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SEDIMENT CORES AND THEIR RADIOCARBON AGES IN THE WESTERN ROSS SEA, ANTARCTICA

Akira NISHIMURA[1], Toru NAKASONE[2], Chikara HIRAMATSU[3]
and Manabu TANAHASHI[4]*

[1] *Geological Survey of Japan, Higashi 1-chome, Tsukuba 305-8567*
[2] *Kawasaki Geological Engineering Co , Ltd , 23-17, Omori-minami 3-chome,*
Ota-ku, Tokyo 143-0013
[3] *Japan Petroleum Exploration Co Ltd , 2-1, Hamada 1-chome,*
Mihama-ku, Chiba 261-0025
[4] *Japan National Oil Corporation, 2-2, Uchisaiwaicho 2-chome,*
Chiyoda-ku, Tokyo 100-0011

Abstract: We describe paleoenvironmental changes related to ice sheet and ice shelf developments in the western Ross Sea in the late Quaternary, based on the three sediment cores collected along *ca* 167° E We distinguish four lithologic units in their sequences as follows (1) Unit I of diatomaceous mud, (2) Unit IIA of mud, (3) Unit IIB of alternating clay and thin laminated silt, and (4) Unit III of consolidated sandy silt with pebbly gravel

Interpreted sedimentary environments based on the time constraints of fifteen AMS ^{14}C dates and characteristics of sediments and diatom assemblages, are summarized as follows (1) Prior to the ice sheet advance, this area was possibly under a marine environment, (2) the grounded ice sheet is thought to have advanced between 35 and 20 ka BP, (3) shelf ice possibly covered the southern site between 25 and 20 ka BP, (4) an open marine environment with moderate productivity existed from 20 ka BP at the northern site, and (5) an open marine environment with high productivity existed from 9 ka BP

The length and timing of the ice sheet advance cannot explain radiocarbon dates of all sites Radiocarbon dating of marine sediments in the Antarctic area shows a large reservoir effect and contamination of reworked dead carbon In our estimation of the ages, two thousand years correction is needed in the upper unit at least Age data for lower units are thought to be older than the true sedimentary ages though these need further consideration

key words Ross Sea, late Quaternary, sea bottom sediments, AMS radiocarbon dating

1. Introduction

Marine sediments from the seas around Antarctica record environmental changes in the seas and ice sheet development The Ross Sea is one of the large inlets of Antarctica, and has been subjected to sedimentological, oceanographic and micropaleontological research (*e.g.* MCCOY, 1991, KELLOGG *et al* , 1979; ANDERSON *et al.*,

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* Present address Geological Survey of Japan, Higashi 1-chome, Tsukuba 305-8567

1984; EDWARDS *et al.,* 1987; DEMASTER *et al.,* 1992). The late Quaternary history of the Antarctic ice sheet has been reconstructed in several studies of this region (*e.g.* DENTON *et al.,* 1989; ANDERSON *et al.,* 1991). In our previous research in the Ross Sea, we also discussed the sedimentary environmental change based on the core lithologies with no time constraint, assuming that the lower consolidated lithologic unit was formed in the Last Glacial time (NISHIMURA *et al.,* 1996).

The reconstruction of the environmental history based on radiocarbon dating of marine cores was difficult, because conventional radiocarbon dating needs a vast amount of sediment with low carbon content and the apparently older sediments of Antarctic seas have been thought to be beyond the sensitivity limit of radiocarbon dating. Recently, AMS (accelerator mass spectrometer) radiocarbon dating, which can be applied to a small amount of sediment, has been used for marine sediments in the Antarctic region (*e.g.* DOMACK *et al.,* 1989; LICHT *et al.,* 1996). In this paper, we describe three new cores from the western margin of the Ross Sea continental shelf, and paleoenvironmental changes related to ice sheet and ice shelf developments are discussed based on sedimentological and micropaleontological data of these cores with fifteen AMS ^{14}C dates of organic carbon in the sediments.

