Title	Diatom records in the Quaternary marine sequences around the Japanese Islands
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Citation	Quaternary international, 397, 436-447 https://doi.org/10.1016/j.quaint.2015.03.043
Issue Date	2016-03-18
Doc URL	http://hdl.handle.net/2115/68358
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Type	article (author version)
File Information	QUATINT-D-14-00525.pdf

Diatom Records in the Quaternary Marine Sequences around the Japanese Islands

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Keywords: *Td´*-derived paleo-SSTs (℃), *Twt*, wavelet analysis, DSDP-ODP, Tohoku Area, Japan Sea

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 the paleoclimatic proxy records of changing the 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 (℃) 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 (℃) 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´* based on the information of Sancetta and Silvestri (1986),

Koizumi et al. (2004), and Ren et al. (2014). Differences between the *Twt* and *Td´*-SSTs (℃) curves at Hole 436 are unremarkable. The remarkable variations of paleo-temperatures based on *Td´*-SSTs (℃) show four conspicuous episodes which correspond to the two steps noted by Ravelo et al. (2004) and the double precession cycle of the interglacial MIS 11 (Lisiecki and Raymo, 2005). 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 (℃) 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 colred cycles. Wavelet analysis of *Td´*-SSTs (℃) at Site 798 indicates a reversed saw-tooth pattern of 48 to 24-kyr periods during 1.2-0.7 Ma, and 24 to 12-kyr 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). 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 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) (℃), 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 (℃) at the core sites (Koizumi, 2008; Table 1). *Td´* -derived annual paleo-SSTs (℃) agree with the $\delta^{18}O$ of benthic foraminiferal tests and Uk'_{37}-derived summer paleo-SSTs (℃) at sites off central Japan. *Td´*-SSTs (℃) 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 (℃) 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).

The *Td´*- SSTs (℃) decrease during the Younger Dryas (YD) due to a weakening of both the Kuroshio and TWC (Koizumi, 2008). The average SSTs (℃) in the YD are 7-9 ℃ lower than the present-day values in the Tohoku Area, and 6-9 ℃ 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 (8.2-3.3 ka) coincides with the Holocene hypsithermal period and is 1-2 ℃ 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; 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).

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 drilling cores. Prior to the onset of NHG, the Pliocene warm period (5-3 Ma) was widely studied as an analogue of a future global climate warmer than today.

On the other hand, diatom records mainly in piston cores have shown oscillations between warm and cold Pleistocene intervals and have recorded glacial-interglacial cycles twice over 150 ka. Diatom associations and *Td´*-SSTs (℃) imply that paleohydrography around the Japanese Islands has corresponded to environmental changes such as Milankovitch cycles, Dansgaard-Oeschger cycles and/or Bond cycles on an orbital timescale between warm and cold intervals (Koizumi and Sakamoto, 2010; Koizumi and Yamamoto, 2010, 2011).

2.1. Paleotemperature Estimates in the late Pliocene to early Pleistocene

The U.S. Geological Survey organized the PRISM (Pliocene Research, Interpretation, and Synoptic Mapping) Project in 1990 (Cronin and Dowsett, 1991). In the PRISM Project, Barron (1992) proposed the use of the *Twt* ratio to interpret the Pliocene paleoclimatic changes in the region of DSDP Site 580 in the northwest Pacific. In the equation $Twt=(Xw+0.5Xt)/(Xc+Xt+Xw)$, *Xw* is the total number of subtropical to tropical (warm-water) taxa. *Xt* is the total number of warm transitional taxa (*Thalassionema nitzschioides*, *Thalassiosira oestrupii*, and *Coscinodiscus radiatus*) and *Xc* is the total number of subarctic to arctic (cold-water) taxa. *Xw* and *Xc* include extinct Pliocene taxa, for instance *Fragilariopsis fossilis, F. reinholdii, Nitzschia jouseae* and *Thalassiosira convexa* as *Xw*, and *Neodenticula kamtschatica* and *N. koizumii* as *Xc*.

The *Twt* ratio in this paper constitutes the associated taxa, which the *Td´* ratio (Table 1; Koizumi, 2008) introduced and includes such extinct Pliocene taxa, in addition to those Barron (1992) adopted, as *Nitzschia miocenica*, *Rhizosolenia praebergonii, Thalassiosira miocenica,* and *T. praeconvexa* as *Xw*, and *Actinocyclus oculatus, Proboscia curvirostris,* and *Thalassiosira nidulus* as *Xc*. These taxa are considered to closely correspond to their descendants based on their morphology, paleogeographic distribution, and ecological requirements. *T. oestrupii* is converted from warm-water species in *Td´* to *Xt* in *Twt* (Table 2) because *T. oestrupii* prefers a relatively cooler environment (Ren et al., 2014). However, *Td´*-derived SST (℃) values still substitute substantially for the paleotemperatures (℃).

2.2. Climatic Changes based on Td´-derived SSTs (℃) in the late Pleistocene

Diatom records in the Tohoku Area have shown glacial-interglacial cycles twice over the past 150,000 years, which corresponds to the environmental changes on an orbital timescale (Koizumi and Yamamoto, 2010). The high *Td´*-derived SSTs (℃) recognized in middle MIS 5e and 1 of the interglacial phase correlate among the cores. *Td´*-SSTs (℃) in MIS 5e are ~5 ℃ higher than modern values from near-shore cores, but in the offshore cores the differences are only up to ~1.5 ℃. On the other hand, the remarkable decline of *Td´*-SSTs (℃), recognized in the MIS event 6.0 at the MIS 6/5 boundary and event 5.2 in MIS 5b, correspond to the ages of Heinrich events 1-6 in the northern North Atlantic (Heinrich, 1988).

Fluctuations in *Td´*-SST (℃) over 150,000 years show a reversed saw-tooth pattern with the duration of about 30-kyr in the southern area, but a shape of a saw-tooth at about 40-kyr periods in the northern area (Koizumi and Yamamoto, 2010). According to the suggestion by modern oceanographic observations and modeling, the winter Aleutian Low develop strong westerly below along the latitude of about 35° N (Ishi and Hanawa, 2005). Correspondingly, the Sverdrup transports as western boundary currents cause both the increase (decrease) in the flow of the Kuroshio Current and the decrease (increase) of the Oyashio Current simultaneously. The *Td´*-SSTs (℃) records fluctuate at 118-kyr, 60-kyr, 30-kyr, and 23-kyr periods. The lower frequencies in 96 to 112-kyr and 7.2 to 12.8-kyr periods correspond to Bond cycles (Alley, 1998). A periodicity of a ~32-kyr period corresponds to the periodicity of the long-term orbital-scale ENSO (Clement et al., 1999). The shorter period of 1.4 to 2.1-kyr corresponds to Heinrich events (Heinrich, 1988), Dansgaard-Oeschger cycles (Alley, 1998), the fluctuations of residual $\Delta^{14}C$ record with variance on ~2-kyr cycle (Stuiver et al., 1991), and the ~2-kyr cycle in the variability of ENSO activity (Moy et al., 2002).

Td´-SSTs (℃) over 160,000 years in the southern area of the Japan Sea fluctuated at a 48-kyr period between 160-90 ka and 45-0 ka due to orbital-obliquity (tilt) cycles, and at a 23-kyr period, orbital precession cycles, during the 140-100 ka interval (Koizumi and Yamamoto, 2011). The predominant periodicities of 2-kyr and 4-kyr periods occurred at intervals of 20 and 40 ka. However, the SSTs (℃) of stadial phases in the northern area could not be reconstructed because of very few marker diatom species. Diatom abundances in the Subarctic Boundary are almost negligible except during MIS 5e, 2, and 1.

2.3. Oceanic Primary Production in the late Pleistocene

The oceanic diatom abundances in the northern area are twice to three times as high as those in the southern area in the Tohoku Area off the northeast Japan. The fluctuations of abundances in the northern area show a reversed saw-tooth pattern from lower abundance to higher values at about 40-kyr periods. This pattern is opposite to a saw-tooth shape in the *Td'*-derived SSTs (℃) because primary production of oceanic diatoms from interglacial to glacial periods due to the orbital forcing should be promoted by vertical and lateral mixing between cold and warm waters by glacio-eustatic sea level changing closely related to the Aleutian Low (Goes et al., 2001).

3. Material and method of study

3.1. Material

We used the original database from DSDP Site 436 (Koizumi and Sakamoto, 2012; Table 4 appendix) in the Tohoku Area off northeast Japan, and ODP Holes 797B (Koizumi, 1992; Koizumi and Ikeda, 1997; Table 5 appendix), Holes 798 A and C (Table 6 appendix) in the Japan Sea (Fig. 1). The chronostratigraphic framework (sub-bottom depth-mcd versus sediment age-Ma) in the three cores is based on the paleomagnetic data (Shipboard Scientific Party, 1990a; Hamano et al., 1992), diatom datum levels (Koizumi, 1992; Koizumi and Sakamoto, 2012) and tephrostratigraphy (Koizumi and Ikeda, 1997; Aoki and Sakamoto, 2003) as shown in Table 3 and Fig. 2.

Site 436 is located near the crest of outer swell seaward of the Japan Trench (39°55.96´N, 145°33.4´E; water-depth 5240 m). The sediments consist of olive gray vitric diatomaceous silty clay in the upper 245 mcd of the Plio-Pleistocene sequence. 26 samples obtained with the average sampling interval is ~7.23 m corresponding to 0.14 m.y. The Pliocene/Pleistocene boundary at ~2.6 Ma is defined by the last common occurrence of *N. kamtschatica* between 135.0 and 122.4 mcd (Table 4 appendix). The sediment accumulation rates are subdivided into three parts (Fig. 2): (1) 50.56 m/m.y. through the late Pliocene to early Pleistocene (3.72 to 1.24 Ma), (2) decrease to 27.13 m/m.y. between 1.24 and 0.3 Ma, and (3) increase to 123. 67 m/m.y.

Hole 797B is located in the southwestern Yamato Basin of south-central Japan Sea (38°10.27´N, 134°8.93´E; water-depth 2862m). Thin interbeds of dark, indistinctly laminated clay and silty clay which contain pyrite, diatoms and organic matter, alternate with light-colored, well-bioturbated clay and silty clay in the upper sequence of the C2n (Olduvai) chron at the sub-bottom depth ~82 mcd. The sequence between 120–82 mcd of uppermost Pliocene to lowest Pleistocene (2.8–1.9 Ma) consists of light gray, moderately bioturbated, diatom-bearing ashy clay and silty clay with few dark-colored layers. The sequence between 170–120 mcd (3.2–2.8 Ma) is characterized by a significant increase of diatoms and the absence of color bands (Table 5 appendix; Fig. 5). We analyzed 38 samples obtained with the average sampling interval is ~4.05 m corresponding to 0.097 m.y. without the basal interval of 61.29–125.47 m (Fig. 2). The paleomagnetic polarity pattern is not always obvious in the sediments from the Japan Sea, because the intensity of magnetization of the sediments is quite weak and polarity intervals are disturbed by reversed polarity intervals. Despite the uncertainties in the polarity pattern, a reasonable correlation with the Geomagnetic Reference Time Scale for the late Pliocene-Quaternary has been defined (Table 3; Shipboard Scientific Party, 1990a; Hamano et al., 1992). The sediment accumulation rates are also subdivided into three parts: (1) inordinately high 237.5 m/m.y. between 3.21 and 3.01 Ma, (2) 33.77 m/m.y. through 3.01 to 1.00 Ma, and (3) 57.52 m/m.y. after 1.00 Ma (Fig. 2).

Holes 798A (37.04°N, 134.80°E; water-depth 903 m) and 798C (37.04°N, 134.08°E; water-depth 900 m) are located on the top of Oki Ridge in the southeastern portion of the Yamato Basin. The uppermost sediments of Hole 798C (0.41-3.40 mcd) were added to the uppermost part of the Pleistocene section (3.67-124.3 mcd) of Hole 798A. The Quaternary sequence is composed of mainly clay, diatomaceous clay and diatom ooze with calcareous inter-beds. The dark, laminated organic-rich diatomaceous sediments and the light- colored clay-rich, bioturbated sediments alternate on a centimeter- to decimeter-scale (Shipboard Scientific Party, 1990b). We analyzed 123 samples obtained with the average sampling interval is 1.00 m corresponding to 10.37 kyr throughout the sequence (Table 6 appendix; Fig. 2). The chronostratigraphic framework was decided by the last occurrences at 0.3 Ma of *P. curvirostris* between 44.9 and 38.8 mcd, and the magnetic polarity of C1n (Brunhes) chron and C1r (Jaramillo) chron (Table 3). Site 798 has a constant sedimentation rate of 96.66 m/m.y. with a break at 84.5 mcd (0.86 Ma) (Fig. 2).

3.2. Methods

We chose wavelet analysis to evaluate the time series of the values in the band ration *Td´*-derived annual paleo-SSTs (℃) at century-millennial timescales in Holes 798A and C. The Fourier spectral analysis is the most common tool to analyze the frequency pattern of a signal. Short-time Fourier transform uses a sliding window to fined spectrogram, which gives the information of both time and frequency. However, the length of window limits the resolution in frequency. The limited ability of classical Fourier spectral analysis to detect a 1500-year climate cycles (e.g. Bond et al., 2001) that evolves through time were discussed by Debret et al. (2007). The wavelet transform, contrary to the Fourier transform, is used to decompose a signal into a sum of small wave functions of a finite length that are highly localized in time, for different exploratory scales.

