to the magnetic polarity in complete Quaternary marine sequences obtained by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP). Within the middle-to-high latitudes, the first occurrence or base (FO) of *Neodenticula seminae* is estimated at 2.7 Ma, the last occurrence or top (LO) of *Neodenticula kamtschatica* at 2.6 Ma, the LO of *Thalassiosira convexa* at 2.3 Ma, the LO of *Thalassiosira zabelinae* at 2.1 Ma, the FO of *Fragilariopsis doliolus* at 2.0 Ma, the LO of *Neodenticula koizumii* at 1.8 Ma, the LO of *Thalassiosira antiqua* at 1.7 Ma, the FO and LO of *Proboscia curvirostris* at 1.6 and 0.3 Ma respectively, the LO of *Actinocyclus oculatus* at 1.0 Ma, and the LO of *Thalassiosira jouseae* at 0.3 Ma (Koizumi, 2009, 2013). These datum levels suggest the following evolutionary lineages: (1) from *N. kamtschatica* to *N. koizumii*, (2) from *N. koizumii* to *N. seminae*, (3) from *Fragilariopsis fossilis* to *F. doliolus*, (4) from *Proboscia barboi* to *P. curvirostris*. The spatial distributions of the appearances and disappearances of diatom species are related to environmental

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changes and/or to evolutionary processes. The temporal migration of species from their "home-area" to other areas is recognized by delayed first occurrences in those regions and is controlled by the fluctuating frontal boundaries between water-masses (Koizumi, 1986). The disappearance of the species in a given region occurs in response to changing surface-water temperatures (and/or salinities), which are beyond the tolerance limitation of the species.

Paleoceanographic proxies of diatoms have been constructed using statistical methods comparing the spatial distribution of diatom species in the seafloor surface sediments to the primary production, sea-surface temperatures (SSTs) (°C), salinity, and other physical–chemical parameters in modern surface waters. Regression analysis was performed between the ratio of warm- and cold-water diatom species (revised diatom temperature ratio, *Td'* ratio) in 123 surface sediments around the Japanese Islands and annual SSTs (°C) at the core sites (Koizumi, 2008, Table 1). *Td'*-derived annual paleo-SSTs (°C) agree with the $\delta^{18}O$ of benthic foraminiferal tests and Uk'_{37}-derived summer paleo-SSTs (°C) at sites off central Japan. *Td'*-SSTs (°C) fluctuate on centennial to millennial timescales, indicating a strong and regular flow of the Kuroshio Current and Tsushima Warm Current (TWC) during the Holocene epoch after 12 ka (Koizumi and Yamamoto, 2010, 2011). The *Td'*-SSTs (°C) in the Tohoku Area off the northeast part of Honshu Island are generally higher than in the Japan Sea despite lower *Td'* values because the warm-water species *Fragilariopsis doliolus* is abundant only in the TWC of the Japan Sea. Those fluctuations are synchronous with abrupt climate events reported from the different paleoclimatic proxy records in many regions of the Northern Hemisphere (Koizumi and Sakamoto, 2010; Koizumi and Yamamoto, 2011).

(8.2–3.3 ka) coincides with the Holocene hypsithermal period and is 1–2 °C warmer than the earlier and later parts of the Holocene. The late Holocene (3.3–0 ka) neo-glacial period is marked by a generally decreasing trend of the SSTs, reflecting the decreased solar insolation in the Northern Hemisphere summer (Koizumi and Sakamoto, 2010).

The middle Holocene warm period in the Tohoku Area is marked by the anti-phased SST relationship with decreasing abundances of the warm-water diatom species *F. doliolus* (Barron and Anderson, 2010) and the alkenone-derived (Yamamoto et al., 2004, 2005; Isono et al., 2009) SSTs in coastal northern California. The anti-phase SST variations between east-to-west margins of the mid-latitude North Pacific Ocean are similar to the behaviors of the El Niño-Southern Oscillation (ENSO). The anti-phase SST variations also correspond to the patterns seen in the modern Pacific-Decadal Oscillation (PDO), where cooler SSTs in the central northwest Pacific Ocean contrast with warmer SSTs in the eastern North Pacific Ocean and eastern equatorial Pacific Ocean during periods of positive PDO (Isono et al., 2009; Barron and Anderson, 2010).