2. Geological Settings

The continental shelf of the Ross Sea is up to 600 m deep, with several NNE-SSW trending banks and troughs, which has formed through the tectonic movement of a sedimentary basin and glacial erosion in the Quaternary (DAVEY, 1987). The shelf break of the Ross Sea is relatively deep (*ca.* 800 m), and the greatest depths on the shelf occur landward near the ice shelf (CHRISS and FRAKES, 1972). The western margin of the Ross Sea continental shelf (Fig. 1) is bounded by the Transantarctic Mountains, and a deep trough, the Drygalsky Basin, exists along the coast with a NE-SW to NNE-SSW trend. To the east of the troughs, there are shallower banks and islands, such as Crary Bank, Franklin Island, and Beaufort Island from north to south. The present ice shelf is south of 77°30′ S in the western Ross Sea. Drygalsky Ice Tongue extends eastward to 165°E along 75°30′ S.

Our previous research has recognized two types of sediment sequences on the continental shelf; continental shelf break and continental shelf facies (NISHIMURA *et al.,* 1996). The sediment sequences of the continental shelf facies consist of two distinct lithologies; upper diatomaceous mud containing poorly sorted ice-rafted debris formed under modern conditions and lower consolidated sandy silt, probably formed under glacial advance conditions (NISHIMURA *et al.,* 1996, TOKUHASHI *et al.,* 1996)

3. Samples and Analytical Methods

We collected the three sediment core samples from the western margin of the Ross Sea (Fig. 1 and Table 1) during the TH95 Antarctic Cruise in 1996 conducted by the Technology Research Center, JNOC, using the R/V HAKUREI-MARU. Site GC1604 is situated on the northwestern slope of Crary Bank, Site GC1605 is situated near Franklin Island, and Site GC1606 is located north of Ross Island. A gravity corer, 11 cm in

