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Neogene and Early Pleistocene diatom biostratigraphy and age synthesis of Site C9001/C0020, Northwest Pacific

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ABSTRACT

Integrated Ocean Drilling Program (IODP) Expedition 337 drilled a new core in 2012 that extended the coring depth of Hole C9001D at Site C9001 below the 647 meters below seafloor (mbsf) that was penetrated in 2006 during the Chikyu Shakedown Cruise CK06-06. Drilling operations at Site C0020 (formerly Site C9001), located 80 km off the Shimokita Peninsula of northeastern Honshu, Japan, penetrated Hole C0020A to a total depth of 2466 mbsf. IODP Exp. 337 sought to explore a deep hydrocarbon system and coalbeds that, prior to drilling, were estimated to be of Eocene age. Combined shipboard diatom and palynological analyses, however, revealed unexpectedly thick sections of Pliestocene and Miocene sediments, an approximately 12-15 million year hiatus at 1086.5 mud depth below sea floor (m MSF), and coalbeds younger than originally predicted. New biostratigraphic results from Hole C0020A indicate the target coalbed is Early Miocene. The age of the youngest sediments obtained in Hole C0020A is revised from Late Pliocene to Early Pleistocene, and the basal age of Hole C9001C is confirmed as Early Pleistocene. The age of the deepest sediments obtained at Site C0020 is Late Oligocene-Early Miocene. All new data are integrated with the overlying interval obtained from Holes C9001C and C9001D to produce a composite chronostratigraphic framework for Site C0020.

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Key Words: Marine diatom, biostratigraphy, Neogene, North Pacific, IODP

1. Introduction

In 2012, Integrated Ocean Drilling Program (IODP) Expedition 337 drilled Hole C0020A at Site C0020 located approximately 80 km off the Shimokita Peninsula of northern Honshu, Japan (Fig. 1). Hole C0020A is a re-entry and continuation of Hole C9001D (Site C9001), which was drilled during the 2006 *D-V Chikyu* Shakedown Cruise (CK06-06). Hole C0020A was drilled to recover the stratigraphic interval below Holes C9001B, C and D. It penetrated from 636.5 mbsf to 2466 mbsf and obtained a diversity of lithologies that yielded microfossil groups of varying degrees of biostratigraphic utility including diatoms, calcareous nannofossils, organic-walled dinoflagellate cysts, pollen and spores (Expedition 337 Scientists, 2013a, b).

Based on microfossil distribution and lithology, Hole C0020A is divided into four units (Table 1). Unit I ranges from 636.5 to 1256.5 mud depth below seafloor (m MSF), Unit II from 1256.5 to 1826.5 m MSF, Unit III from 1826.5 to 2046.5 m MSF, and Unit IV from 2046.5 to 2466 m MSF. Unit I was entirely rotary cored, and samples were provided from cuttings. Units II-IV were spot-cored. Diatoms are present and identifiable almost entirely through Unit 1, and are the focus of this study.

Expedition 337 sought to explore a deep hydrocarbon system and coalbed that, prior to drilling, were estimated to be Eocene (Inagaki et al., 2010). In addition, a regional unconformity between marine and terrestrial sediments was predicted to mark the Eocene/Oligocene boundary at approximately 1650 mbsf (Fig. 2). Combined shipboard diatom and palynological analyses, however, revealed unexpectedly thick sections of Pleistocene and Miocene sediments and a complete absence of Middle Miocene sediments. The oldest sediments obtained from Exp. 337 are Late Oligocene-Early Miocene (Exp. 337 Scientists, 2013a).

1.1 Previous Work

Diatoms are abundant and highly diverse in the middle- and high-latitude North Pacific where they have been developed as the primary biostratigraphic tool for dating and correlating Neogene sediments (Yanagisawa and Akiba, 1998). This biostratigraphic framework was initially established through the works of Donahue (1970), Koizumi (1973a, b) and Schrader (1973a). Koizumi's (1973a, b) zonation has become the standard workable zonation through continuous revision and refinement by subsequent studies. The development of diatom biostratigraphy progressed as biostratigraphic studies of numerous continuous sequences of deep sea cores and on-land sequences facilitated detailed taxonomic and stratigraphic studies (Simonsen and Kanaya, 1961; Simonsen, 1979; Akiba and Yanagisawa, 1986) through which new species were identified and biohorizons were refined in studies including, but not limited to, Schrader (1973a, b) Maruyama (1984a, b; 1992) and Akiba and Yanagisawa, (1986). A complete list of these studies is referenced in Yanagisawa and Akiba (1998).

In addition, Gladenkov and Barron (1995a, b) firmly established Oligocene through Pleistocene diatom zonations. Their studies directly correlated diatom zones to magnetostratigraphy and provided precise ages for primary zonal marker biohorizons, making the biostratigraphy for the middle- to high-latitude North Pacific a precise and high-resolution correlation tool (Barron and Baldauf, 1995; Motoyama and Maruyama, 1998).

Finally, Yanagisawa and Akiba (1998) presented a more refined high-resolution Neogene North Pacific diatom (NPD) biostratigraphy and zone code system for precise dating and correlation in the northwest Pacific around Japan. Yanagisawa and Akiba (1998) identified several useful secondary diatom biohorizons and updated ages for both primary and secondary biohorizons based on the geomagnetic polarity time scale of Cande and Kent (1995) and the chronostratigraphic time scale of Berggren et al. (1995a, b). The diatom-based biostratigraphy of Hole C0020A is constructed primarily on the occurrences of stratigraphically diagnostic diatoms following Yanagisawa and Akiba's (1998) NPD biostratigraphy

2. Materials and Methods

Samples for diatom-based biostratigraphic analysis were collected from rotary core barrel (RCB) cuttings at 10-meter intervals between the depths of 636.5 m MSF and 1246.5 m MSF. These 10-meter sample intervals are labeled from 24 SMW through 97 SMW for this study (Table 2). “SMW” is an abbreviation describing the type of material obtained by drilling operations and refers to “solid taken from drilling mud”. Of these, only large sample cuttings suitable for processing to mitigate downhole contamination were used. Each sample cutting was first washed and soaked/softened in Milli-Q water and then scraped with a razor-blade to remove the outer surface, in order to minimize surficial contamination. Freshly exposed sediment surfaces were scraped and materials sieved to a maximum 45 μm size-fraction. Strewn slides were prepared qualitatively from a slurry by first stirring/shaking the sediment into suspension, immediately removing part of the upper suspension with a disposable pipette and injecting it into a droplet of Milli-Q water on a 24 x 36 mm coverslip. The strewn sample was dried on a hot plate (50°-60°C) then mounted to a glass slide using *Norland* Optical Adhesive #61 and cured under UV light. Species were identified using an Olympus BH2 microscope.