The Pliocene/Pleistocene boundary was changed to 2.58 Ma at the top of magnetic polarity C2An (Gauss) chron by the International Union for Quaternary Research (INQUA) and International Commission on Stratigraphy (ICS) (Head et al., 2008).

The purpose of this paper is to define the paleoclimatic and paleoceanographic events based on the original database for *Td'*-SSTs and diatom assemblages in a series of excellent biosiliceous sequences after 3.6 Ma at DSDP Site 436 in the Tohoku Area off the northeast Japan, and after 3.3 Ma at ODP Hole 797B and after 1.3 Ma at Holes 798A and 798C in the Japan Sea (Fig. 1).

Table 1
Species composition for *Td'* (Koizumi, 2008).

Td'	
Warm-water species	Cold-water species
Actinocyclus ellipticus Grunow	*Actinocyclus curvatulus* Janisch
A. elongatus Grunow	*A. ochotensis* Jousé
Alveus marinus (Grunow) Kaczmarska & Fryxell	*Asteromphalus hyalinus* Karsten
Asterolampra marylandica Ehrenberg	*A. robustus* Castracane
Asteromphalus arachne (Brebisson) Ralfs	*Bacterosira fragilis* Gran
A. flabellatus (Brebisson) Greville	*Chaetoceros furcellatus* Bailey
A. imbricatus Wallich	*Coscinodiscus marginatus* Ehrenberg
A. pettersonii (Kolbe) Thorrington-Smith	*C. oculus-iridis* Ehrenberg
A. sarcophagus Wallich	*Fragilariopsis cylindrus* (Grunow) Krieger
Azpeitia africanus (Janisch) Fryxell & Watkins	*F. oceanica* (Cleve) Hasle
A. nodulifera (Schmidt) Fryxell & Sims	*Neodenticula seminae* (Simonsen & Kanaya) Akiba & Yanagisawa
A. tabularis (Grunow) Fryxell & Sims	*Porosira glacilis* (Grunow) Jorgensen
Fragilariopsis doliolus (Wallich) Medlin & Sims	*Rhizosolenia hebetata* (Bailey) Gran
Hemidiscus cuneiformis Wallich	*Thalassiosira gravida* Cleve
Nitzschia interruptestriata Simonsen	*T. hyalina* (Grunow) Gran
N. kolaczekii Grunow	*T. kryophila* (Grunow) Joergensen
Planktoniella sol (Wallich) Schütt	*T. nordenskioldii* Cleve
Pseudosolenia calcar-avis (Schültze) Sundstrom	*T. trifulta Fryxell*
Rhizosolenia acuminata (Peragallo) Gran	
R. bergonii Peragallo	
R. hebetata (Bailey) Gran f. *semispina* (Hersen) Gran	
R. imbricata Brightwell	
Roperia tessellata (Roper) Grunow	
Thalassiosira leptopus (Grunow) Hasle & Fryxell	
T. oestrupii (Osterfeld) Proshkina-Lavrenko	

The *Td'*-SSTs (°C) decrease during the Younger Dryas (YD) due to a weakening of both the Kuroshio and TWC (Koizumi, 2008). The average SSTs (°C) in the YD are 7–9 °C lower than the present-day values in the Tohoku Area, and 6–9 °C lower than those in the Japan Sea. The early Holocene (11.6–8.2 ka) is a transitional period characterized by a long-term increasing trend of temperatures punctuated by several cooling events, while the middle Holocene

2. Background

The onset of significant Northern Hemisphere Glaciation (NHG) at ~2.7 Ma occurred within the context of progressive Cenozoic cooling (Koizumi, 1985; Barron, 1998; Shimada et al., 2009), and also a gradual increase in the mean global ice volume began in the interval of 3.6 Ma to 2.4 Ma (Ravelo et al., 2004) based on deep-sea