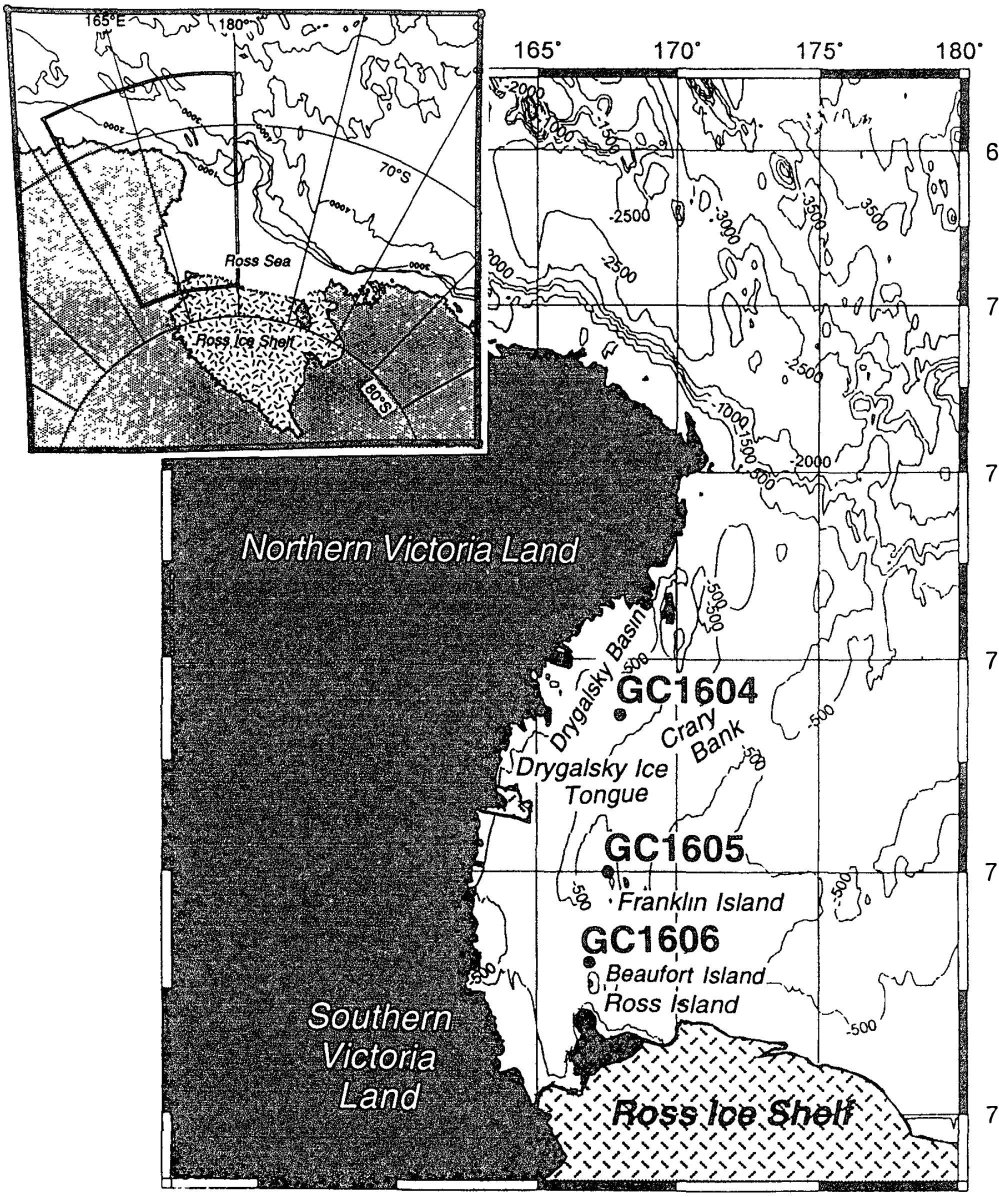

Fig 1 Map of the western Ross Sea Continental Shelf, Antarctica, showing the sampling locations

Table 1 Location data for core samples in the western Ross Sea

Sample No	Location		Water depth (m)
	(Latitude)	(Longitude)	
GC1604	74°32′55″S	168°00′06″E	922
GC1605	76°00′03″S	167°34′30″E	595
GC1606	76°46′14″S	166°52′36″E	751

diameter and 5.4 m long, was used but the recovered core lengths were shorter than 3 m (Fig. 2).

The samples were processed as follows through on-board and shore-based work:

(1) Sediment lithologies and structures were described based on visual observation, soft X-ray photos, and smear slide observations.

(2) Water content (weight percent water), dry bulk density and sand content (weight percentage of grains larger than 63 μm) were measured for syringe samples of several cc's (4–5 cc) at 10-cm stratigraphic intervals.

(3) Magnetic susceptibilities were measured for one-cubic inch samples at every inch using a Martison Type-2 apparatus in 0.47 kHz and 4.7 kHz frequency modes. Magnetic susceptibility shows the amount of magnetic minerals, most of which are supposed to have terrigenous origin in this region, and its profiles in the core sequence may be used to infer content of terrigenous materials in the sediments. Larger values of frequency