The wavelet software provided by Torrence and Compo (1998) are available at URL: http://paos.colorado.edu/research/wavelet/. N=1283 by statistical complement. The time series were padded with zero, and parameters × interval=0.001, start scale=4, scale width=0.001 and mother wavelet=Morlet. Significance levels were set at 10 %, and a red-noise (autoregressive lag 1) background was estimated from the alpha parameter described in Torrence and Compo (1998).

Blanks /gaps in the data were filled up/interpolated using a cubic spline interpolant (passes exactly through each data point).

Wavelet transform is a band-pass filter which consists of convoluting the signal with scaled and translated forms of a highly time-localized wave function (the filter), so-called “mother wavelet”. We chose the Morlet wavelet (a gaussian-modulated since wave) for continuous wavelet transform:

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}$$

where ψ_0 is the wavelet value at non-dimensional time *eta*, η is a dimensionless time parameter and ω_0 is the wavenumber that defines the basic resolution of the mother wavelet. A wavenumber of 6 was used (Farge, 1992).

To avoid edge effects and spectral leakage that are produced by the finite length of the time series, the series were zero-padded to twice the data length. However, zero-padding causes the lowest frequencies near the edges of the spectrum to be underestimated as more zeros enter the series. The area delineating this region is known as the cone of influence ((Debret et al., 2007).

The Cone of influence (COI) is the region of the wavelet spectrum in which edge effects become important and is defined here as the e-folding time for the autocorrelation of wavelet power at each scale (Table 1 of Torrence and Compo, 1998). For concreteness, the width of a wavelet function is defined here as the e-folding time of the wavelet amplitude. This e-folding time is chosen so that the wavelet power for a discontinuity at the edge drops by a factor e-2 and ensures that the edge effects are negligible beyond this point. The size of the COI at each scale also gives a measure of the decorrelation time for a single spike in the time series. By comparing the width of a peak in the wavelet power spectrum with this decorrelation time, one can distinguish between a spike in the data (possibly due to random noise) and a harmonic componentat the equivalent Fourier frequency.

For all local wavelet spectra, monte carlo simulation was used to assess the statistical significance of peaks.

4. Tohoku Area off the Northeast Japan

4.1. Hydrographic Condition

The ocean waters off the east coast of the Japanese Islands have four different surface water regions (Fig. 3): (1) the Subtropical Gyre with the Kuroshio and Kuroshio Extension flowing eastward, (2) the Mixed Water Region offshore between 35° and 40° N, (3) the Transition Domain in the eastern than 150° E with increasing flows eastward under the influences of Kuroshio and Oyashio waters, and (4) the Subarctic Gyre (Masujima et al., 2003). The Oyashio is the western boundary current of the western Subarctic Gyre in the North Pacific. The hydrographic complexities in the Mixed Water Region cause local upwelling due to the isopycnal mixing between the subarctic and subtropical water masses, different velocities and vertically different salinities, and thus cause high phytoplankton productivity.

4.2. Diatom Assemblages in the Plio-Pleistocene Sequence

The difference between the *Twt* and *Td´*-SST (℃) curve is unremarkable off the northeast Japan, but the *Twt* ratio remarkably drops due to the predominance of cold-water extinct species *N. kamtschatica* at 3.6-3.2 Ma and *N. koizumii* at 2.2 Ma, while the *Td´*-SST (℃) curve does not (Fig. 4).

The remarkable variations of paleo-temperatures based on *Td´*-SSTs (℃) at DSDP Site 436 show four conspicuous episodes: (1) decreasing from 18.5 ℃ at 3.5 Ma to 15.1 ℃ at 2.65 Ma, when approximately coincide with the lithologic change from oxidized clay to anoxic biosiliceous clay and indicate the onset of significant NHG at the first step (between 3.0 and 2.5 Ma) indicated by Ravelo et al. (2004), (2) afterwards increasing to 21.7 ℃ at 2.1 Ma, and then (3) decreasing from 21.7 ℃ at 2.1 Ma to 10.1 ℃ at 1.4 Ma, which occurred well after the onset of significant NHG at the second step (between 2.0 and 1.5 Ma) of Ravelo et al. (2004), (4) slight fluctuations occurring around space 0.3 Ma and corresponding to the Mid-Brunhes Event (Jansen et al., 1986) were forced by the orbital eccentricity cycle. Recent research has focused on MIS 11 (between 0.42 and 0.40 Ma) as a possible analog for the present interglacial, because MIS 11 spans two precession cycles with $\delta^{18}O$ values below 3.6 ‰ for 20 kyr (Lisieck and Raymo, 2005). After this event, the climatic trend changes towards more glacial conditions in the Northern Hemisphere.

5. Japan Sea

5.1. Hydrographic Condition

The Japan Sea is a semi-enclosed marginal sea located on the eastern end of the Asian continent with its eastern margin bounded by the Japanese Island Arc (Fig. 3). Water exchange between the Japan Sea and adjacent seas have mainly occurred through four narrow and shallow straits, the Tsushima Strait (TSS) connecting to the East China Sea, the Tsugaru Strait (TGS) to the Pacific Ocean, and the Soya Strait (SS) and Mamiya Strait (MS) to the Okhotsk Sea. It has responded to eustatic sea-level fluctuations influenced by global climatic change during the late Quaternary, especially the glacial-interglacial period. Four main currents, the Tsushima Warm Current (TWC), the East Korean Warm Current (EKWC), the Liman Current (LC) and the North Korean

Cold Current (NKCC), exist in the Japan Sea (Senjyu, 1999). The TWC, which is a branch of the Kuroshio, meanders in the southeastern part and diverges again into two branches in the western area of the Tsugaru Strait.

5.2. Late Pliocene-Pleistocene Sequences

The period from the latest Pliocene to Pleistocene is characterized by a significant decrease in diatomaceous sedimentation, an increase in volcanic-ash production and terrigenous input, and oscillating climate. The last occurrences at 2.00 Ma of *N. koizumii* between 90.49 and 84.49 mcd and at 0.3 Ma of *P. curvirostris* between 18.45 and 12.69 mcd were confirmed by comparing with the paleomagnetic time scale (Table 3).

Low frequency and high amplitude fluctuations of both *Twt* and *Td´*-SSTs (℃) occur between 3.2 and 3.0 Ma, when *Twt* gradually increases due to the remarkable decrease of cold-water taxa including extinct *N. kamtschatica* and *N. koizumii* (Fig. 5). After then, the *Twt* ratio remarkably decreases at 2.6 Ma due to a large increase of cold-water taxa, and indicates the beginning of the glacial age defined as the Pliocene and Pleistocene boundary (Head et al., 2008). Both *Twt* and *Td´*-SSTs (℃) increase from 2.6 Ma to 2.0 Ma due to a large decrease of cold-water taxa. This time level approximately coincides with the lithologic change from diatom-bearing ashy clay and silty clay with few dark-colored layers to fine-grained sediments with distinct dark-light colored cycles (Shipboard Scientific Party, 1990a).

Diatom abundance decreased at the time when the Japan Sea was isolated from surrounding seas due to the drop of eustatic sea-level during the glacial to stadial phase, especially causing dissolution and/or low diatom counts in the northern area (Koizumi and Yamamoto, 2011).

5.3. Pleistocene Sequence

Diatom abundances are higher with sharp and short-term fluctuations during four intervals: 1.05-0.95 Ma, 0.68-0.62 Ma, 0.55-0.47 Ma, and 0.12-0.03 Ma (Fig. 6). The sublittoral taxa increased at both1.3-1.2 and 0.85-0.75 Ma and are composed of *Paralia sulcata*, *Actinoptychus senarius, Stephanopyxis turris*, and *Diploneis* spp., but species composition changed into *Cyclotella striata* and *P. sulcata* at 0.1 Ma.

The *Td´*-SSTs (℃) remarkably decrease from 16 ℃ to 7 ℃ at 1.17 Ma due to increases of the cold-water species *Neodenticula seminae*, and then at 0.66 Ma from 13 ℃ to 8 ℃ due to increases of the cold-water species *Actinocyclus curvatulus*. Those time levels are just after the increase of the warm-water species *Thalassiosira oestrupii* at 1.19 Ma and 0.68 Ma. The changing times from warm-water to cold-water phase are correlated to MIS 37-36 and MIS 17-16 of the LR04 benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005). Around magnetic polarity C1r.1n (Jaramillo) subchron, relative abundances (3-21 %) of cold-water taxa including *N. seminae* display marked fluctuations within a short time interval. The relative abundances of cold-water taxa are also correlated to MIS 30-26 (around the top of the Jaramillo subchron) of the LR04 stack. The pronounced occurrences of warm-water taxa including both *Fragilariopsis doliolus* and *T. oestrupii* at 0.16-0.13 Ma may have been caused by conditions 4 ℃ warmer than the present-day 16 ℃, which is correlated to MIS 5, Termination II.

Wavelet analysis for *Td´*-SSTs (℃) indicates a reversed saw-tooth pattern, which is characteristic in warm-water mass (Koizumi and Yamamoto, 2010), of 48 to 24-kyr periods during 1.2-0.7 Ma, and 24 to 12-kyr periods during 0.7-0 Ma, resulting in a change from longer cycles to shorter cycles (Fig. 7). Those periods indicate as black line (variance) is fully distinguished from red-noise showing by the dashed line (Fig. 7c). Variability of 48 to 24-kyr periods correspondence to the orbital obliquity (tilt) and precession cycles, and also 24 to 12-kyr periods to the precession. Variability of 130-kyr periods, corresponding to orbital eccentricity, is recognized around 1.1 to 0.8 Ma. The transitional change in dominance from obliquity to precession with minor effect of eccentricity, suggesting local ocean-related climate influences around 0.8-0.7 Ma.

6. Conclusions

Deep-sea drilling around the Japanese Islands has provided excellent Quaternary marine materials for the study of diatom biostratigraphy and paleoceanography. Results from Site 436 in the Tohoku Area off the northeast Japan have shown remarkable variations of *Td´*-SSTs (℃) at four conspicuous episodes: (1) decreasing from 18.5 ℃

at 3.5 Ma to 15.1 ℃ at 2.65 Ma, (2) afterwards increasing to 21.7 ℃ at 2.1 Ma, (3) decreasing from 21.7 ℃ to 10.1 ℃ at 1.4 Ma, and (4) slightly fluctuating around 0.3 Ma.

In the Japan Sea, the *Twt* ratio of Hole 797B remarkably decreases at 2.6 Ma due to large increases of cold-water taxa. Both *Twt* and *Td´*-SSTs (℃) increase from 2.6 Ma to 2.0 Ma due to a large decrease of cold-water taxa. Diatom abundances are higher with sharp and short-term fluctuating during four intervals: 1.05-0.95 Ma, 0.68-0.62 Ma, 0.55-0.47 Ma, and 0.16-0.03 Ma. The change from warm-water taxa to cold-water taxa at both 1.19-1.17 Ma and 0.68-0.66 Ma is correlated with MIS 37-36 and MIS 17-16 of the LR04 benthic $\delta^{18}O$ stack respectively (Lisiecki and Raymo, 2005). Remarkable fluctuation of cold-water taxa around magnetic polarity C1r.1n subchron is also correlated to MIS 30-26. The pronounced occurrences of warm-water taxa at 0.16-0.13 Ma is correlated to MIS 5 (Tertination II), but a pronounced peak of warm-water taxa was not recognized at MIS 11 (Termination V). The *Td´*-SSTs (℃) at Site 798 changed from longer cycles, corresponding to the orbital eccentricity and obliquity (tilt) to shorter cycles of the obliquity and precession around 0.8-0.7 Ma in the middle Pleistocene.

Paleoceanographic analysis should be performed based on diatoms also because they are the most diverse and abundant microfossil group in the region.

Acknowledgements

We wish to thank Prof. Richard Jordan of the Yamagata University for his critical reviews and for improvements of English of the draft. We acknowledge with special thanks to Dr. John A. Barron of the USGS at Menlo Park and anonym for reviewing critically and suggestions for improving the manuscript better. We also thank Editors, Drs. Norm Catto and Yoshiki Saito for their reviews and editorial work.

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Explanation of Figures and Tables

Figure 1 Map showing the location (black star) of four DSDP-ODP holes used in this paper. Black circles are the locations of piston cores used in previous papers around the Japanese Islands. 1: MD01-2421 (Koizumi et al., 2004; Koizumi and Yamamoto, 2010). 2: ODP Hole 1150A, and 3: ODP Hole 1151C (Koizumi and Sakamoto, 2003; Koizumi and Yamamoto, 2010). 4: DGC-6, 5: KH-86-2-9, 6: KH-84-3-33, 7: KH-84-3-9, 8: MD01-2409, and 9: MR97-04-1 (Koizumi et al., 2006). 10: POI-J3 and 11: CGC-8 (Koizumi, 2008). 12: MR02-03-2, 13: MR99-04-3, 14: MR00-05-2, and 15: MR99-04-2 (Koizumi and Yamamoto, 2010). 16: MD01-2407, 17: MD01-2408, and 18: KT94-15-5 (Koizumi and Yamamoto, 2011).