The diatom-based biostratigraphy of Hole C0020A is constructed primarily on the occurrences of stratigraphically diagnostic diatoms following the Neogene North Pacific diatom (NPD) zone code system of Yanagisawa and Akiba (1998). Respective geologic time zones have been calibrated to the 2012 geologic time scale of Gradstein et al. (2012). In order to further mitigate complications associated with downhole contamination, the last occurrences (LO) of marker species were the primary biohorizons used.

The following counting methods were described by Schrader and Gersonde (1978). Qualitative abundance estimates of diatom index fossils are based on the following outline:

A = abundant (≥ 6 specimens per field of view [FOV] at 750x magnification)

C = common (1–5 specimens/FOV at 750x)

F = few (1–4 specimens/5 FOV at 750x)

R = rare (1–10 specimens/horizontal traverse at 750x)

Diatom preservation is recorded as G (good), M (moderate) and P (poor) based on the degree of breakage and dissolution of diatom valves as described by Akiba (1986).

3. Contamination

Considerable challenges were posed by contamination from drilling mud that affected core samples, core catchers, and especially cuttings samples for diatom analysis. In some intervals material was unsuitable for both processing and biostratigraphic analysis.

Downhole contamination worsened progressively with depth. Microfossil-bearing sediments from overlying stratigraphic intervals were incorporated into the drilling mud that recirculated through the hole, resulting in downhole contamination in nearly every sample to the base of the hole. The first major indication of contamination was observed at ~1185.5 m MSF (Table 2), just below the first lost interval near the base of Unit I. Downhole contamination can also be inferred in deeper cutting samples as specimens observed and marking the top of the hole were noted as well preserved, compared to the rest of the assemblage. Contamination proved especially problematic for core catcher samples and cutting samples of the smallest size fraction (<1 mm). However, even samples of larger size fractions (1-4 mm) often contained contaminants, especially those possessing larger grain size or greater porosity. Cutting samples of the smallest size fraction often contained no rock cuttings and were of a sandy or muddy consistency and therefore were completely saturated with contaminated drilling mud. Some samples were washed with tap water before distribution and analysis, but these samples also contained contaminants in quantities that proved problematic. The most abundant contaminants were those of Late Miocene and Pliocene ages, including marker species *Neodenticula kamtschatica*, *Neodenticula koizumii* and *Neodenticula seminae.* Two Pleistocene diatoms, *Actinocyclus oculatus* and *Proboscia curvirostris*, were also identified as downhole contaminants.

4. Results

Domitsu et al. (2010) developed an age model for holes C9001C and C9001D based on the biostratigraphy of four microfossil groups including calcareous nannofossils, diatoms, foraminifera and radiolarians down to 645 mbsf for a total depth age of ~1.6 Ma within the lower Pleistocene NPD Zone 10. The upper 350 mbsf were cored continuously with over 100% recovery (Aoike, 2007). A complete oxygen isotope record from these cores was also produced using benthic foraminifera and tuned to Lisieki and Raymo’s (2004) global benthic stack, providing precise age control for the upper 350 mbsf through 640 ka (Domitsu et al., 2010). The diatom-based age model for the underlying stratigraphic interval obtained in Hole C0020A continues from NPD Zone 10 at 636.3 m MSF and continues down into the lower Miocene at 1246.5 m MSF, to the base of Unit I, where the useful diatom record stops. Diatom biohorizons constraining the age of sediments in Unit I are listed in Table 2, and constrain the age/depth interpretations in Table 3.

Biostratigraphically useful diatoms do not occur below 97-SMW at 1246.5 m MSF. Age information below this level is based on palynomorphs (Expedition 337 Scientists, 2013b; Gross et al. 2015). The age interpreted at the total depth of Hole C0020A is Late Oligocene.

An interval of loosely consolidated sand between the depths of 1116.5-1186.5 m MSF resulted in a significant 70-meter zone of loss. A shift in diatom assemblage from what is interpreted to be the Late Oligocene-Early Miocene *Thalassiosira praefraga* NPD Zone 1 and/or the Early Miocene *Thalassiosira fraga* NPD Zone 2A into the *Neodenticula kamtschatica-Nitzschia rolandii* NPD Zone 7Ba, is recognized between samples 80-SMW and 79-SMW at 1086.5 m MSF. This age assignment in 80-SMW is based almost solely on the marker species *Kisseleviella ezoensis. Kisseleviella carina* is also present, and although it isn't a marker species, it has a reliable biostratigraphic range from the Late Oligocene through the Early Miocene. In at least one sample, 97-SMW at the base of Unit I, *K. carina* is the only biostratigraphically useful and identifiable species present.

Unfortunately, several samples between 79-SMW and 61-SMW were unsuitable for biostratigraphic investigation, offering only a rough progression through time. Samples 79-SMW through 74-SMW (1086.5-1056.5 m MSF) are assigned to NPD Zone

7Ba based on the common occurrence of *N. kamtschatica* and the absence of *Shionodiscus (Thalassiosira) oestrupii.* A specimen and fragments of *Thalassionema schraderi* and *Rouxia* spp., respectively, were observed, but are considered reworked because *T-ma. schraderi* should not occur in this zone (Yanagisawa and Akiba, 1998), and *Rouxia* spp. fragments could not be identified to the species level due to fragmentation.

The first common occurrence (FCO) of *N. kamtschatica* is observed in 66-SMW (996.5 - 1006.5 m MSF). Along with the co-occurrences of *S. oestrupii* and *Shionodiscus (Thalassiosira) preaoestrupii*, this sample interval is the closest representation of the Miocene/Pliocene boundary in this hole.