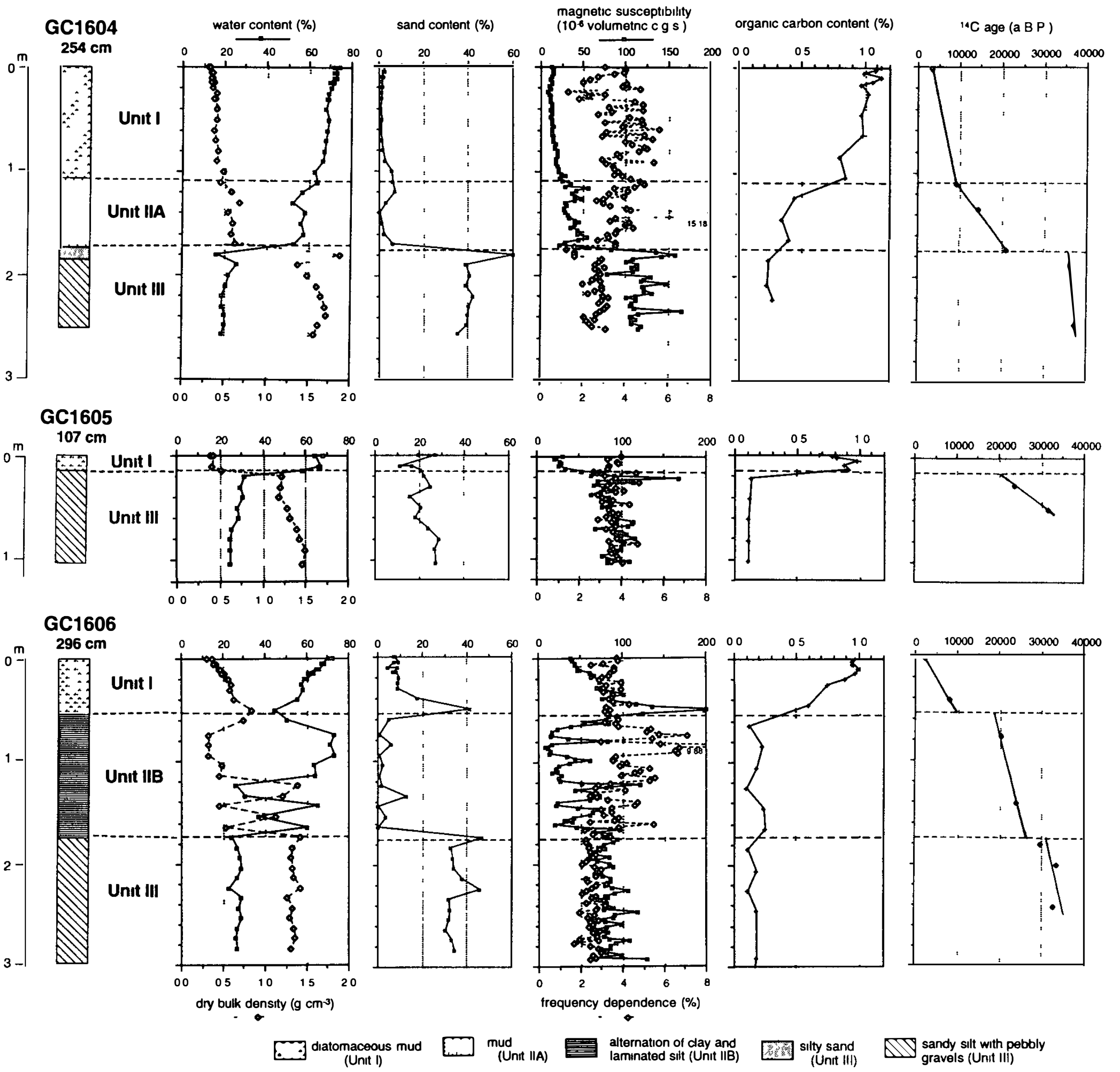

Fig. 2 Lithologies, physical properties, sand contents, carbon contents, and AMS ^{14}C ages of the core samples from the western Ross Sea

dependence suggest that the grain sizes of magnetic minerals are relatively small (YAMAZAKI and KATSURA, 1990). The frequency dependence was calculated from the differences of measured susceptibility values between the two modes using the equation.

$$\chi_{FD}=(\chi_L-\chi_H)/\chi_L\times 100\ (\%),$$

where χ_{FD} indicates frequency dependence, χ_L magnetic susceptibility of 0.47 kHz frequency, and χ_H that of 4.7 kHz frequency.

(4) Organic carbon contents were measured at 10 to 20 cm intervals. Samples were stored frozen before drying at 50°C. Bulk carbon contents were measured using a Yanako CHN analyzer; the bulk carbon contents are assumed equal to organic carbon contents, because the inorganic carbon contents of several survey samples are less than 0.04%. Organic carbon contents of sediments depend on biogenic productivity and supply of terrigenous materials.

(5) Diatoms were analyzed at 20-cm intervals using unprocessed strewn slides (AKIBA, 1982). One hundred diatom specimens were identified along with resting spores. If there were fewer than 100 specimens on the whole slide, diatom assemblages were described based on the total number of specimens on the slide. Diatom species which became extinct before the Pliocene with poorly preserved and/or fragmentary appearances were counted as reworked diatoms. A part of *Denticulopsis* spp. and *Actinocyclus ingens* are also possibly reworked (HARWOOD and MARUYAMA, 1992) but excluded from reworked diatoms and counted separately in this paper.

(6) Acid-insoluble organic carbon of the sediment samples was used for AMS ^{14}C dating, because carbonates were lacking in the sediments. The sediment samples for dating were taken at 3 to 6 cm stratigraphic intervals on board (Table 2) and stored frozen before drying at 50°C. ^{14}C ages were determined and corrected for isotopic

Table 2. AMS radiocarbon age date of the organic carbon in Cores GC1604, GC1605, and GC1606 form the western Ross Sea.