Figure 2 Sedimentation rates (sub-bottom depth-mcd versus sediment age-Ma curves based on chronostratigraphic framework (x) for three Sites in Table 3. Symbols on each accumulation curves indicate sampling points (Table 4-6 appendix).

Figure 3 Map showing the location of four DSDP-ODP cores (black circles), annual sea-surface temperatures (℃), generalized distribution of surface water currents, and surface water-masses (Senjyu, 1999; Masujima et al., 2003). TSS: Tsushima Strait, TGS: Tsugaru Strait, SS: Soya Strait, MS: Mamiya Strait, TWC: Tsushima Warm Current, LC: Liman Current, EKWC: East Korean Warm Current, NKCC: North Korean Cold Current.

Figure 4 Compositions of *Twt* and comparison of annual sea-surface temperatures (SST) records between *Twt* and *Td´*-derived SST (℃) at Site 436. The occurrences of characteristic warm- and cold-water taxa of *Twt* are indicated. Arrows indicate diatom datum levels. Vertical dashed-dotted lines represent the present-day values.

Figure 5 Stratigraphic variation of diatom abundance (10^7/g), relative abundance (%) of sublittoral taxa, compositions of *Twt* and *Td´*, and comparison *Twt* and *Td´*-derived SSTs (℃) at Hole 797B. Vertical broken line (0.214 at diatom abundance–10^7/g) indicates the levels of samples under 100 diatoms in a relative abundance of 200 diatoms. Vertical dashed-dotted lines indicate the present-day values.

Figure 6 Stratigraphic variation of diatom abundance (10^7/g), relative abundance (%) of sublittoral taxa, comparison of warm- and cold-water taxa of *Td´*, and *Td´*-derived SSTs (℃) at Holes 798A and C. Vertical dashed-dotted lines indicate the present-day values.

Figure 7 The wavelet analysis for the values of the band ration annual *Td´*-derived SST (℃) at Site 798. a.: *Td´*- SST (℃). b.: The wavelet power spectrum. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Solid black contour indicates the 10 % confidence level, using a red-noise (autoregressive lag 1) background spectrum. c.: The global wavelet power spectrum (black line). The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in b. Reference: Torrence, C. and G. P. Compo, 1998: A Practical Guide to Wavelet Analysis. Bull. Amer. Meteor. Soc., 79, 61-78.

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

Table 2 Species composition for *Twt* [=(*Xw*+0.5*Xt*)/(*Xc*+*Xt*+*Xw*)]. *Xw*: the total percentage of tropical-tropical (warm-water) taxa, *Xt*: the total percentage of warm-water transitional taxa, *Xc*: the total percentage of subarctic (cold-water) taxa.

Table 3 Chronostratigraphic framework (depth vs. calendar age) in three cores used in this study. LC: last common occurrence, L: last occurrence, B: base, T: top.

Table 4 appendix The occurrences of diatoms in Site 436.

Table 5 appendix The distribution of diatom abundance (10^7/g) and occurrence of diatoms in Hole 797B.

Table 6 appendix The distribution of diatom abundance (10^7/g) and occurrence of diatoms in Holes 798A and C.

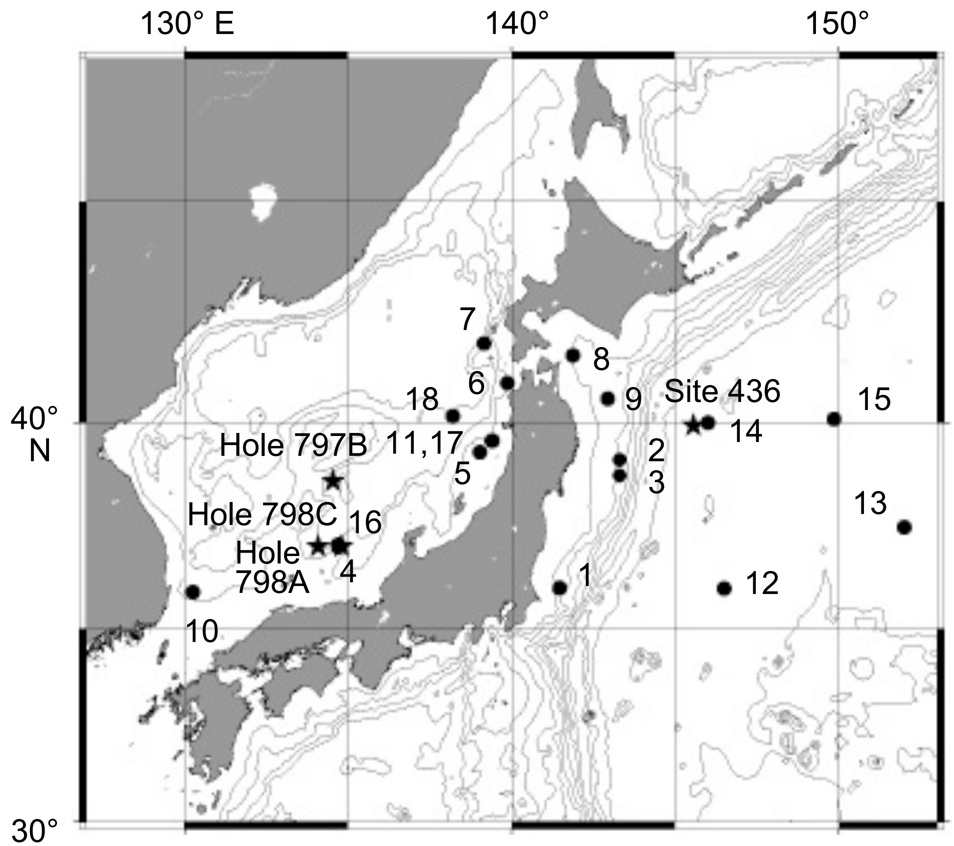
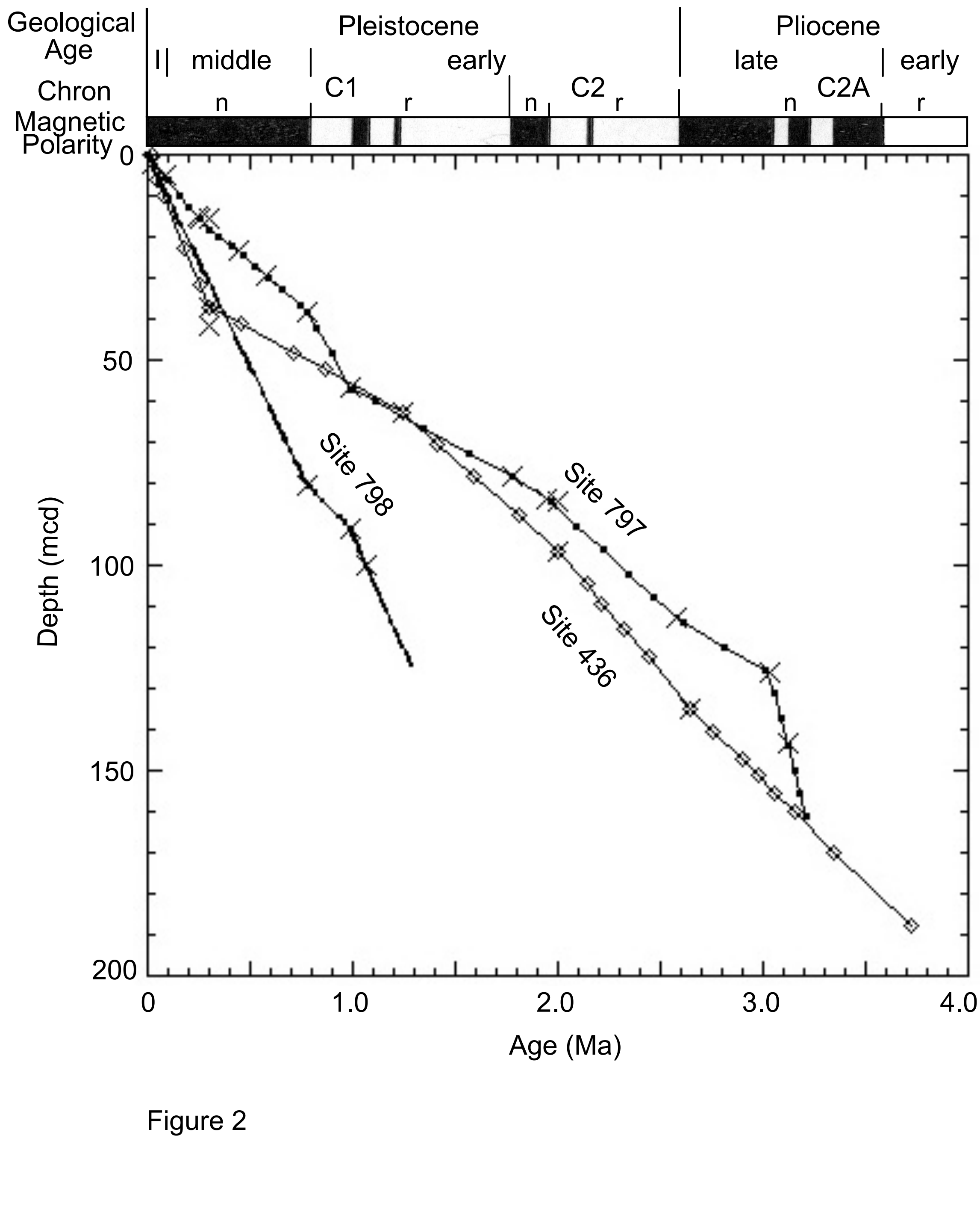
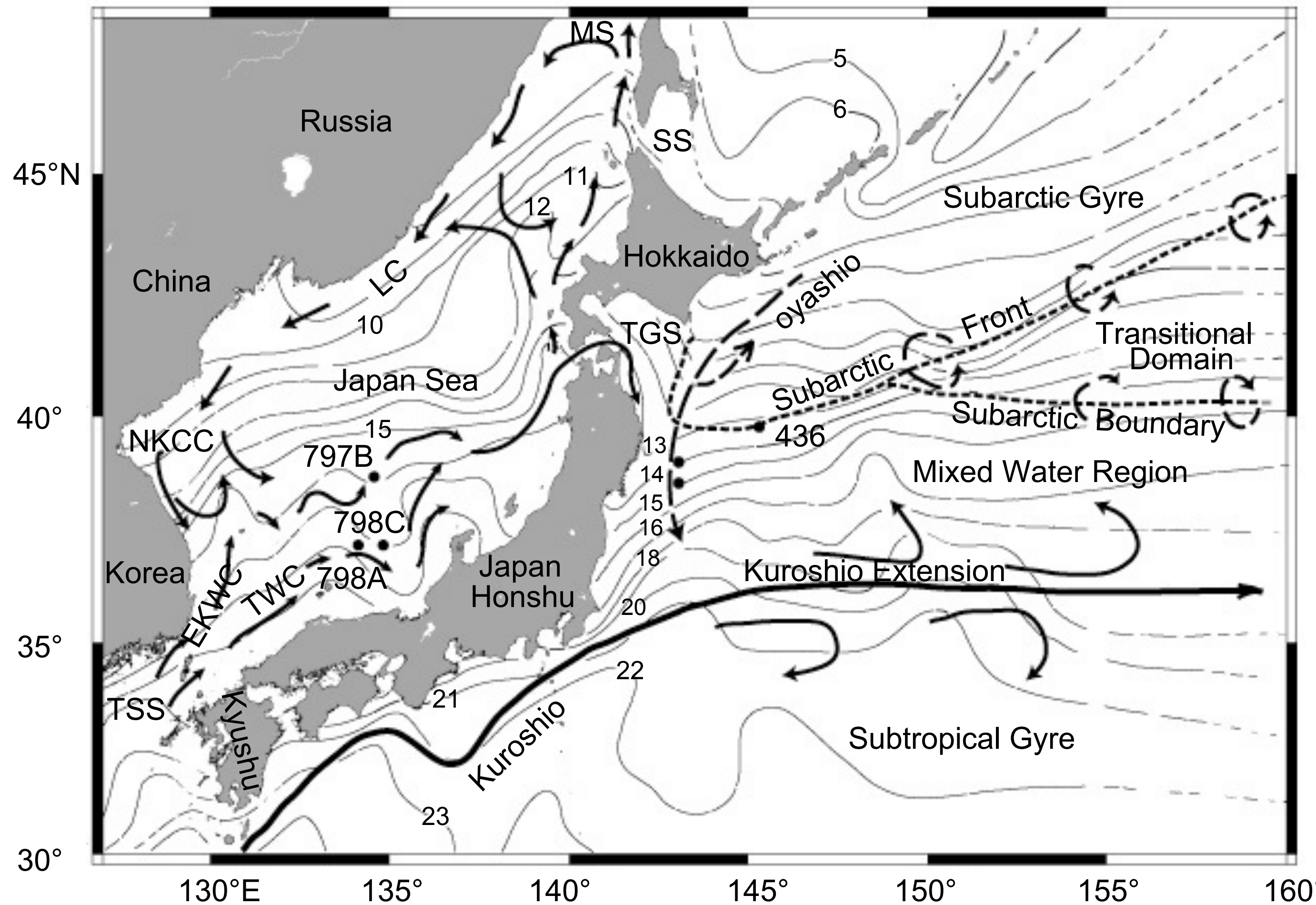