Samples 66-SMW through 60-SMW are assigned to the Early Pliocene *Thalassiosira oestrupii* NPD Zone 7Bb, with the exception of 61-SMW, based primarily on the abundant occurrence of *N. kamtschatica* with *S. oestrupii* and *S. preaoestrupii*. Sample 61-SMW yielded diatoms that range from the Late Miocene to the Late Pliocene, including species from genera *Denticulopsis* and *Neodenticula.*

The *Neodenticula koizumii-Nedenticula kamtschatica* NPD Zone 8 is represented by samples 59-SMW through 56-SMW, based on the co-occurrences of *N. koizumii* and *N. kamtschatica*. In samples 57-SMW and 56-SMW, however, *N. seminae* co-occurred with *N. kamtschatica.* The ranges of these two species are not believed to overlap, although, the FO of *N. seminae* has been documented to coincide with the LO of *N. kamtschatica* at ODP Leg 127 sites in the Japan Sea (Koizumi, 1992) and at ODP Leg 145 sites in the North Pacific (Barron & Gladenkov, 1995a). These two species are very similar in valve morphology, and it is possible that the apparent diachroneity of the FO of

N. seminae is a result of misidentification as suggested by Yanagisawa and Akiba (1998). In this particular case, however, the co-occurrence of *N. seminae* is considered to be an effect of downhole contamination.

Fragments from the genus *Denticulopsis* were observed in samples 58-SMW and 57-SMW. This genus existed through the Middle and Late Miocene, however, so these fragments are considered reworked here.

Samples 55-SMW through 28-SMW (896.5 - 676.5 m MSF) represent the Pleistocene *Neodenticula koizumii* NPD Zone 9. These samples have virtually the same assemblage as that defining NPD Zone 10, but now include *N. koizumii.* The absence of *N. kamtschatica* from these samples further supports this age.

Samples 27- through 24-SMW (676.5-636.5-m MSF), the uppermost sediments obtained from Hole C0020A, are Pleistocene in age and are assigned to the *Actinocyclus oculatus* NPD Zone 10, based on the presence of *A. oculatus* and *N. seminae*. This age is further supported by the absence of *N. koizumii.*

5. Discussion

A two-dimensional seismic profile was produced for Site C0020A (Fig. 2) (Inagaki et al., 2010). Integrated with data from regional industry wells, a preliminary geologic age model was produced, and regional geologic features were identified to a depth of 2200 mbsf. New marine microfossil data presented herein revise the age of this profile. Results from the diatom assemblages reported here update those published in the IODP Expedition 337 Initial Results (Expedition 337 Scientists, 2013a, b) as downhole contamination caused much confusion in the diatom shipboard results. The age is revised from Late Pliocene at the top Hole C0020A (636.5 m MSF) to Early Pleistocene. Revisions to the age of seismic reflectors, stratigraphic boundaries, regional unconformities, and ultimately, of the target coalbed interval are presented on Figures 2.4a and 2.4b.

Three major stratigraphic boundaries are identified based on diatom assemblages in Unit I: 1) an unconformity between Late and Early Miocene sediments at approximately 1086.5 m MSF, between samples 80- and 79-SMW; 2) a disconformity between samples 60- and 59-SMW (NPD Zones 8 and 7Bb) at ~936.5 m MSF; and 3) the Pliocene/Pleistocene boundary between samples 56- and 55-SMW at approximately 895.5 m MSF (Fig. 3).

Hiatuses of varying magnitude of Middle Miocene sediments have been recognized in several deep ocean drilling cores and on-land sequences around northeastern Honshu and Hokkaido (Akiba, 1986). Akiba (1986) recognized a hiatus of Middle Miocene sediments in DSDP Hole 584 and correlated it with one in Hole 438A. Both of these holes are located within approximately 150 km of Hole C0020A to the southwest near the Japan Trench.

What was predicted to be the Miocene/Pliocene boundary at 1100 m in Hole C0020A actually proved to be an unconformity representing between 12-15 mya between Early and Late Miocene sediments. Toward the east-center margin of the 2-D seismic profile (Inagaki et al., 2010), a package of eastward down-dipping reflection events below ~1100 m and 2.7 two-way travel time (TWT) is truncated and overlain by a succession of continuous reflections offering a visual explanation for the missing Middle and early Late Miocene sediments (Figs. 4a, 4b). This event was identified by the diatom biostratigraphy at ~1086.5 m MSF between samples 80- and 79-SMW.

A hiatus representing ~1.3-1.8 m.y between NPD Zones 8 (Late Pliocene) and 7Bb (Early Pliocene) was first recognized by the LO of *S. preaoestrupii* (5.3 Ma) in sample 60-SMW and the FO of *N. koizumii* (3.5-3.9 Ma) in sample 59-SMW around 936.5 m MSF. This disconformity is likely the effect of an erosional event, and it is represented by a low-amplitude reflection event on the seismic profile (Fig. 4b). Close examination of the seismic profile shows that this disconformity occurs with the first series of reflections overlaying the Miocene unconformity, which appear to be onlapping against the low-dipping unconformity boundary toward the west at ~2.7 TWT.

An integrated age model for the entire stratigraphic section drilled at Site C9001/C0020 is presented in Figure 5 and includes the results presented here for Hole C0020A, as well as those produced by Domitsu et al. (2010) for the overlying section in holes C9001C and C9001D and the underlying section to the total depth, which is constrained by palynomorphs (Expedition 337 Scientists, 2013b; Gross et al. 2015).

6. Conclusions

The diatom biostratigraphy of Hole C0020A presented herein yields a smooth continuation of Early Pleistocene sediments from the base of Hole C9001D (Domitsu et al., 2010) through the top of Hole C0020A (636.5 m MSF) and suggests an Early Miocene age at the base of Unit I (1246.5 m MSF) where diatoms cease to be preserved.

Palynological investigations suggest an age of Late Oligocene-Early Miocene at the bottom of Hole C0020A (2466 m MSF) (Expedition 337 Scientists, 2013a,b).

Diatoms were the most useful and most abundant microfossil group present in the upper section of Hole C0020A. In addition to successfully constraining the geologic age in Unit 1, and despite many challenges due to downhole and drilling mud contamination, diatom assemblages in conjunction with the seismic profile produced for Site C0020 were successful in adjusting ages of seismic reflectors.