Core No.	Depth (cm)	Uncorrected ^{14}C Age (a BP)	δ^{13}C (‰)	Corrected ^{14}C Age (a BP)
GC1604	0–5	3450±60	−35.6	3280±60
	109–114	9220±70	−31.5	9120±70
	133–138	14440±70	−27.7	14400±70
	172–175	21200±170	−28.6	21140±170
	187–192	36320±980	−27.7	36280±980
	244–249	37640±1130	−36.4	37460±1130
GC1605	24–29	23650±260	−32.9	23530±260
	48–53	31540±570	−30.2	31460±570
GC1606	0–5	2440±50	−31.2	2340±50
	40–44	8120±40	−29.7	8040±40
	75–80	20540±180	−31.2	20440±180
	139–144	24040±260	−32.8	23920±260
	178–182	29660±190	−27.8	29620±190
	198–204	33430±690	−28.3	33380±690
	239–243	32560±270	−27.8	32520±270

fractionation based on $^{13}C/^{12}C$ ratios, using a half-life of 5568 years. The AMS measurements were performed at Groningen University (Netherlands) after preparation at Beta Analytic Inc. (USA).

4. Lithologic Units and Their Characteristics

In the three core sequences, we distinguished four lithologic units, Unit I, Unit IIA, Unit IIB, and Unit III based on their lithologies. The lithologies of these units are briefly summarized as follows:

(1) Unit I is dark grayish yellow to grayish olive diatomaceous mud and includes 0–109 cm in GC1604, 0–14 cm in GC1605, and 0–55 cm in GC1606 (Fig. 3).

(2) Unit IIA is dark greenish gray mud. This unit corresponds to 109–175 cm in GC 1604 and is not observed in other cores. Volcanic glass is abundant from 109 to 140 cm of GC1604. The boundary between this unit and Unit I is marked by a downward gradual color change from gray to grayish olive.

(3) Unit IIB is alternation of clay and thin (mm-scaled) laminated silt This unit corresponds to 55–173 cm in GC1606 (Fig. 3) and is not observed in other cores. The upper contact with Unit I is not visually defined but smear slide observation shows clear contrast of contents of siliceous biogenic materials between these units. Several minor fault structures, apparently normal, are observed in several thin laminae of this unit

(4) Unit III is composed of consolidated dark olive gray to dark greenish gray silty sand and sandy silt with pebbly gravels and includes 175–254 cm in GC1604, 14–107 cm in GC1605, and 173–296 cm in GC1606 (Fig. 3). The silty sand layer at 175–185 cm of GC1604 is included in this unit because its consolidation is the same as that of the material below it. The contacts between this unit and the upper units are marked by the contrast of consolidation.

The characteristics of these units and the results of diatom analysis are shown in Figs. 2 and 4

4.1. *Water contents, dry bulk densities, and sand contents*

Water contents of Unit I are generally high, 60% on average, and gradually decrease down-core in GC1604 and GC1606. Water contents of Unit IIA show moderate values, decreasing downward from 62% to 52%, and those of Unit IIB vary greatly, between 73% and 24%, depending on the lithologies. Unit III shows low water contents of 18–30%.

Dry bulk density shows a generally inverse relation to water content, *ca.* 0.5 g/cm^3 in Unit I, *ca.* 0.6 g/cm^3 in Unit IIA, 0.3–1.3 g/cm^3 in Unit IIB, and 1.3–1.7 g/cm^3 in Unit III.

Contents of sand-sized grains of Unit I vary among the sites, less than 5% in GC 1604, *ca.* 20% in GC1605, and *ca.* 10% in GC1606. Content of sand-sized grains in Unit IIA is less than 10%, the same as that in Unit I, at the same site. Unit IIB shows the lowest content of sand-sized grains, less than 10% in the GC1606 core sequence Contents of sand-sized grains of Unit III are generally high, exceeding 30%, *ca.* 40% for GC1604 and GC1606 and 30% for GC1605.