130° E
140°
150°
40°
N
30°
7
8
6
9
Site 436
15
18
14
Hole 797B
11,17
2
5
3
13
Hole 798C
16
Hole
798A
4
1
12
10

Figure 1



Geological Age
Pleistocene
l
middle
early
Pliocene
late
early
Chron
C1
C2
C2A
Magnetic Polarity
n
r
n
r
n
r
Site 798
Site 797
Site 436
Depth (mcd)
0
50
100
150
200
0
1.0
2.0
3.0
4.0
Age (Ma)

Figure 2



MS
Russia
SS
45°N
Subarctic Gyre
Hokkaido
China
LC
oyashio
TGS
Front
Transitional
Domain
Japan Sea
Subarctic
40°
Subarctic
Boundary
NKCC
797B
436
Mixed Water Region
798C
Korea
EKWC
TWC
798A
Japan
Honshu
Kuroshio Extension
35°
TSS
Kyushu
Kuroshio
Subtropical Gyre
30°
130°E
135°
140°
145°
150°
155°
160°

Figure 3

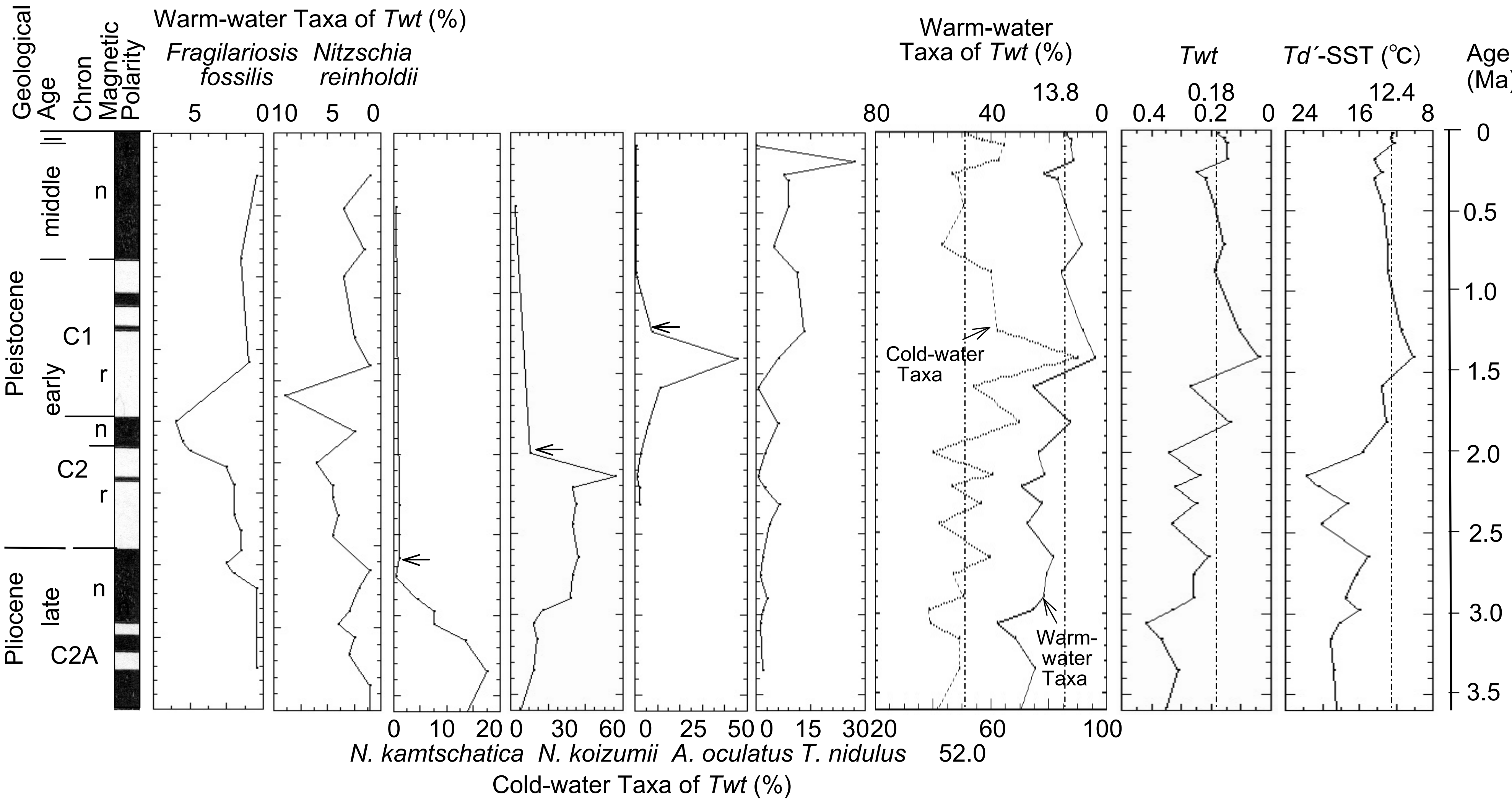
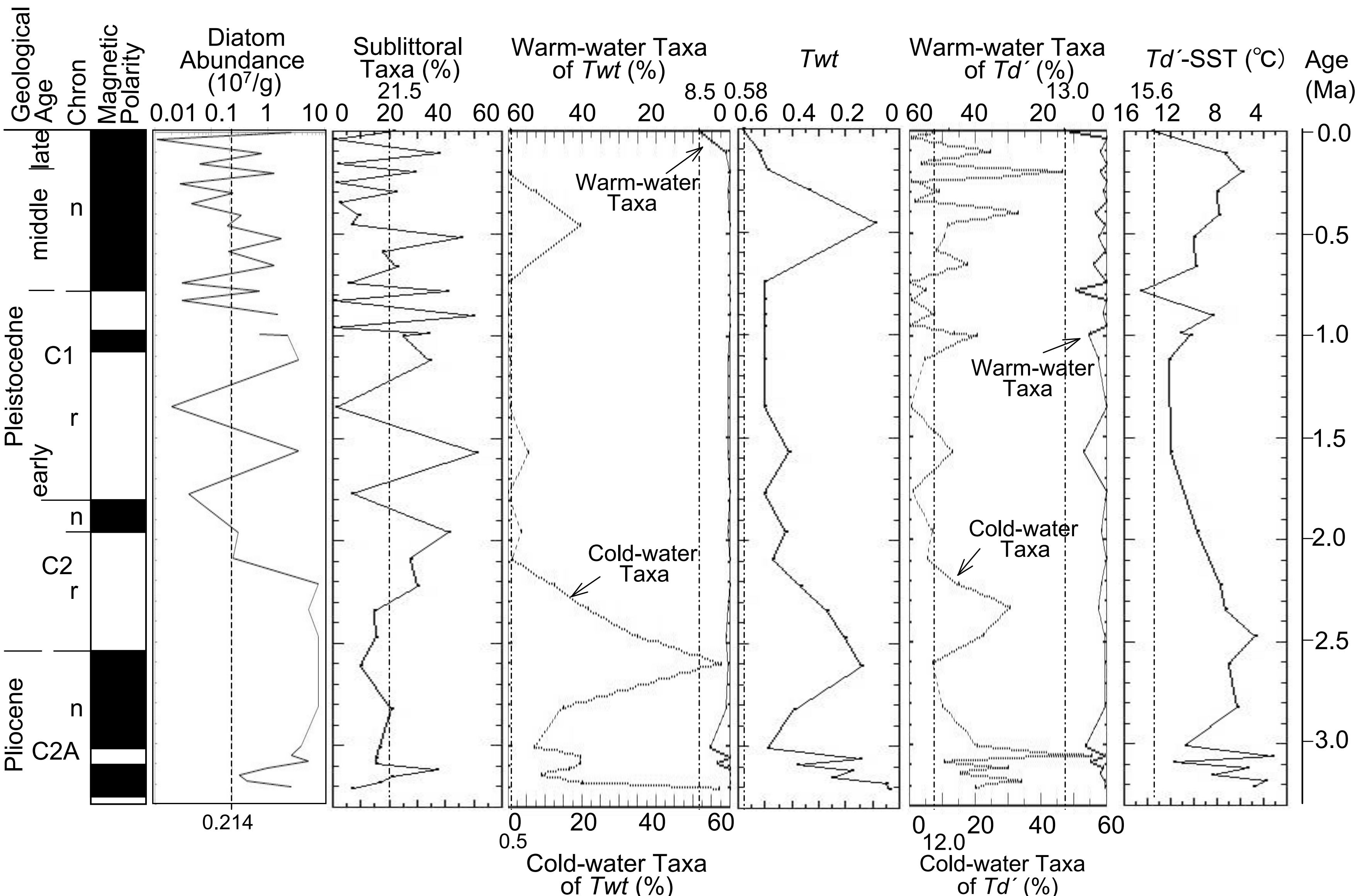
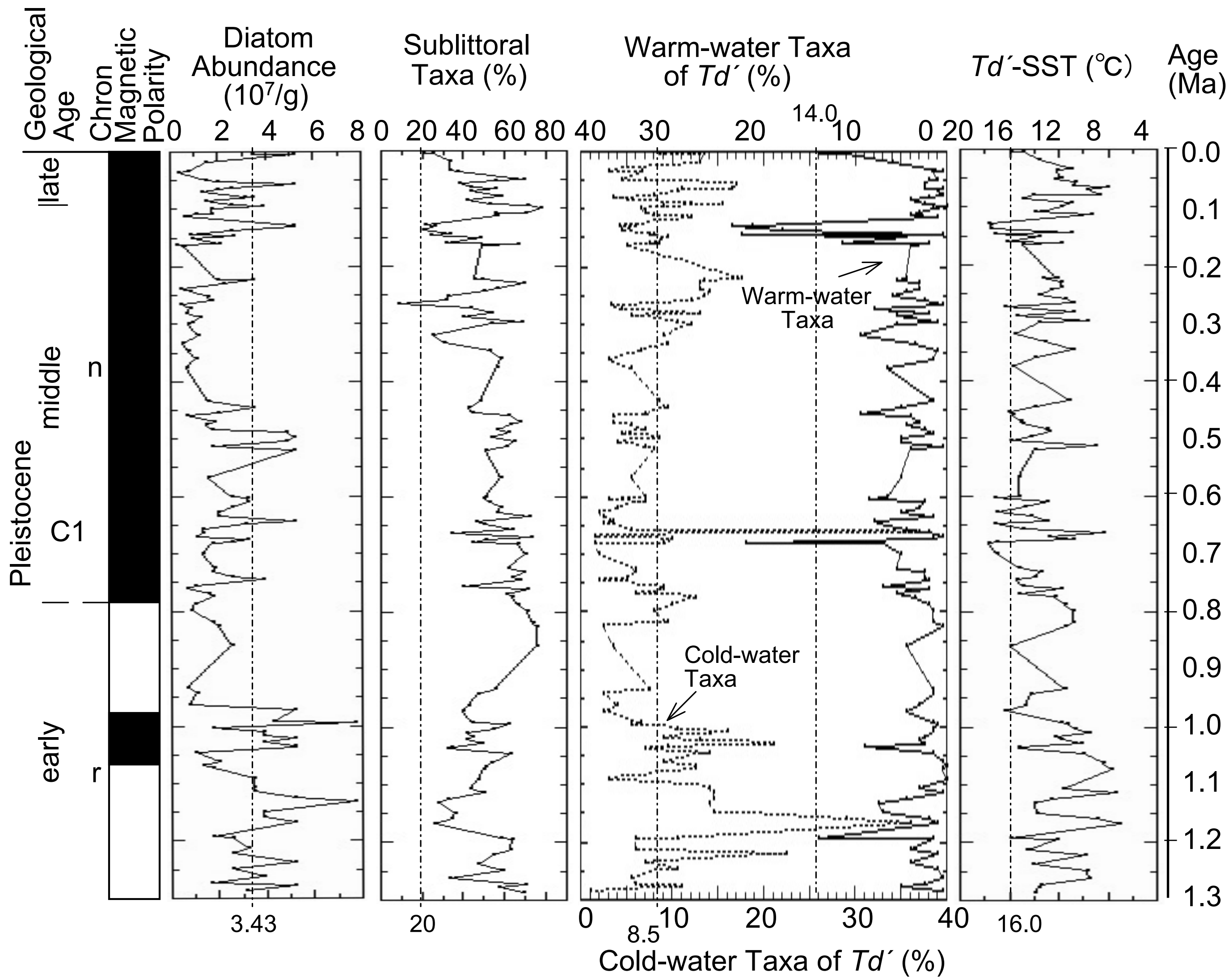

Geological Age
Chron
Magnetic Polarity
Warm-water Taxa of Twt (%)
Fragilariosis fossilis
Nitzschia reinholdii
5 0
10 5 0
Warm-water Taxa of Twt (%)
13.8
80 40 0
Twt
0.18
0.4 0.2 0
Td´-SST (℃)
12.4
24 16 8
Age (Ma)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
middle
n
Pleistocene
early
C1
r
n
C2
r
Pliocene
late
n
C2A
Cold-water Taxa
Warm-water Taxa
0 10 20
0 30 60
0 25 50
0 15 30
20 60 100
N. kamtschatica
N. koizumii
A. oculatus
T. nidulus
52.0
Cold-water Taxa of Twt (%)