The target coalbed intervals for this Expedition were originally predicted to be Eocene in age, but micropaleontological investigations revealed an unexpectedly thick section of Early Miocene sediments extending from at least the base of Unit III (2046.5 m MSF), and maybe even the base of the hole (2466 m MSF), up to 1086.5 m MSF (Expedition 337 Scientists, 2013a,b). A hiatus spanning 12-15 mya occurs between the Early Miocene and latest Miocene. The remaining upper Miocene sediments in this hole are about 150 m thick. The Pliocene sediments are approximately 50 meters thick and Pleistocene sediments compose the upper ~900 meters of sediment. Therefore, sediment accumulation rates at Site C9001/C0020 for the Late Miocene to Pleistocene was ~170 m/mya Most of the coalbeds, if not all, obtained from Hole C0020A are of Early Miocene age.

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Appendis I: Floral List

Taxonomic references to diatom taxa tabulated in Hole C0020A are listed below in alphabetical order. Chief references utilized in this study for species identification include Akiba (1986), Akiba and Yanagisawa (1986) and Schrader (1973a). The reader should also refer to the listed author reference for the original taxon description.

Actinocyclus oculatus Jousé 1968

Denticulopsis Simonsen 1979

Denticulopsis hustedtii (Simonsen & Kanaya) Simonsen s.l.

Denticulopsis katayama Maruyama 1984

Kisseleviella carina Sheshukova 1962

Kisseleviella ezoensis Akiba 1986

Neodenticula koizumii Akiba & Yanagisawa 1986

Neodenticula kamtschatica (Zabelina) Akiba & Yanagisawa 1986

Neodenticula seminae (Simonsen & Kanaya) Akiba & Yanagisawa 1986

Rouxia spp. Brun & Héribaud-Joseph *in* Héribaud 1893

Thalassionema schraderi Akiba 1982a

Shionodiscus oestrupii (Ostenfeld) Alverson, Kang & Theriot 2006

Shionodiscus praeoestrupii (Dumont, Baldauf & Barron) Alverson, Kang & Theriot 2006

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Figure 1. Regional map of the Shimokita region and Hidaka Trough showing bathymetry, seismic survey track lines and location of Site C0020, including other existing drill holes. Inset map shows site location relative to the Japanese Islands and basic modern ocean current circulation (after Expedition 337 Scientists, 2013).

Figure 2. Original seismic profile produced for Site C9001/C0020A including pre-drilling interpretations of geologic features, stratigraphic boundaries and ages (from Inagaki et al., 2010).

Figure 3. Time/depth plot and sediment accumulation rate curve showing diatom biostratigraphy through Hole C0020A Unit 1 (636.5 - 1236.5 m MSF). The column on the left beside depth, indicates which samples were used for biostratigraphic analysis. Diatom biohorizons are correlated to North Pacific Diatom (NPD) Zones on the right. The gradient through NPD 7Ba-7Bb indicates that some biohorizons separating each subzone are inferred due to missing samples. Refer to Table 2 for biohorizon codes (Phillips et al., this study).

Figure 4. (a) Original seismic line ODSR03-8W and profile produced for Site C9001/C0020 (from Inagaki et al., 2010); **(b)** Seismic profile reinterpreting stratigraphic boundaries and ages based on diatom biostratigraphy. The green line outlines a package of east-ward down-dipping reflection events truncating up against the Early Miocene/Late Miocene unconformity (blue line). The Pliocene disconformity (purple

line) bounds onlapping reflections between it and the unconformity (after Inagaki et al., 2010).

Figure 5. Integrated time/depth plot and accumulation rate curve based on the biostratigraphy for Site C9001/C0020A (0-2466 mbsf). Columns right of depth indicate the Hole and/or unit from which age was determined and the corresponding study. Geologic eras are indicated along the x-axis and right-side column.

Plate 1. Diatom marker species used to constrain the age of Unit I of Hole C0020A.

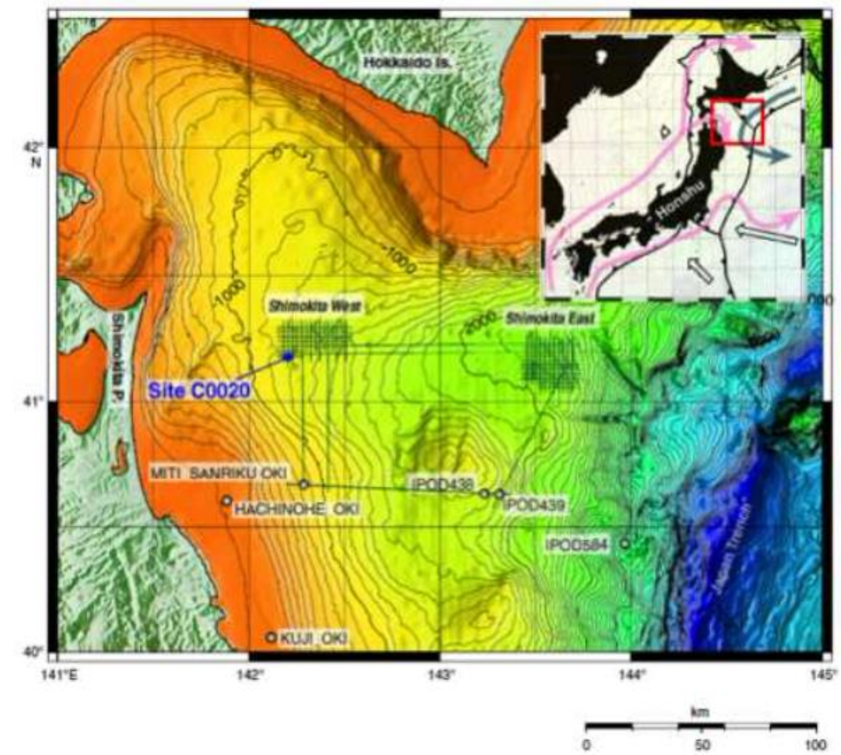
1. *Neodenticula seminae* (Simonsen & Kanaya) Akiba & Yanagisawa 1986
2. *Actinocyclus oculatus* Jousé 1968
3. *Neodenticula koizumii* Akiba & Yanagisawa 1986
4. *Neodenticula kamtschatica* (Zabelina) Akiba & Yanagisawa 1986
5. *Shionodiscus praeoestrupii* (Dumont, Baldauf & Barron) Alverson, Kang & Theriot 2006
6. *Kisseleviella ezoensis* Akiba 1986
7. *Shionodiscus oestrupii* (Ostenfeld) Alverson, Kang & Theriot 2006

Table 1. Unit divisions in Hole C0020A, lithology and approximate age (from Expedition 337 Scientists, 2013a).