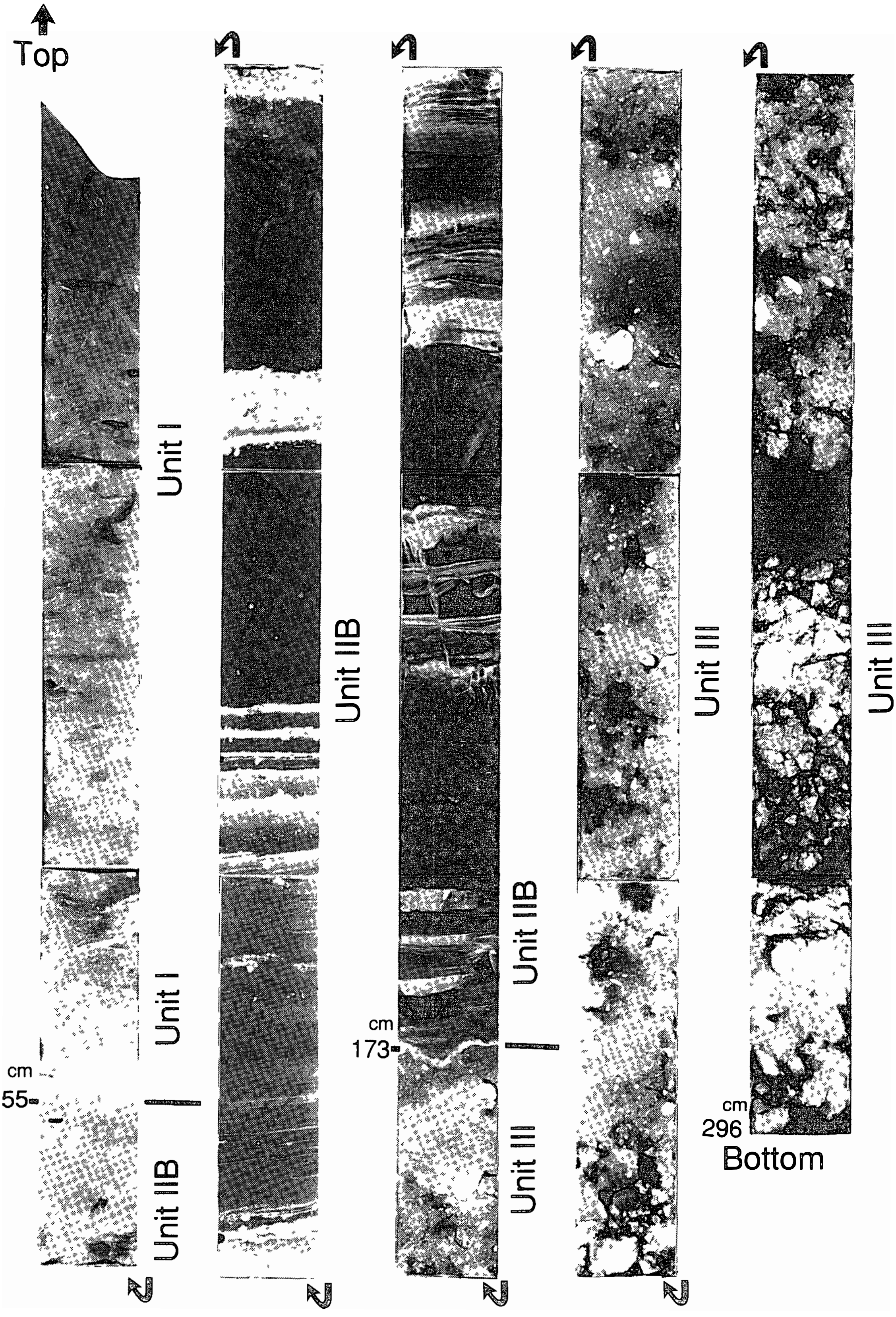

Fig 3 X-ray radiograph of the whole core sequence of Core GC1606

4.2. Magnetic susceptibility

Vertical profiles of magnetic susceptibility show generally similar changes to those of sand-sized grain content (Fig. 2). In Unit IIB of GC1606, magnetic susceptibility is generally lower than in other units of GC1606; frequency dependence is high in parts with larger values of magnetic susceptibility. They correspond to the clay parts of this unit, but the detailed correlation is not shown in Fig. 2. In Unit III, the average values of magnetic susceptibility are high, with large variations

4.3. Organic carbon content

Organic carbon contents are high, exceeding 0.7%, in Unit I. Organic carbon contents in Unit IIA are between 0.4% and 0.3%, and those in Unit IIB are between 0.3 % and 0.1%. Organic carbon contents are less than 0.2% in Unit (III).

4.4. Occurrence of diatoms

All analyzed samples yield diatom tests. The occurrence of diatoms are shown in Fig. 4.