Figure 4



Geological Age
Chron
Magnetic Polarity
Diatom Abundance (10^7/g)
0.01 0.1 1 10
0.214
Sublittoral Taxa (%)
21.5
0 20 40 60
Warm-water Taxa of Twt (%)
8.5
60 40 20 0
Warm-water Taxa
Cold-water Taxa
0.5
0 20 40 60
Cold-water Taxa of Twt (%)
Twt
0.58
0.6 0.4 0.2 0
Warm-water Taxa of Td´ (%)
13.0
60 40 20 0
Warm-water Taxa
Cold-water Taxa
0 20 40 60
12.0
Cold-water Taxa of Td´ (%)
Td´-SST (℃)
15.6
16 12 8 4
Age (Ma)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
late
middle
Pleistocedne
early
Pliocene
n
C1
r
n
C2
r
n
C2A

Figure 5



Geological Age
Chron
Magnetic Polarity
Diatom Abundance (10^7/g)
Sublittoral Taxa (%)
Warm-water Taxa of Td´ (%)
Td´-SST (℃)
Age (Ma)
Pleistocene
late
middle
early
C1
n
r
Warm-water Taxa
Cold-water Taxa
14.0
3.43
20
8.5
16.0
Cold-water Taxa of Td´ (%)

Figure 6

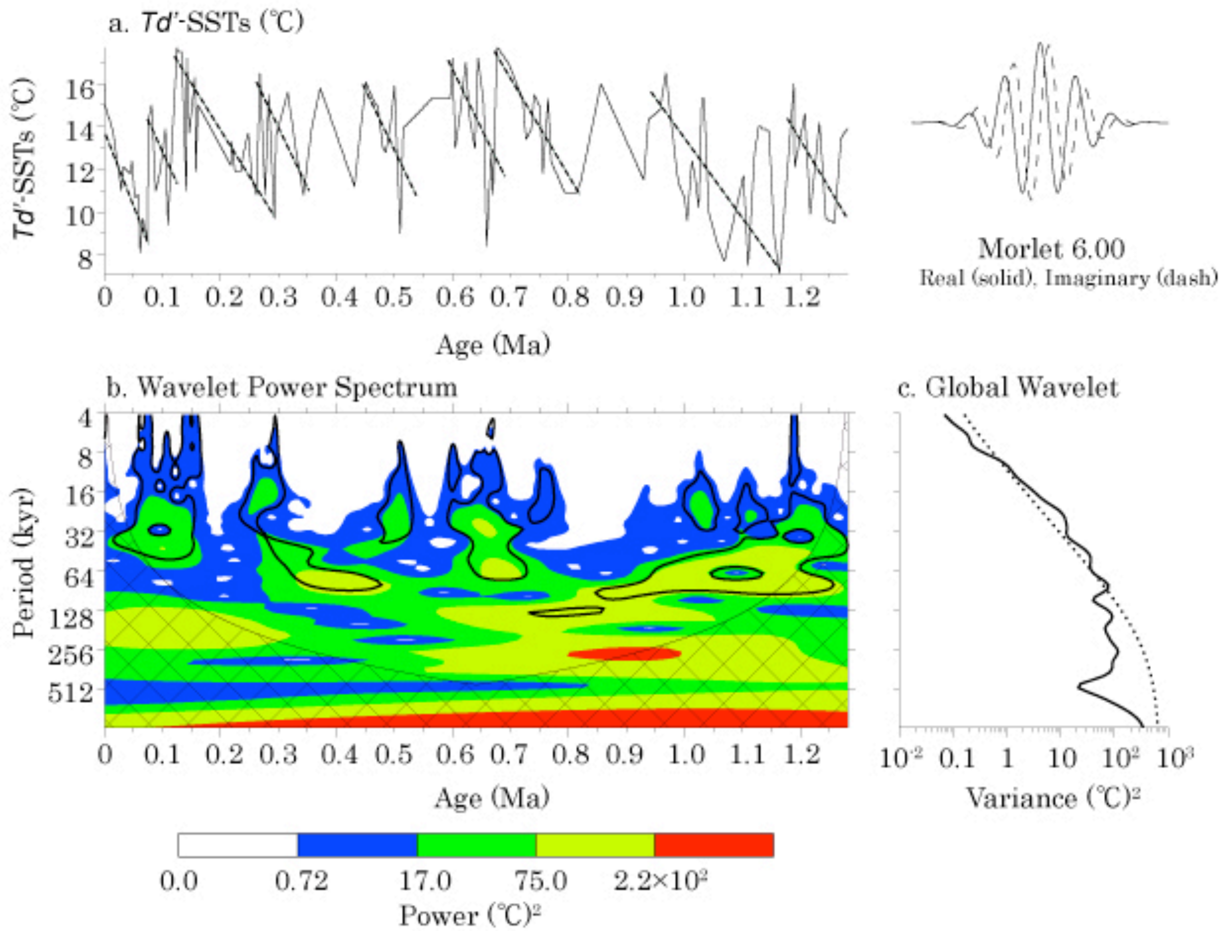


Figure 7 for online

Table 1

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	

Table 2

Twt	
Xw of *Twt*	*Xt* of *Twt*
Warm-water species without *T. oestrupii* of *Td'*	*Coscinodiscus radiatus* Ehrenberg
Fragilariopsis fossilis (Frenguelli) Medlin & Sims	*Thalassionema nitzschioides* Grunow s.l.
F. reinholdii (Kanaya emend Barron & Baldauf) Zielinski & Gersonde	*Thalassiosira oestrupii* (Osterfeld) Proshkina-Lavrenko
Nitzschia jouseae Burckle	
N. miocenica Burckle	
Rhizosolenia praebergonii Mukhina	
Thalassiosira convexa Mukhina	
T. miocenica Schrader	
T. praecovexa Burckle	

Xc of *Twt*
Cold-water species of *Td'*
Actinocyclus oculatus Jousé
Neodenticula kamtschatica (Zabelina) Akiba & Yanagisawa
N. koizumii Akiba & Yanagisawa
Proboscia barboi (Brun) Jordan & Priddle
P. curvirostris (Jousé) Jordan & Priddle
Thalassiosira nidulus (Tempère & Brun) Jousé

Table 3

Age Controls	Age (Ma)	Sub-bottom Depth (mcd)		
		Site 436	Hole 797B	Holes 798A and C
AT tephra	0.024		2.24	
Aso-4 tephra	0.088		5.21	
Ata-Th tephra	0.244		15.22	
L *Proboscia curvirostris*	0.30	37.10	15.57	41.85
Aso-1 tephra	0.255		15.66	
B-Og tephra	0.447		23.58	
Baegdusan tephra	0.580		29.46	
B C1n (B Brunhes)	0.78		38.30	80.5
T C1r.1n (T Jaramillo)	0.99		56.64	91.0
B C1r.1n (B Jaramillo)	1.07			100.0
LC *Actinocyclus oculatus*	1.24	62.60		
T C2n (T Olduvai)	1.78		78.43	
B C2n (B Olduvai)	1.95		83.90	
L *Neodenticula koizumii*	2.00	96.70	84.5	
T C2An (T Gauss)	2.58		113.00	
LC *Neodenticula kamtschatica*	2.65	135.00		
T C2An.1r (T Kaena)	3.03		126.00	
B C2An.1r (B Kaena)	3.12		143.50	

Table 4

Depth (mcd)	0.2	6.2	10.0	22.7	31.7	37.1	41.4	48.2	52.5	62.6	70.4	78.5	88.0	96.7	104.7	109.2	115.6	122.4	135.0	140.6	147.5	151.4	155.6	160.2	169.9	188.0
Age (Ma)	0.02	0.05	0.08	0.18	0.26	**0.30**	0.46	0.71	0.87	**1.24**	1.41	1.59	1.81	2.00	2.14	2.21	2.32	2.44	2.65	2.76	2.90	2.98	3.06	3.16	3.35	3.72
Actinocyclus ellipticus																										2
Alveus marinau	2	3	5	5	3	3	1	1	3	3		1	2	2		3	2		1	1	2	1	2	1	1	2
Azpeitia africanus								1																		
A. nodulifera	2	1	2			1		1	1					1	1	2	1	1		5	3	3	12	1		17
A. perpolatus				1									1													
A. tabulatus	4	1		5		1	2	1	2		3		2					1	1		1		1		1	1
Fragilariopsis doliolus	1					1		1																		
Hemidiscus cuneiformis	1		1				1	3	1	1		1	1	6	4	1	1	7	3	1	3	1	6	38	23	4
Nitzschia kolazekii		2																								
Plankyoniella sol						2			1	1	1					1										
Rhizosolenia bergonii					1	2			1									1	1				1			
Roperia tesselata													2			2	1									
Thalassiosira leptopus			1	3					1	1			1	1		1	3	4	3	2	1	2	1	2	6	5
T. oestrupii	2	7	5	3	9	7	8	2	3	1		12	8	6	19	22	6	4	2	1	3	2	2		1	2
Warm-water species of *Td'*	12	14	14	17	13	17	12	10	13	7	4	14	17	16	24	32	14	18	11	10	13	9	25	42	32	33
Actinocyclus curvatulus	5	7	8	4	4	5	2	7		5	3	1	20	11		3	9	5	8	3	1		9			1
A. ochotensis	2	1	3	1	2	6		1	3	2	15		9	25	2	1	10	2		2		1			1	1
Asteromphalus robustus														2				1				1		1		1
Bacterosira fragilis	16	12		6	6	1	3	1	5	2				1												
Coscinodiscus marginatus	3	1	16	5	10	1	2	8	4	11	2	6	4	2	2	2		2	25	10	14	16	9	38	32	40
C. oculus-iridis					1					1	1		1							1						
Neodenticula seminae	14	28	12	9	13	9	8	4	30	11	47	70	51	1												
Porosira glacilis	4	3		2	1	1	4	6	7	2			1	2												
Rhizosolenia barboi		2			1		1	1			1	6	3	2	1	13	4	1	4	4	5	4	12	3		3
R. hebetata	9	6	9	3	3	3																				
Thalassiosira gravida	42	36	64	42	22	33	47	41	47	50	9	1	27	4	1		2	1	1	3	2	1	4	1		
T. hyalina		4	1	3		5	3	1																		
T. kryophila			1			2	2	3																		
T. nordenskioldii	2	4	4		5	9		1		1										1		1				
T. trifulta s.l.	7	10	10	5	12	4	4	2	1				1				1		4	1	1	1	2		3	
Cold-water species of *Td'*	104	114	128	80	80	79	76	76	97	85	78	84	117	50	6	19	26	12	42	25	23	25	36	43	36	46
Td'	10.3	10.9	9.9	17.5	14.0	17.7	13.6	11.6	11.8	7.6	4.9	14.3	12.7	24.2	80.0	62.7	35.0	60.0	20.8	28.6	36.1	26.5	41.0	49.4	47.1	41.8
Td'-derived SST (℃)	12.4	12.6	12.3	14.4	13.5	14.4	13.4	12.8	12.9	11.4	10.1	13.6	13.2	15.7	21.7	20.3	17.3	20.1	15.1	16.4	17.5	16.1	18.1	19.1	18.8	18.2
Warm-water species without *T. oestrupii* of *Td'*	10	7	9	14	4	10	4	8	10	6	4	2	9	10	5	10	8	14	9	9	10	7	23	42	31	31
Fragilariopsis fossilis						1			3			2		12	11	10	5	4	4	3	3	5	4	1		1
F. reinholdii					2		7	3	7	5	2	18	5	12	9	9	8	9	2	4	6	8	5	6	2	2
Nitzschia jouseae																		1					9	2		
Rhizosolenia praebergonii																	2						2			
Thalasssiosira convexa			1			3		3		2				3			2			1	3	4	7	3	5	
T. praeconvexa																										1
Xw of *Twt*	10	7	10	14	6	14	11	14	20	13	6	22	14	37	25	29	25	28	15	17	22	24	50	54	38	35
Coscinodiscus radiatus	1		3	4	7	4				2			3					1								
Thalassionema nitzschioides	32	28	22	11	59	28	26	5	20	4	4	46	12	15	17	39	35	49	42	48	40	52	50	18	22	55
Thalassiosira oestrupii	2	7	5	3	9	7	8	2	3	1		12	8	6	19	22	6	4	2	1	3	2	2		1	2
Xt of *Twt*	35	35	30	18	75	39	34	7	23	7	4	58	23	21	36	61	41	54	44	49	43	54	52	18	23	57
Cold-water species of *Td'*	104	114	128	80	80	79	76	76	97	85	78	84	117	50	6	19	26	12	42	25	23	25	36	43	36	46
Actinocyclus oculatus			1						1	15	91	23	12	5	2	4	4									
Neodenticula kamtscatica							1										2		2	1	9	15	15	27	35	24
N. koizumii							5							21	112	66	70	66	72	66	64	34	25	28	24	4
Proboscia curvirostris						3	4	2	3	2	1															
Thalassiosira nidulus				45	13	15	15	8	19	22	10	1	10	4	1	4	11	6	3	2	5	3	2		3	
Xc of *Twt*	104	114	129	125	93	97	101	86	120	124	180	108	139	80	121	93	113	84	119	94	101	77	78	98	98	74
Xw	0.18	0.16	0.15	0.15	0.25	0.22	0.19	0.16	0.19	0.11	0.04	0.27	0.14	0.34	0.24	0.32	0.25	0.33	0.21	0.26	0.26	0.33	0.42	0.37	0.31	0.38
Asteromphalus sp.																										2
Coscinodiscus pustulatus																										1
Nitzshic cf. *oceanica*																										2
N. sicula						1																				
Pseudopodosira elegans					1		2															6				
Thalassiosita bramaputurae													1	1	3										1	
T. decipiensis						1												1								
T. eccentrica	6	3	6	8	1	2	4		4	8	2		2	4	10	4	2	1	1	1	2	1	3		2	7
T. lineata	2	4	1	1		4	2	3	1	2	1				1				2		1				6	
T. nodulolineata																									2	
T. pacifica			3					1		2	1							1								
T. sp. 1	12	4	8	5	3	11	9	21	5							1	2	1		3		4	2	3		
Oceanic species without species of (*Td´*+*Xwt*)	20	11	18	14	5	19	17	25	10	12	4		3	5	14	5	4	4	3	4	3	11	5	3	11	12
Actinocyclus ocutonarius	1	1	1	4		1	2	2	1				1								1	3	1			
Actinoptychus senarius	1	1	2	3	1	2		7	3	1		5	9			7		1		1	3	3	2	8	10	11
Cocconeis californica																				1	1					
C. costata	1				3		1				1		1				1			2	1	1	1			
C. pseudomarginatus			1																							
C. scutellum							1	1				1						2					1	1		
C. vitrea																										1
Cyclotella striata	1	2			3	1			2														1			
Delphineis surirella	1	2		1	1		4						2			1		2		4		2				
Diploneis bombus						1		1	1	2	1						2									
D. smithi					1		1																			
Grammatophora spp.		1																				1				
Hemidiscus weissflogii																									2	
Nitzschia constricta														1												
Odontella aurita	11	6	1	12	1	2		1	12	2		1	3	1						2						
Palaria sulcata	3	5		3	1	3	1	1	2		1	2				2	2	3		1	1	2				
Rhaponeis amphiceros			1								2															
Stephanopyxis turris	12	14	4	6	10	21	27	55	6	39	1	3	1	55	4	2	10	15	16	23	23	14	7	10	11	1
Sublittoral (Tychopelagic-Benthic) species	31	32	10	29	21	31	37	68	27	44	6	12	17	57	4	12	15	23	16	34	30	26	13	19	23	13
Aulacosira praeislandica		1	1														1	1				1				
Fresh-water species		1	1														1	1				1				
Denticulopsis hustedtii																										1
Koizumia tatsunokuchiensis																					1			1	1	
Stephanopyxis horidus																		3		1						
Thalassiosira antiqua			1										4				1	1				6		2	4	7
T. jacksoni																		1								
T. zabelinae			1															1	3	1		1	2	5	2	1
Extinct species without fossils species of *Xwt*			2										4				1	6	3	2	1	7	2	8	7	9
Total Valves	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