Table 2. Cutting sample intervals from Unit I used for diatom biostratigraphy in Hole C0020A including depth, age, zonal assignment, preservation and qualitative abundance of diatoms. Abundance: A = abundant, C = common, F = few, R = rare, r = reworked specimens, X = inferred downhole contaminating specimens. Preservation: G = good, M = moderate, P = poor.

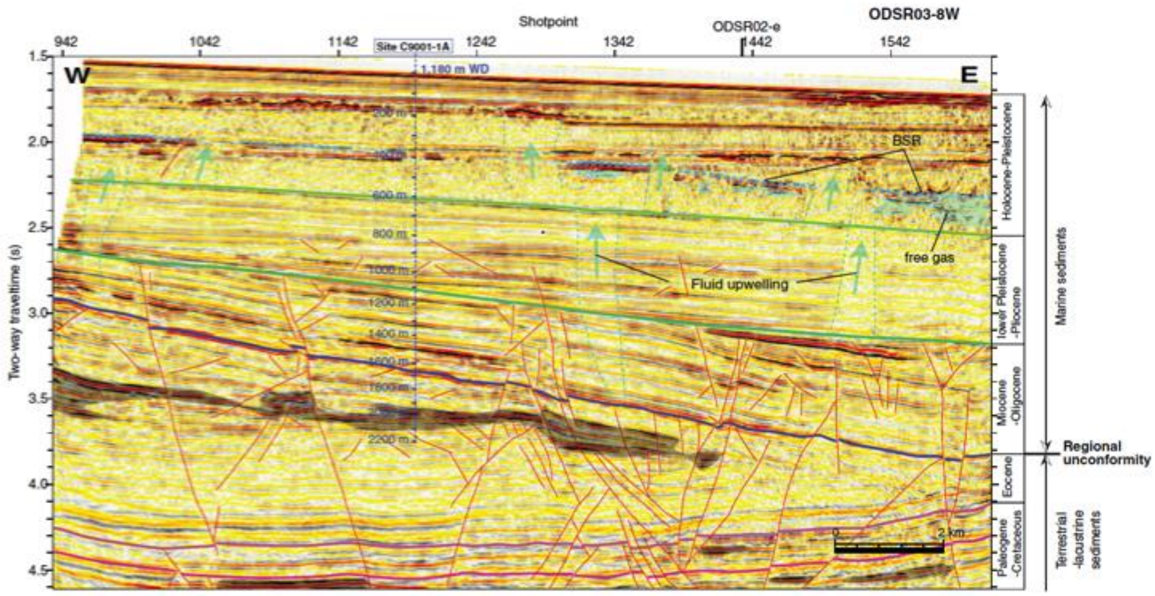
Table 3. Diatom biohorizons used to constrain age in Unit I, Hole C0020A.

Figure 1



(after Expedition 337 Scientists, 2013).

Figure 2



(after Expedition 337 Scientists, 2013).