Unit I has abundant well-preserved diatoms, with dominance of *Nitzschia curta*, accompanied by *Thalassiosira antarctica*. These two species exceed 70% of the total in Unit I. Unit IIA has abundant moderately preserved diatoms. The diatom assemblages of Unit IIA are similar to those of Unit I, with the presence of *Nitzschia kerguerensis* and *Paralia sulcata*, though the diatom contents are smaller than those in Unit I. Resting spores are abundant in the lower part of Unit IIA.

The diatom tests of Unit IIB and Unit III are poorly preserved. Reworked specimens are observed in Unit IIA, the lower half of Unit IIB, and Unit III of GC1605 and GC1605. Diatoms on the smear slides of Unit III are almost all fragmented. The diatom assemblages of the upper part of Unit IIB are similar to those of Units I and IIA. The diatom assemblages of the rest of Unit IIB and Unit III are different from those of Unit I and IIA, and are characterized by high contents of *Actinocyclus ingens, Thalassionema nitzchioides, P. sulcata, Stephanopyxis* spp., and *Denticulopsis* spp.

4.5. Radiocarbon ages

Fifteen radiocarbon dates are available for these three cores (Table 2 and Fig. 2). The age assignment and sedimentation rates from the radiocarbon dates, uncorrected for the ^{14}C reservoir effect are as follows. Unit I is younger than 9 ka BP in two of the cores, with average sedimentation rates of 18.7 cm kyr^{-1} for GC1604 and 6.0 cm kyr^{-1} for GC1606. Extrapolated core top ages for GC1604 and GC1606 are *ca.* 3 ka and *ca.* 2 ka BP, respectively. The age of Unit IIA is from *ca.* 22 to *ca.* 9 ka BP, with a sedimentation rate of 5.6 cm kyr^{-1}. The age of Unit IIB is from 26 to 19 ka BP, with a sedimentation rate of 20.0 cm kyr^{-1}. The ages of Unit III are variable at the three sites. In GC1604, the two age dates in this unit are 36280 and 37460 years BP with an apparent sedimentation of 48.3 cm kyr^{-1}; and the top of this unit is probably *ca.* 36 ka BP or younger. Dates of GC1605 indicate that this unit is from *ca.* 20 to 30 ka BP with a sedimentation rate of 3.0 cm kyr^{-1}. The ages of this unit of GC1606 are *ca.* 30 to 33 ka BP; the middle and lowest age data show apparent stratigraphical reversal, but these values are equal within the analytical error.