Table 5

Depth (mcd)	0.13	2.75	6.33	9.79	12.69	15.55	18.45	20.20	22.22	24.27	26.99	29.78	32.83	36.57	38.29	42.42	48.35	56.97	57.52	60.09	66.52	72.54	78.28	84.49	90.49	96.33	101.99	107.99	113.79	119.79	125.47	131.29	137.29	143.79	150.03	155.66	161.29
Age (Ma)	0.001	0.035	0.106	0.159	0.205	0.252	0.300	0.350	0.408	0.463	0.524	0.587	0.656	0.741	0.780	0.827	0.895	0.994	1.000	1.115	1.348	1.567	1.775	1.963	2.093	2.219	2.342	2.472	2.607	2.815	3.012	3.057	3.088	3.122	3.154	3.183	3.212
Abundance (10*7/g)	2.57	0.01	0.77	0.06	1.29	0.03	0.24	0.04	0.34	0.19	1.71	0.20	1.29	0.03	0.70	0.03	1.47	0.70	2.20	3.43	0.02	3.43	0.04	0.30	0.24	7.71	5.14	7.71	7.71	7.71	3.86	2.57	5.14	0.96	0.31	0.43	2.57
Alvius marina	1														1																						
Asteromphalus flabellatus	1																																				
Azpeitia nodulifera	3								1						8												1			1							
A. tabularia	4																																				
Coscinodiscus perforatus							1		1										2																		
Fragilariopsis doliolus	6		2				1								3																						
Hemidiscus cuneiformis																						1									11		7				
Nitzschia kolaczekii															1																						
Rhizosolenia bergonii									1						1									1													
R. imbricata	2																																				
Ropelia tesselata	1																																				
T. oestrupii	9		2		4		1		4	1	5	1	8		5		2	10	9	5		13		2		3	4	1	1		2	1	3	2	4	1	1
Warm-water species of *Td'*	27		4		4		3		7	1	5	1	8		19		2	10	11	5		14		3		3	5	1	1	1	13	1	10	2	4	1	1
Actinocyclus curvatulus			3		1		3	1	35	2	4	2	2					6	17	1					3	7	1	1			1						
A. ochotensis									2										2					1	2	1		1	1								
Asteromphalus robustus																			2			1								1	1						
Bacterosira fragilis					1																																
Chaetoceras furcellatus												2			1				4																		
Coscinodiscus marginatus	12	1	5	5	3	1	3	1	10	11		11	1			1	4	6	4	2	1	10	1	5		1	49	34	10	11	37	104	15	57	28	64	31
C. oculus-iridis	6									1										1						3	1	2									
Neodenticula seminae	3		6		12		2		5	4	9	1	7		7		7	9	10	4		12	1	7	4	14	5										
Porosira glacialis																	2					1					1										
Rhizosolenia hebetata			23	2	63		3	1	2		4						1	4	1								1	2								3	1
Thalassiosira gravida			1						1				1		2									1		3	1	3			1	4		1			4
T. nordenskioldii											2																1										
T. trifulta	4		13		13		7		11	5	2		24				1	2	1	1		2			2	1	1	2	3	8	1	3	6	2	3	1	4
Cold-water species of *Td'*	25	1	51	7	93	1	18	3	66	23	21	16	35		10	1	15	27	41	9	1	26	2	14	11	30	61	45	14	20	41	111	21	60	31	68	40
Td'	0.52	0.00	0.07	0.00	0.04	0.00	0.14	0.00	0.10	0.42	0.19	0.06	0.19	0.00	0.66	0.00	0.12	0.27	0.21	35.70	0.00	35.00	0.00	17.60	0.00	9.10	7.60	2.20	6.70	4.80	24.10	0.90	32.30	3.20	11.40	1.40	2.40
Td' -derived SST (℃)	15.6		9.3		7.9		11.0		9.9		12.0		11.9		16.6		10.5	13.1	12.3	14.1		14.0		11.7		9.8	9.3	6.7	9.0	8.2							
Warm-water species without *T. oestrupii* of *Td'*	18		2				2		3						14				2			1		1			1			1	11		7				
Fragilariopsis reinholdii																				1	1																
Thalassiosira convexa																												2	1	1							
Xw of *Twt*	18		2				2		3						14				2	1	1	1		1			1	2	1	2	11		7				
Coscinodiscus radiatus	12		4				4		3						4															1			1				
Thalassionema nitzschioides	61	1	47	2	41	1	22	2	24	7	12	10	2	3	51	1	73	56	47	99	3	33	2	26	32	70	47	42	41	100	91	16	88	17	14	3	9
Thalassiosira oestrupii	9		2		4		1		4	1	5	1	8		5		2	10	9	5		13		2		3	4	1	1		2	1	3	2	4	1	1
Xt of *Twt*	82	1	53	2	45	1	27	2	31	8	17	11	10	3	60	1	75	66	56	104	3	46	2	28	32	73	51	43	42	101	93	17	92	19	18	4	10
Cold-water species of *Td'*	25	1	51	7	93	1	18	3	66	23	21	16	35		10	1	15	27	41	9	1	26	2	14	11	30	61	45	14	20	41	111	21	60	31	68	40
Actinocyclus oculatus	1										1				7			8	6					1							1		1	1			
Neodenticula kamtschatica				2		2				14		6	2		3	1		4	3	1		2		3		1	4	10	6	3	5	32	30	29	18	37	107
N. koizumii						1		1		8	1				1			2	2			6		1	2	21	37	58	106	21	5	4	7	3			5
Rroboscia barboi																					1	1		2		3	1	1	2	5	3	1	1			2	2
P. curvirostris							15	2	4	13	48	1	2		1			2	5			2															
Thalassiosira nidulus										1		1			1												1	1	1	1		2				1	
Xc of *Twt*	26	1	51	9	93	4	33	6	70	59	71	24	39		23	2	15	43	57	1	1	11	0	7	2	25	43	70	115	30	14	39	39	33	18	40	114
Twt	0.58	0.00	0.52	0.00	0.49	0.00	0.34	0.00	0.00	0.09	0.00	0.00	0.00	0.50	0.00	0.50	0.50	0.00	0.00	0.50	0.50	0.41	0.50	0.42	0.47	0.37	0.27	0.20	0.14	0.39	0.49	0.15	0.38	0.18	0.25	0.05	0.04
Bacillaria paradoxa																	1																				
Coscinodiscus elegans										1																											
C. obscurus																																1					
Nitzschia braarudii	8																																				
N. cylindra											1																										
N. grunowii																								1													
N. sicula															1					1	1																
Odontella aurita															1																						
Rhizosolenia alata															1																						
R. barboi										3	16	1	1		1			5	7		1	1		2		3	1	1	2	5	3	1	1			2	2
R. setigera	4		2			1	2								2		3	1	1	3	1	3			6	1	2				2		1	2			
R. styliformis	3	1		1				1		2	1		2		1			8	6	1	1	1			1	1			1				1	1	7	17	7
R. spp.																	1	3	2																		
Stellarima stellaris															1				1																		
Thalassiosira eccentrica		1	6		1				2				1		5		2	1	2	1		4			1						1						
T. lineata	2		1		1										1			1	1	1				1									1		1		
T. pacifica									1						1					1																1	
T. spp.									1			1					1		2									1									
Thalassiothrix frauenfeldii																				3					1	2			1		1						
T. longissima	14		9	1			3	1	4	1	2	2	102		6		3	4	10	3	2	1	1	3		1	8	6	4	4	3	1	4	2	10	16	10
Oceanic species without *Td'* and *Twt*	104	3	69	4	43	4	31	4	35	14	32	14	108	3	76	1	84	79	79	14	6	10	1	7	9	8	11	8	8	10	10	3	9	5	18	36	19
Actinocyclus octonarius	6		5		1		1			1	1	4					8			2			1			2		2	2	1	4		2	2	1	1	
Actinoptychus senarius	13		3								3	2	3		9		21	3	3	7		8		2		1	1	2	1	1		3	5	16	2	9	9
Amphora sp.														1																							
Cocconeis spp.									1				4				2	1		10		2	2	1		4				1		1		2	3	1	
Cyclotella striata			4					3	9	1	4	3			2		4	1																			
C. styloreum	3		1	1	1		1										3																				
Cymatosira debyl																									1												
Cymatotheca weissflogii																									1		1							1			
Delphineis amphiceros	1		1		1		1						1				1																				
D. ischaboensis																									1			2								1	
D. surirella	3		12		4		4		2		6	2	9		5		4	1						1		2	7	7	4	1				2	2		1
Diploneis spp.	9		10		10		1	1	2	1	10	2	5	4	37		12	18	12	11		6	1	3	9	7		3	4	2	4	2	1	2	1		
Fragilaria construens																														1							
Grammatophora spp.		1	1		1						1		1	1										1					1							1	
Hyalodiscus spp.													1																								
Melosira westii																		3																			
Navicula directa							1													1												1					
N. lyra			1																																		
N. pygmia	1																																				
Paralia sulcata	6		27	1	27	1	33	1	1		24	13	9	3	14		27	25	10	19	1	74	6	62	37	15	6	5	3	7	8	3	4	21	16	1	2
Plagiogramma spp.																				1																	
Rhaphoneis amphiceros																									1	2				1							
R. elegans																										1											
Stephanopyxis turris	1		7	2	14	2			2	10	41	9	7	2	14	1	15	15	25	13	1	12	3	10	4	24	15	10	5	24	16	21	17	24	17	14	1
S. spp.																				4						2				3	1		2	4		5	
Thalassiosira bramaputrae			1						1				5																								
Trachyneis aspera			2				1				1						1			1				2	1												
Sublittoral (tychopelagic-benthic) species	43	1	75	4	59	3	43	5	18	13	91	35	45	11	81	1	98	67	50	69	2	102	13	82	55	60	30	31	20	42	33	31	31	74	42	33	13
Achnanthes spp.					1																																
Aulacosira spp.				2			1																1	1											1		1
Caloneis bacillum							1																														
Cyclotella spp.																	1		1	1		2			1		1										
Eunotia spp.														1																							
Melosira westii																								2							1	1					2
Navicula mutica											1																										
Stephanodiscus spp.			1				1							1	1			1																			
Fresh-water species	0	0	1	2	1	0	3	0	0	0	1	0	0	2	1	0	1	1	1	1		2	1	3	1		1				1	1			1		3
Actinocyclus ingens				4								2																									
Coscinodiscus vetustissimus																										2											
Denticulopsis spp.									1			3							2																		
Koizumia tatsunokuchiensis																													1					1		1	
Melosira albicans																						1				1											
Nitzschia extincta																						1				3	2	2									
Pseudopodosira elegans																				1																	
Thalassiosira antiqua																						1				1	1		1	1			1	1	2	5	3
Extinct species without *Twt*																				1		3				7	3	2	2	1			1	2	2	6	3
Total Valves	200	5	200	23	200	11	113	15	131	87	200	79	200	16	200	4	200	200	200	200	13	200	19	140	110	200	200	200	200	200	200	200	200	200	145	200	200