Figure 3

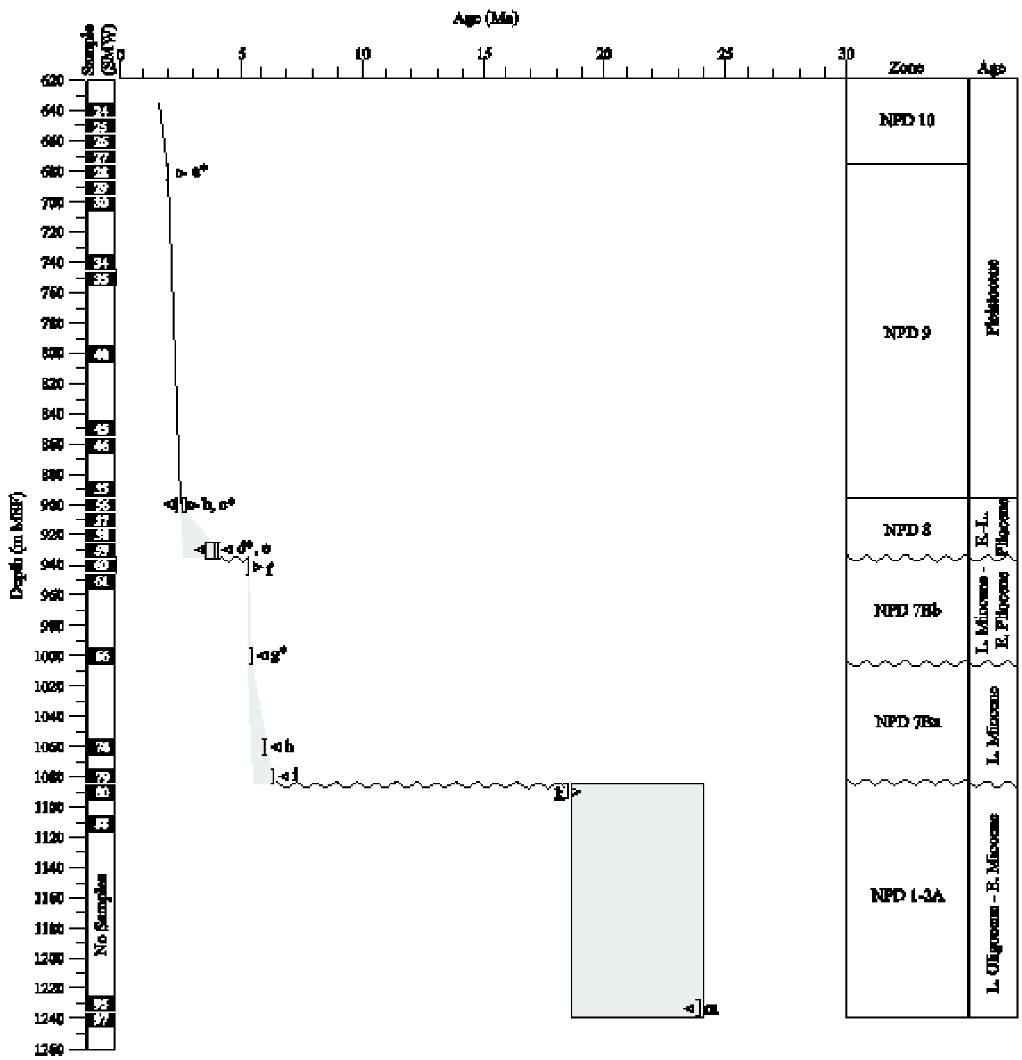

Age (Ma)
Sample (SMW)
Depth (m MSF)
Zone
Age
NPD 10
NPD 9
Pleistocene
NPD 8
E.-L. Pliocene
NPD 7Bb
L. Miocene - E. Pliocene
NPD 7Ba
L. Miocene
NPD 1-2A
L. Oligocene - E. Miocene
No Samples

Figure 4a

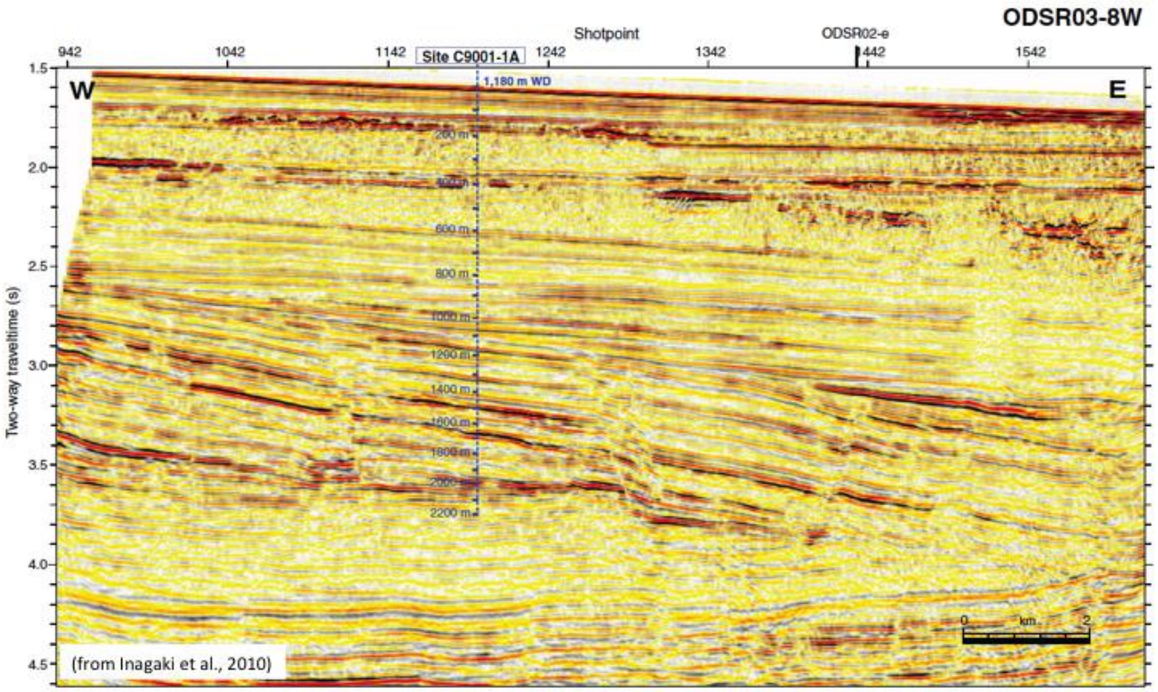

ODSR03-8W
Shotpoint
ODSR02-e
942
1042
1142
Site C9001-1A
1242
1342
1442
1542
1,180 m WD
W
E
Two-way traveltime (s)
1.5
2.0
2.5
3.0
3.5
4.0
4.5
200 m
600 m
800 m
1000 m
1200 m
1400 m
1600 m
1800 m
2200 m
0
km
2
(from Inagaki et al., 2010)

Figure 4b

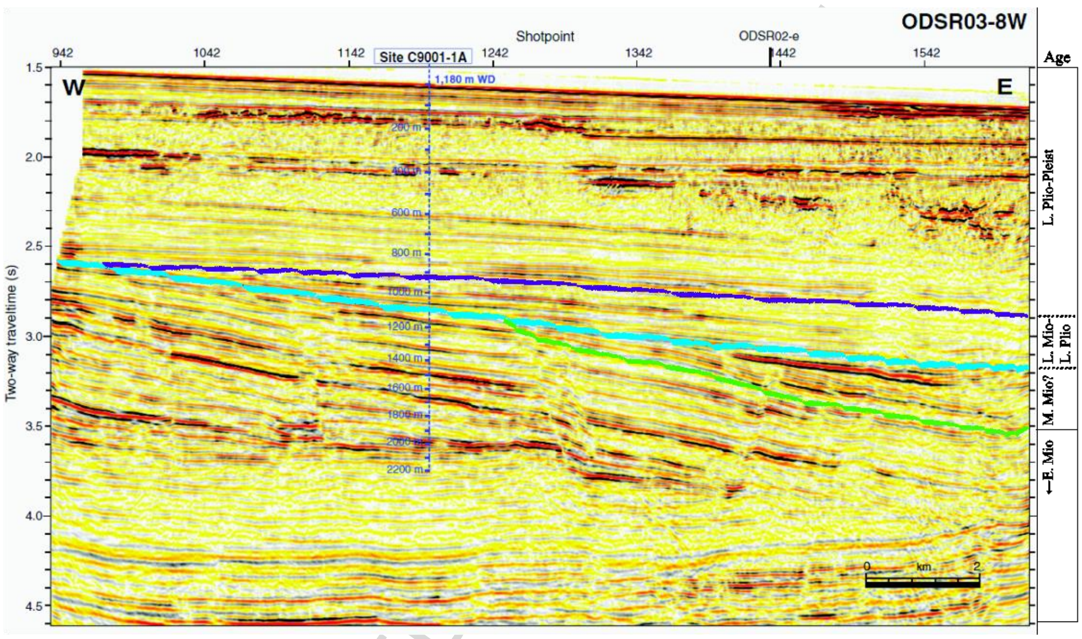

ODSR03-8W
Shotpoint
ODSR02-e
942
1042
1142
Site C9001-1A
1242
1342
1442
1542
Age
1,180 m WD
W
E
Two-way traveltime (s)
1.5
2.0
2.5
3.0
3.5
4.0
4.5
200 m
400 m
600 m
800 m
1000 m
1200 m
1400 m
1600 m
1800 m
2000 m
2200 m
L. Plio-Pleist
L. Mio-L. Plio
M. Mio?
←E. Mio
0 km 2

Figure 5

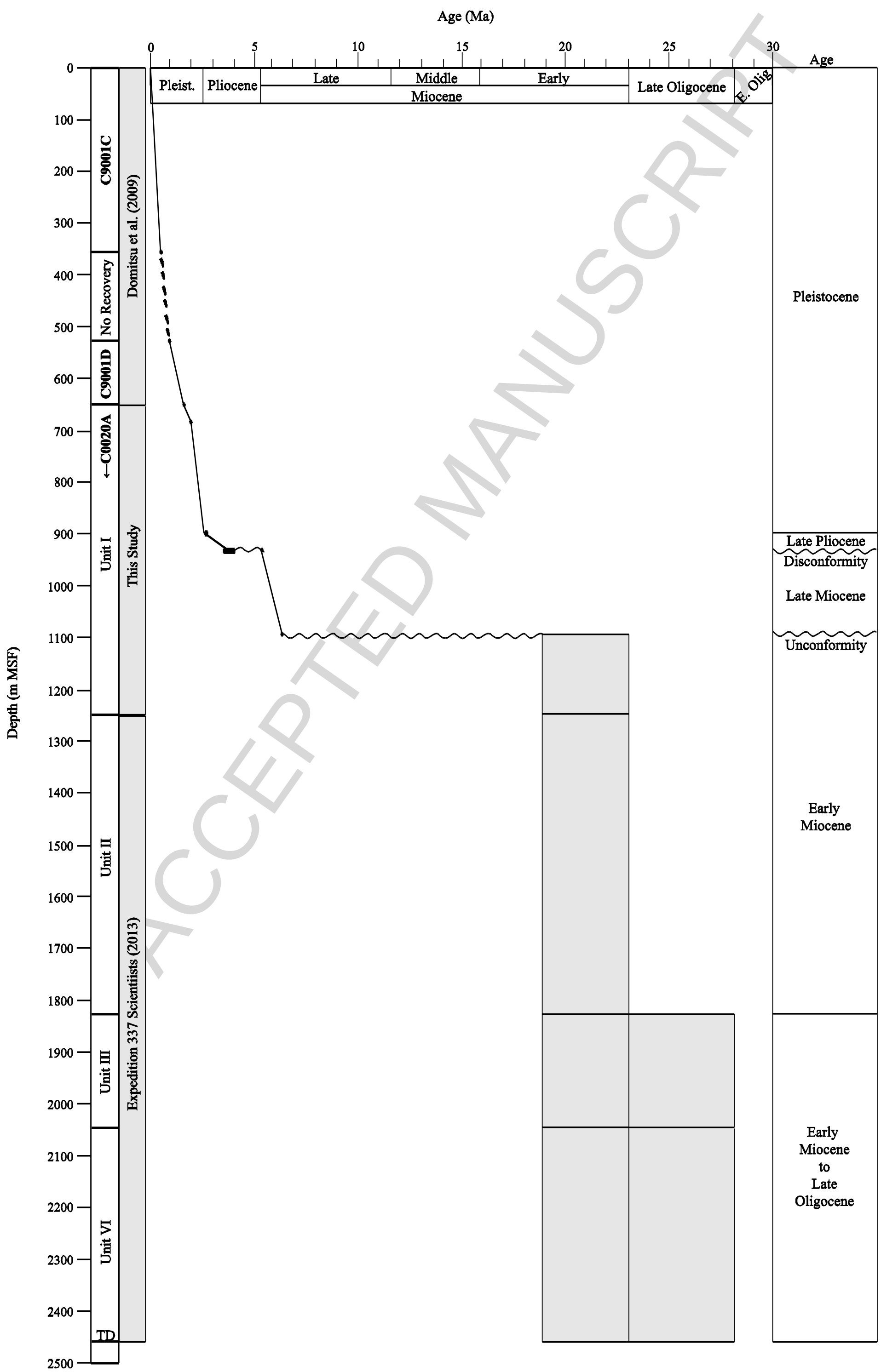

Age (Ma)
0 5 10 15 20 25 30
Age
Pleist.
Pliocene
Late
Middle
Early
Miocene
Late Oligocene
E. Olig.
Depth (m MSF)
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500
C9001C
No Recovery
C9001D
←C0020A
Unit I
Unit II
Unit III
Unit VI
TD
Domitsu et al. (2009)
This Study
Expedition 337 Scientists (2013)
Pleistocene
Late Pliocene
Disconformity
Late Miocene
Unconformity
Early Miocene
Early Miocene to Late Oligocene