Table 6

Depth (mcd)	0.41	0.47	1.92	3.40	3.67	5.04	5.25	5.74	6.55	6.75	7.24	8.04	8.20	8.73	9.53	9.74	10.20	11.00	11.21	11.70	13.33	13.4	14.1	15.0	15.1	15.5	16.5	16.6	17.0	22.9	23.0	23.6	24.7	25.1	26.0	26.6	27.5	28.1	29.0	29.6	30.7	31.0	33.0	34.4	35.8	37.3	38.8	44.9	46.0	47.0	47.5	48.5	49.0	49.9	50.5
Age (ka)	18.2	18.7	30.7	41.7	43.3	53.1	54.6	58.0	63.8	65.2	68.7	75.0	76.3	80.4	87.0	88.9	93.0	99.4	101.1	105.0	117.3	117.8	123.1	129.1	129.5	132.8	139.3	139.7	142.6	187.0	187.8	191.8	199.7	202.9	209.9	214.1	221.0	225.2	232.2	236.3	244.2	246.9	262.0	272.6	284.3	295.3	306.2	352.8	361.2	368.4	371.9	379.2	382.8	390.4	395.5
Abundance (10*7/g)	3.43	5.14	1.47	0.74	0.36	1.47	1.93	5.14	2.57	1.93	1.29	3.09	3.43	1.47	2.57	3.86	1.71	1.71	1.03	0.55	44	51	101	44	60	100	45	52	100	1.93	3.43	2.20	0.43	0.86	1.54	1.71	0.43	0.82	0.64	1.19	0.94	0.77	1.14	0.51	0.74	1.03	0.69	1.54	3.43	1.93	0.64	1.82	1.47	1.71	4.82
Alveus marina	1																		1		1	2	2		1		2				1			1					1			1					1			1					
Asterolampra marylandica																					1																																		
Asteromphalus flabellatus	1	2																																1						1															
Azpeitia nodulifera	1	2																	1			2	2		4		3			2				1													2				1	1	1	2	
A. tabularia	2	2	9																				1		3		3		1														1												
Coscinodiscus perforatus													2						1		1	1									1									1		1								1	1	1	1	1	
Fragilariopsis doliolus	7	8																	2		25	25	9		3		1			1			1	2									5		1		2		1	8	4		1	1	
Hemidiscus cuneiformis																						1																																	
Nitzschia kolaczekii																																															1								
Planktoniella sol																																															1								
Pseudosolenia calcar-avis																					1		1											1																					
Rhizosolenia bergonii	4	1							1				1										2			1			1	2	2							2	1	2			3		1										
R. imbricata																					1	3	4																													1			1
Roperia tesselata																							1																																
Thalassiosira leptopus	1	2					3	4	2			1		3	1			2	1		5	1		1	3	1		2	3		1	3					2	1	1		1	2		1		3	1	1	1				1		
T. oestrupii	11	5	3	1	4	2	1	1	2	1	2		1	5	4		3	4	2	2	10	12	14		31	7	14	2	3	4	6	3	5	3	12	5		13	1	7	1	7	10	6			5	2	8	9	2	3	5	1	2
Warm-water species of *Td'*	28	22	12	1	4	2	4	5	5	1	2	1	4	8	5		3	6	8	2	45	47	36	1	45	9	23	4	8	9	11	6	6	9	12	5	2	16	4	11	2	11	19	7	2	3	13	3	10	19	8	6	9	5	3
Actinocyclus curvatulus		2	1	3	3		3	2	2	4	3				4	4	1		4	3				9		4	2	10	2	2			1	1	2	6	2	5	5		1			9	3	3	2	7	1	5		2	2	1	
A. ochotensis	1																												1															1	1			2							
Asteromphalus robustus																								2				2										1																	
Bacteriosira fragilis	4	5					3		1											1			1		1															1															
Chaetoceras furcellatus					2																		2								2	1							2	2		1							3	2					1
Coscinodiscus marginatus	12	18	13		1			2	5	9	2		3		7	4	2	5	5	3	6	11	3	2	9	2	9	2		15	7	5	4	12	1	1	5	1	5	3	7	3	11	4	1	1	5	2	2	4	4	4	2	6	2
C. oculus-iridis		2	1									2		2	5	1	1						1		2	1	2			2	6		1	6			1		1		2	2	1	1	1		1		1				1	3	
Neodenticula seminae			8		1	1	1	11	4		5	6		3			1	1	2	3	2		1	1	1	2	1			10	7		2	1	9	5			5	1	3	10	2	3	6	1	3	5	10	2	1		5	3	2
Nitzschia cylindra																																																							1
Porosira glacialis																																																							
Rhizosolenia hebetata					1			1	3			2		3	3	1		3		4									1	1	1	2	15	5	7	1	1		5	1	7	4	4		1	1					1		1		
Thalassiosira gravida																										1			1							1		1						1											1
T. hyalina																																																							
T. nordenskioldii			2					5	1	1			1			2	1			1															2				1											1	1	1		1	2
T. trifulta			1	3	8	8	7	13	17	8	11	6	3	2	12	6	7	5	5	9	1	1	1	2	2	9	1	3	5	5	4	8	3	3	6	10	4	1	2	3	1	4						1	2						
Cold-water species of *Td'*	17	27	26	6	16	9	14	34	33	22	21	16	7	10	31	18	13	14	16	24	9	12	9	16	15	19	15	17	10	35	27	26	26	28	27	24	13	9	26	11	21	24	18	19	13	6	11	17	19	14	7	7	11	14	9
Td'	62.2	44.9	31.6	14.3	20.0	18.2	22.2	12.8	13.2	4.4	8.7	5.9	36.4	44.4	13.9	0.0	18.8	30.0	33.3	7.7	83.3	80.0	80.0	14.3	75.0	32.1	60.5	19.0	44.4	20.5	28.9	18.8	18.8	24.3	31.8	17.2	13.3	64.0	13.3	50.0	8.7	31.4	51.4	26.9	13.3	33.3	54.2	15.0	34.5	57.6	53.3	46.2	45.0	26.3	25.0
Td'-derived SST (℃)	16.0	15.0	13.7	11.0	12.1	11.8	12.4	10.7	10.8	8.1	9.7	8.7	14.2	15.0	11.0		11.9	13.5	13.9	9.4	17.7	17.5	17.5	11.0	17.2	13.7	16.3	11.9	15.0	12.2	13.3	11.9	11.9	12.7	13.7	11.6	10.8	16.5	10.8	15.5	9.7	13.6	15.6	13.1	10.8	13.9	15.8	11.2	14.0	16.1	15.7	15.1	15.0	13.0	12.8
Actinocyclus oculatus																																								3															
A. spp.																													1																										
Actinoptychus splendens																																											1				1								
Asteromphalus darwinii																																																							
A. heptactis																																																							
Bacillaria paradoxa																																																							
Coscinodiscus asteromphalus																					2																						1												
C. radiatus																									1																		3								1				
C. rothii																																																							
C. spp.																					1																																		
Gyrosigma sp.																																																							
Nitzshia braarudii	4	5	5																		2	2			2		2			1				1																					
N. grunowii																																																							
N. sicula	2	1																		1	1	1	1		1										1																				
Rhizosolenia alata																					1															1									1										
R. setigera	5	7	9	1	4	1	7	9	7	3	1	3	6	5	1	5	3	4	5	1	2	3	6		8	6	7	2	5	2	5	5	2	4	7		2		7	6	4	3	1	2	1	1		3			1		1	1	
R. styliformis	7	2	6		1	7	1		1	1	1				1		1	1		5	2	4	6		4	2	7	1	2	1	1		2	2	9	3	1	2	4	5	8	7	3	1	4	12	2	1	3		1	2			4
R. spp.	6	3	1					1		1	1				1	1									1			1					1	1			1	1		2															
Stellarima stellaris								1													5	2	2		2		1			1													2												
Thalassionema nitzschioides	62	69	51	37	26	31	48	60	48	45	72	51	54	79	44	24	19	24	46	36	67	65	88	82	58	53	67	19	56	46	45	24	45	47	60	77	39	75	44	57	20	38	90	84	66	40	36	60	72	62	43	38	47	55	49
Thalassiosira decipiens																																												6	2	5	1	1	3	2		1	1	1	4
T. eccentrica	2	5	8	1		1	1						2	2	2	3			3	3	3	2	4	1	6	1	3	2		4	1	1			2	4		2	1	2	3	5	3	8	2	6	5	2	2	3	4	3			1
T. lineata	9	4	5		1		1	1			1		4	1	1			4	2	3	3	2	1		2	2	2	1	1		4		1	3			1		1	3	2	2	1	1	1	2	3			3	2		2		
T. pacifica																1											1					1	1			1		1	1	1			1	4		1	2	3	2	1	2		1		
T. spp.	3	1	8	14	5	3	4	7	11	7	2	8	2	4	2	3	4	5	3	4	2	1	2	8	2	8	4	9	6	2	2	6	1	2	5	6	4	2	3	7	2	1	1	2		4	2	4	1	2		1			
Thalassiothrix longissima	15	5	2	66	15	8	10	5	4	8	11	4	6	6	8			1	4	7	12	8	5	22	6	3	5	12	12	8	7	3	1	3	6	11	3	5		7	1	2	6	2	2	2	9	6	3	3	6	4	3	9	4
Oceanic species without *Td'*	115	102	95	119	52	51	72	84	71	65	89	66	74	97	60	37	27	39	63	60	103	90	115	113	93	75	99	47	83	65	65	40	54	63	90	103	51	88	61	93	40	58	113	110	79	73	61	80	86	76	60	49	55	66	62
Actinocyclus octonarius	2	6	6	3	6	5	3	2	3	5	3	2	3	3	8	2	1	5		4	1	4	3	1	1		4	4	5	6	2	3	2	1		2	1		7	3	2	3	6	4	3	6	5	1		7	11	13	11	3	5
Actinoptychus senarius	5	8	14				2	1	2	1	1	1	5		1	1		1	2	3	6	2	5				3			4	1		1	2	2	1		2	5	3	3	4	2	2		6	3	2	5	12	2	5	3	2	4
Cocconeis spp.	1			4	1	1	2		1	2		1	1						2					1		1		6	2	1					1	3		3	1	2	1		1	5	2		2	2	1		1				
Coscinodiscus nitidus							1																																							1					1				
Cyclotella striata	2	8	5		1	7	8	6	7	4	7	24	24	11	22	16	15	19	11	7	5	2	4		1		4			2	2		3	4	5		1	7	2	5	4	4	1	2	12	29	41	10	5	10	12	20	15	12	10
C. styloreum						8	4	3	4	9	1		8		7	1	7	11	6	5	2		1		2	2	2	3	1	4	1	5	9	5	4	4	1	4	2	1	17	3													
Delphineis amphiceros				2				1		1						2												1							1					1				1						1					1
D. surirella	2	1	3	8	7	9	2	12	7	5	6	13	12	16	6	8	15	6	9	13	2	4	5	13	4	8	3	10	4	4	7	4	5	2	7	4	2	7	10	3	6	7	2	5	11	4	1	3	6	7	3	3	5	5	2
Diploneis spp.	13	12	8	2	7	6	7	4	8	19	12	4	5	5	2	8	6	8	7	13	5	7	5	5	5	4	3	4	6	4	11	6	4	10	1	1	4	7	7	11	5	3	5	7	4	11	20	6	8	15	27	30	25	32	32
Grammatophora sp.	1			1	1		1		1							1		1		1						1			1		1			2	1	1						3		4	1		2	1				1			
Hyalodiscus spp.				1	1	1	1								1					2					1								1		1				1	1	2	1													
Melosira westii																		1	6	1			1							1			2	2																					
Navicula directa								1																																							2								
N. lyra																													1																							1			
N. spp.											1																																												
Nitzschia punctata													3								1		1							1																1									
N. trybionella						3																																					1					1							
N. spp.																																											1												
Odontella aurita																1	1	1		1	1		2		1																		1				1	1	1		5		2	1	1
Opephora spp.																																																							
Paralia sulcata	11	13	30	25	60	92	73	40	50	62	54	65	52	41	53	97	99	80	59	59	15	24	10	40	21	64	38	92	74	56	62	47	73	62	19	31	21	50	62	42	86	72	25	28	67	54	28	50	43	24	43	51	50	20	29
Plagiogramma spp.																												1			1						1						1					1							
Rhabdonema sp.																																																							
Stephanopyxis turris	1		1	3	2	4	4	3	1	1		1		6	3	4	11	6	9	2	5	6	3	6	10	14	6	11	3	8	9	71	12	7	22	1	1		7	7	7	5	4	1	5	2	6	17	15	13	18	10	13	37	38
Surirella sp.																																																							
Thalassiosira bramaputrae				17	1	1	1	1																1												13		5						1											
T. tenera												3																																											
Trachyneis aspera	2			1	2	1	1	1	2	1	1	2	1	1	1					2		2			1	1						1	1	2		1	1	2	3	1	3	2				1	2		1		1	1	1		1
T. antillarum		1																																																					
Sublittoral (tychopelagic-benthic) species	40	49	67	67	89	138	110	75	86	110	86	116	114	83	104	141	155	139	111	113	43	51	40	67	47	95	63	132	97	91	97	137	113	99	64	62	33	87	107	80	136	107	50	60	105	115	113	95	85	89	124	135	125	112	123
Achnanthes sp.																																																							
Amphora spp.				1	2				1							1	1																																						
Aulacosira granulata				1										1				1	1															1																					
Cyclotella meneghiniana																																																							
C. chaetoceras																								1					1																										
C. spp																																													1						1				
Cymbella sp.																								1												1																			
Epithemia sp.																																																						1	
Eunotia spp.																																																2							
Fragilaria spp.					1																																									1									
Gomphonema spp.				3												1																																							
Neidium spp.					1																																																		
Pinnularia spp.											2																		1															1		2	1							1	
Rhopalodia spp.																																																							