Plate 1

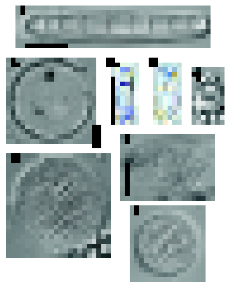


Table 1

Unit	Subunit	Core/Cuttings number	Depth interval MSF (m)	Thickness (m)	Lithology	Age
I	a	Samples 337-C0020A-24-SMW through 58-SMW	647-926.5	279.5	Diatom-bearing siltstone and claystone	late-middle Pliocene
	b	Samples 337-C0020A-59-SMW through 88-SMW	926.5-1116.5	190	Semiconsolidated diatom-bearing clayey siltstone with common fine sandstone	middle Pliocene/early Pliocene-late Miocene
	c	Samples 337-C0020A-92-SMW through 95-SMW	1116.5-1236.5	120	Unconsolidated to semiconsolidated sandstone and silty sandstone with rare clayey siltstone	early Pliocene-Miocene
	d	Samples 337-C0020A-97-SMW through 98-SMW	1236.5-1256.5	20	Semisonsolidated clayey siltstone with medium loose sand	early Pliocene-Miocene
II	a	Samples 337-C0020A-98 SMW through 153-SMW; Cores C0020A-1R through 6R	1256.5-1506.5	250	Sandstone and siltstone associated with marine fossiliferous material	Miocene
	b	Samples 337-C0020A-153-SMW through 216-SMW; Cores C0020A-7R through 14R	1506.5-1826.5	320	Organic-rich shale and sandstone associated with plant remains	Miocene
III		Samples 337-C0020A-216-SMW through 261-SMW; Cores C0020A-15R through 25R	1826.5-2046.5	220	Organic-rich sandstone and shale associated with coalbeds	early-middle Miocene
IV	a	Samples 337-C0020A-261-SMW through 384-SMW; Cores C0020A-26R through 29R	2046.5-2426.5	380	Shale and sandstone associated with carbonate and glauconitic material	early Miocene-late Oligocene
	b	Samples 337-C0020A-384-SMW through 391-SMW; Cores C0020A-30R through 32R	2426.5-2466	39.5	Sandstone and shale associated with coalbed	early Miocene-late Oligocene

Table 2

Sample No. (SMW)	Depth (mBRT)	Depth TOP (mbsf)	Depth BOTTOM (mbsf)	Geo Age	NPD Zone	Abundance	Preservation	*K. carina*	*K. ezoensis*	*D. hustedtii*	*D. katayama*	*Denticulopsis spp.*	*Rouxia spp.*	*T-ma. schraderi*	*N. kamtschatica*	*S. praeoestrupii*	*N. koizumii*	*S. oestrupii*	*A. oculatus*	*N. seminae*
24 SMW	1855.0	636.5	646.5			A	G											R	R	C
25 SMW	1865.0	646.5	656.5		NPD 10	A	G											R	R	C
26 SMW	1875.0	656.5	666.5			A	G											R	R	C
27 SMW	1885.0	666.5	676.5			A	G											R	F	C
28 SMW	1895.0	676.5	686.5			C	G										R	R	F	C
29 SMW	1905.0	686.5	696.5			C	G										R	R	R	C
30 SMW	1915.0	696.5	706.5	E. Pleistocene		C	G										F		R	F
34 SMW	1955.0	736.5	746.5			F	M												R	
35 SMW	1965.0	746.5	756.5		NPD 9	F	P										R			
40 SMW	2015.0	796.5	806.5			F	P										F	R	R	C
45 SMW	2065.0	846.5	856.5			C	M										R	R		R
46 SMW	2075.0	856.5	866.5			R	P										R			R
55 SMW	2105.0	886.5	896.5			F	M										R		R	R

56 SMW	2115.0	896.5	906.5			F	G								R		F		F	X
57 SMW	2125.0	906.5	916.5	E. - L. Pliocene	NPD 8	C	M					r			R		F		F	X
58 SMW	2135.0	916.5	926.5			C	M					r			R		F			
59 SMW	2145.0	926.5	936.5			F	M								R		R		R	
60 SMW	2155.0	936.5	946.5	E. Pliocene		C	M					r			C	R		R		
61 SMW	2165.0	946.5	956.5	L. Mio - L. Plio	NPD 7Bb	C	M			r	?				C		X			X
66 SMW	2215.0	996.5	1006.5	Mio/Plio		A	G								A	R		R		X
74 SMW	2275.0	1056.5	1066.5	L. Miocene	NPD 7Ba	F	M								F	R				
79 SMW	2295.0	1076.5	1086.5			F	P						r	r	C					
80 SMW	2305.0	1086.5	1096.5			R	P	R	R						X					
88 SMW	2325.0	1106.5	1116.5			R	P	R	R											
92 - LOST	2335.0	1116.5	1186.5	E. Miocene									LOST ZONE							
95 SMW	2445.0	1226.5	1236.5		NPD 1-2A	R	M	R	R						X		X		X	
97 SMW	2455.0	1236.5	1246.5			R	M	R												
	END UNIT I																			

r = reworked specimens, X = contaminating specimens

Table 3

Code number	Occurance	North Pacific diatom biohorizon	Age (Ma)	Depth (mbsf)	Sample
a*	LO	*Neodenticula koizumii*	2.0	676.5	28 SMW
b	FO	*Neodenticula seminae*	2.4?	896.5	55 SMW
c*	LO	*Neodenticula kamtschatica*	2.6-2.7	896.5	56 SMW
d*	FO	*Neodenticula koizumii*	3.5 - 3.9	936.5	59 SMW
e	FO	*Actinocyclus oculatus*	4.0	936.5	59 SMW
f	LO	*Thalassiosira praeoestrupii*	5.3	936.5	60 SMW
g*	FO	*Shionodiscus oestrupii s.l.*	5.5	1006.5	66 SMW
h	FO	*Shionodiscus praeoestrupii*	6.1	1066.5	74 SMW
i	FCO	*Neodenticula kamtschatica*	6.4	1086.5	79 SMW
k	LO	*Kisseleviella ezoensis*	~19.0	1086.5	80 SMW
m	FO	*Kisseleviella ezoensis*	~24.0	1246.5	97 SMW

Code number: (*) indicates primary biohorizons

Neogene and Early Pleistocene diatom biostratigraphy and age synthesis of Site C9001/C0020, Northwest Pacific

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RESEARCH HIGHLIGHTS

1. Prior to drilling, target coalbeds were estimated to be Eocene.
2. All new data are integrated with the overlying interval obtained from Holes C9001C and C9001D to produce a composite chronostratigraphic framework.
3. New biostratigraphic results indicate the target coalbed is Early Miocene.
4. The age of the deepest sediments recovered at Site C0020 is Late Oligocene.
5. Sediment accumulation rates at Site C9001/C0020 are calculated to be ~120m/myr.