Stauroneis spp.				2																								
Stephanodiscus astrae																								1				
Synedra ulna																												
Fresh-water species				7	4				1		2			1		2	1	1	1					3				
Actinocyclus ingens																												
Cosmiodiscus insignis																												
Denticulopsis spp.					1																							
Melosira albicans																												
Neodenticula kamtschatica																												
N. koizumii																												
Probosia curvirostris					1																							
Thalassiosira antiqua								2	4	2				1		2	1	1	1	1						2		
T. convexa												1	1															
T. jacksonii																												
T. nidulus																												
Pseudopodosira elegans																												
Extinct species					2			2	4	2		1	1	1		2	1	1	1	1						2		
Total valves	200	200	200	200	167	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	189	200	200	200	200	200	200	200

Stauroneis spp.																											
Stephanodiscus astrae					1															1							
Synedra ulna																											
Fresh-water species	2				1	1		1								1	1	3	1	3			1			2	
Actinocyclus ingens																			1								
Cosmiodiscus insignis																											
Denticulopsis spp.																											
Melosira albicans																											
Neodenticula kamtschatica																1											
N. koizumii																2											
Probosia curvirostris											2	5								2		2		3		1	1
Thalassiosira antiqua				1			7	5	1				1														1
T. convexa																											
T. jacksonii																											
T. nidulus																											1
Pseudopodosira elegans																											
Extinct species				1			7	5	1		2	5	1			3				2		2		3		1	3
Total valves	200	200	200	200	200	200	200	200	100	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

51.4	52.0	53.0	53.6	58.6	61.9	62.3	62.9	63.8	64.7	65.4	66.4	66.9	67.9	68.4	69.3	69.6	70.2	70.3	72.2	74.8	75.4	76.4	76.9	77.9	78.4	79.4	79.9	80.9	81.4	82.4	82.8	84.5	88.2	88.6	89.6	90.1	91.1	91.6	92.6	93.1	94.0	94.5	95.4	95.9	96.9	97.4	99.0	99.8	101.0	102.0	104.0	105.0	106.0	107.0	109.0	110.0	111.0	113.8	114.0	116.0
402.8	407.6	413.9	417.7	454.7	479.2	482.2	487.3	493.7	500.3	505.5	512.3	515.6	522.2	525.6	532.8	535.5	540.9	541.3	558.1	572.8	577.5	585.4	589.5	597.2	600.6	607.4	610.8	617.6	621.1	628.2	631.1	642.9	674.2	678.2	686.2	690.8	697.1	700.7	706.8	710.1	716.3	720.2	727.0	731.0	738.9	742.3	752.0	757.3	766.6	771.9	782.3	788.6	804.6	813.1	829.7	838.1	851.0	873.0	877.2	891.0
5.14	4.82	1.71	5.14	1.54	2.57	3.21	3.21	2.57	1.93	1.93	5.14	3.09	1.29	1.29	1.03	3.21	2.57	1.71	1.29	1.82	1.71	2.57	3.86	0.96	0.64	1.54	1.71	1.00	0.86	1.71	1.93	2.57	0.64	1.03	0.74	5.14	4.29	7.71	1.71	3.86	3.86	5.14	3.86	5.14	5.14	0.96	1.93	1.29	1.71	3.43	3.43	3.43	5.14	7.71	3.86	3.86	5.14	1.71	2.57	3.21
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5	6	1	7	8	4	5	5	4	6	3	6	7	4	4			42	6	2	5	2	3	3	14	3	7	5	2	2	1	1	4	1	3	4	6	1	1		2	2	1	4	8	3	3	1		1		5	1	4	5	4	3	2	13	1	2
10	10	1	8	10	13	17	5	6	10	3	16	15	9	4	1	3	44	14	10	11	5	5	4	14	4	11	7	4	3	3	1	9	3	3	6	9	3	2	3	3	5	6	5	18	13	3	1		1		6	1	9	15	14	4	2	28	3	8
			3	2		1	2	2		2		1	3	62		8	6	1	1		1	1	2	7	4	2	4	2		1		2	3	1	1	1							1	1	3	3	1	1		4	2	2			1	2	4		2	2
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4	3	3	1	1	8	1			1	2	2	1	2			1		1	2	3	2	2	1	2		2	1			2	2	2	4	1	1	2	2		1		2			3	4	2	2	1	3		2	3	5	4	5	3		9	5	1
1		1		2	2						3	2	1								1								1													2			1		2							1	2		1	5	1	1
10	2	6	7	5	4	3	9	1	2			1		2	1			1	1	7	7	6	1		12	5	17	13	11	11	2	3	3	2	4	2	9	10	17	32	13	23	38	11	5	16	9	13	18		16	16	20	18	19	23	53	4	4	4
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17	8	14	16	11	14	6	14	8	4	5	7	5	11	74	3	20	18	3	4	12	12	10	4	18	18	12	25	20	16	19	5	7	15	5	8	5	13	11	21	32	18	26	42	19	14	28	18	25	25	6	28	29	29	28	29	58	72	21	12	12
37.0	55.6	6.7	33.3	47.6	48.1	73.9	26.3	42.9	71.4	37.5	26.1	75.0	45.0	5.1	25.0	13.0	71.0	82.4	71.4	47.8	29.4	33.3	50.0	43.8	18.2	47.8	21.9	16.7	13.6	13.6	16.7	56.3	16.7	37.5	42.9	64.3	18.8	15.4	12.5	8.6	21.7	18.8	10.6	48.6	48.1	9.7	5.3	0.0	3.8	0.0	17.6	3.3	23.7	34.9	32.6	6.5	2.7	57.1	20.0	40.0
14.3	15.9	9.0	13.9	15.3	15.3	17.2	13.0	14.8	17.0	14.3	13.0	17.2	15.0	8.4	12.8	10.8	17.0	17.7	17.0	15.3	13.4	13.9	15.5	14.9	11.8	15.3	12.4	11.5	10.9	10.9	11.5	16.0	11.5	14.3	14.8	16.5	11.9	11.3	10.7	9.6	12.4	11.9	10.2	15.3	15.3	10.0	8.5		7.7		11.7	7.5	12.7	14.0	13.8	8.9	7.1	16.0	12.1	14.6
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4	3	2	1	2	1	1	3		2		1		1	4	6	4	1			1		1		1		2	3	1		1	1		1				1	4	3	1					2	1					2	1		1	5	2	5	3		
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53	39	50	56	59	56	57	54	63	53	41	71	66	38	10	11	52	26	37	37	36	28	43	51	64	27	42	29	35	25	26	37	27	55	94	96	97	85	50	52	67	81	75	48	86	92	32	66	66	63	79	58	59	78	78	72	46	26	22	53	39
2		1	2		1	1	3	1		1			1	3	2			1						1				3	1	1			2												1															
1	1	3	5		2	4	5	1	10	3	1	2	4	25	5	3	18	3	1	4	6	5		4	2	2	4	2	5	1	4		4	2	3	3	5	3	1	1	2	3	4	1	5	1	1	1	7	11	13	7	3	5	3	2	5	4	2	1
	2	1	1	1	3	2	2	2	2		2		1					1	1	1	4	1				3	1	1		1		1													1		1	1	2	2			1	2				1		2
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2	1	1	2						1		2		2	1	4	2		2	1	3	1			3	2	3			3	1								1	7	2	2		2	2	1	2	1	5	1	3			2		1	4	13			4
3	5	2	4	2	4	6	6	3		2	4	3	2	4	1	5	2	4	4	5	2	5	3	2		3	4	1			1	1	1		2	5	2	1	1	3		4		1	1	3	3			3	2	1	6	7		6	19	3	2	4
65	52	60	73	64	70	77	73	71	73	47	84	75	49	49	30	69	47	49	44	53	44	56	55	83	32	54	42	43	39	31	44	32	68	97	102	107	95	62	65	75	89	86	56	93	108	41	72	73	75	101	78	69	96	100	85	63	72	33	57	54
7	3	4	7	17	22	5	2	10	10	19	6	10	11	2	1			9	6	4	4	8	5	2	1	2		3	4	1	4	3	4	2	5	18	5	3	3	4	1	2	4	2		2	3	3	1	1	3	2	3	2	1	1			11	17
3	2			2	6	3		2	6	9	23	13	7	2	2	2	3	12	20	8	20	15	24	1	6	11	12	3	4	22	35	37	7	5	6	10	24	11	21	33	31	31	26	18	19		13	8	13	13	28	17	25	17	3	2		7	20	18
1		1			1	1		1		1			1		8	6	2	2	1					6	1	1			1	1			2												1		1								1	1				
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7	6	9	10	8	2	4	13	5	6	3	3	1	3	12	10	17	16	11	2	1	1	3	3	7	9	3	3	17	7	11	6	5	4	5	7	3	4	4	3					1	1	12	3	6	3	1		1	1		3	2	4	1	1	3
15	24	20	20	24	23	17	16	24	26	38	25	25	39	9	45	6	12	32	27	26	26	30	37	17	27	33	25	17	11	13	22	26	11	18	17	4	13	24	16	11	18	12	19	16	11	2	17	10	15	23	10	8	16	15	9	3	1	17	19	19
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3		3	1	4	3	2	2	3	2		2	1	1	2	1	1				1	2	1	3	1	1	1				1	4	4	1	2						2	1		2												1			5		
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30	46	34	33	44	28	50	46	59	51	52	19	30	41	25	48	47	42	55	68	42	49	51	26	23	90	34	24	39	48	68	58	51	52	45	30	31	15	50	53	23	32	19	32	15	10	22	33	56	28	28	17	39	5	9	12	15	30	47	29	29
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35	40	49	27	9	11	11	24	8	8	10	5	10	8	5	7	17	9	9	9	28	26	6	19	19	5	31	57	50	64	26	17	15	24	15	17	10	24	25	10	7	4	9	13	4	11	79	25	11	20	7	14	18	2	5	32	38	15	22	12	20
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1	1		1		1	1		3		2		1	1			1			3	5	1				1	2	1	2	2	2	1	2	3		2	1		4	2	1		2							2		1	2						1	1	1
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107	129	122	102	115	102	100	104	115	112	143	92	99	127	68	146	102	89	133	140	123	138	126	135	79	141	121	126	132	142	147	150	151	111	94	84	79	88	124	109	83	88	82	97	69	65	125	107	102	99	93	86	100	65	55	72	68	52	116	127	125
							1					127		1	6	1								1									1																											
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200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

117.0	119.0	120.0	121.7	123.0	123.3	124.3
904.9	921.2	950.1	962.3	992.9	1000.0	1023.7
2.57	5.14	2.57	3.86	1.63	5.14	3.09
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					1	
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2	8	2	1	5	10	1
			1	1	5	1
	1					
	1				1	
3	3	1	3	1	2	
1	1	1	1	1	7	1
33	7	17	6	4	5	
1						
7		1		3		
	1	1		2	2	
45	14	21	11	12	22	2
9.4	36.4	8.7	8.3	29.4	31.3	33.3
9.9	14.2	9.7	9.5	13.4	13.6	13.9
	2					
					2	
					1	
	3	1				
	1	1		1	1	2
					2	1
37	63	49	116	35	32	49
		2	1			
3	1	3	1	2	7	4
2	1	2			3	
					2	1
	4					2
2	9		3	1	3	
44	84	58	121	39	53	59
13	10	4	10	5	1	4
11	20	10	4	5	7	15
		2				
11	11	11	7	2	7	20
9	7	3	6	2	8	3
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1	2	1	1	1	1	2
11	7	21	5	22	15	15
	1					
1		3	1	2	1	5
30	24	24	18	50	39	61
17	10	38	14	47	34	11
4		1	1		1	1
108	93	118	67	139	114	137
						1

						1
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1	1	1		3	1	
1	1	1		5	1	
200	200	200	200	200	200	200