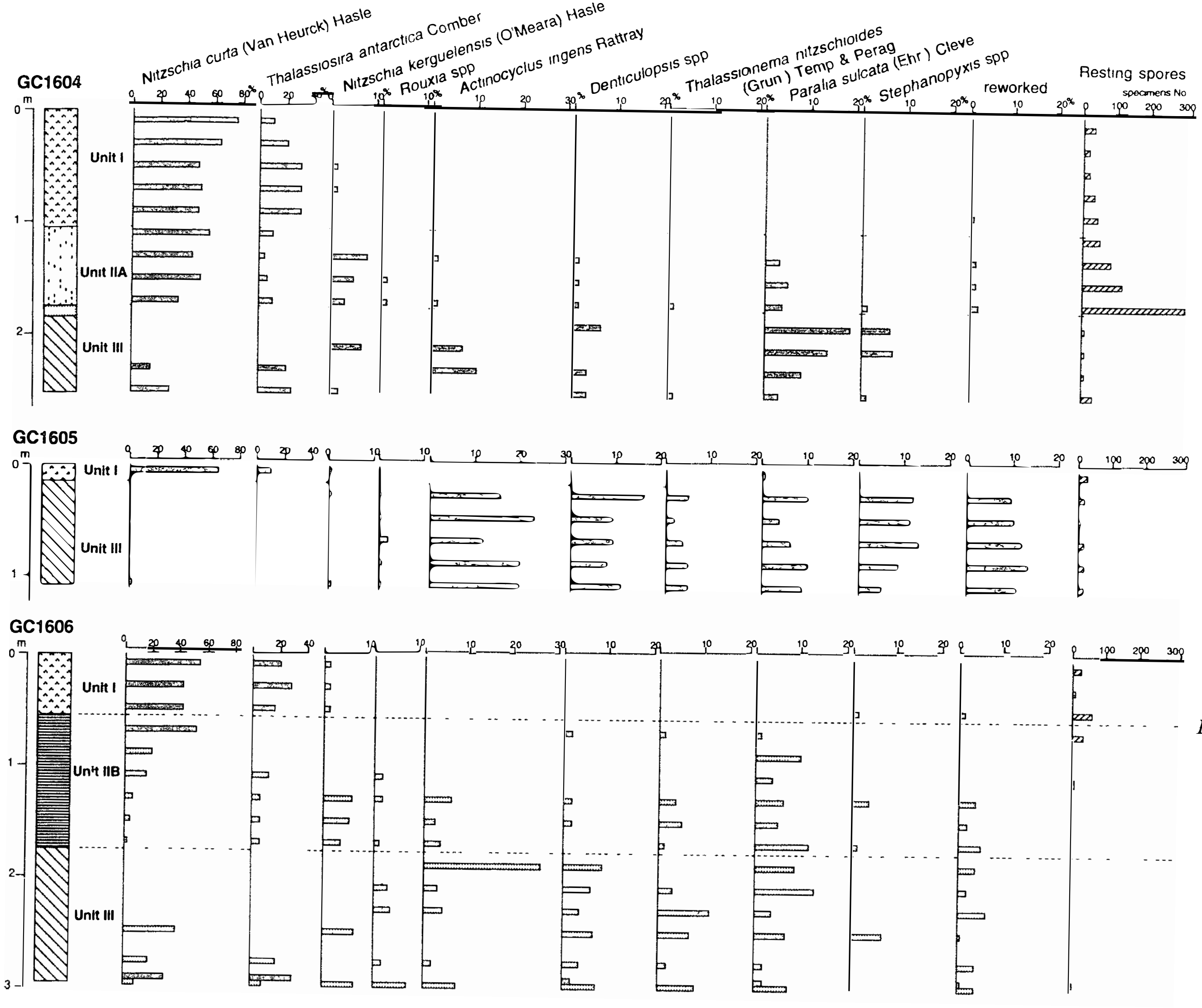

Fig 4 Diatom distribution in Cores GC1604, GC1605, and GC 1606 from the western Ross Sea Percentages of species in black filled pattern were calculated based on identification of 100 specimens, those in gray pattern less than 100 specimens Lithologic patterns are the same as those in Fig 2

5. Dating of Sediments

Absolute ages for marine sediments in the Antarctic region are very difficult to establish, primarily because of the large and regionally variable reservoir age for radiocarbon (OMOTO, 1983; DOMACK *et al.*, 1989; GORDON and HARKNESS, 1992; LEVENTER *et al.*, 1996) The reservoir effects are due to upwelling water with an aged deep-water origin and ice sheet melt water with ^{14}C-dead carbon (UJIIE *et al.*, 1995). In addition, radiocarbon ages of organic carbon in sediments, which possibly include reworked organic detritus, are more complicated than those of the carbonate carbon. Nevertheless, radiocarbon analysis remains the best tool for evaluating dating and sediment accumulation rates over several tens of thousands of years

In the several core sequences in the marine environment, the radiocarbon ages of organic and carbonate carbon show almost the same reservoir effect for the last several thousand years (LEVENTER *et al.*, 1996). Based on the extrapolated core top ages in this area, *ca.* 2 ka BP and 3 ka BP, we suggest deducting 2 ka from our ^{14}C ages at least for Unit I to correct for the reservoir effect in this area. But we have no data for Units IIA, IIB and III, which were formed under different conditions with more reworked sediments. Diatom analysis of the sediments suggests that the sediments of Unit IIA, lower half of Unit IIB and Unit III of GC1605 and GC1606 include possibly reworked carbon induced with reworked diatom fossils. Large values of magnetic susceptibility of Unit III also suggest high contents of terrigenous components affecting the organic carbon dating, but the amount of contaminated carbon cannot be estimated. The true sedimentary ages of these units are possibly a good deal younger than the radiocarbon ages of these units due to the effect of terrigenous dead carbon contamination.

6. Sedimentary Environments

The following sedimentary environmental conditions are inferred from the lithologic features and characteristics of units. The schematic section along the sampling sites is shown in Fig. 5, a part of which is sketched referring to the facies models of ANDERSON *et al.* (1991) and core lithologies.

(1) Environment affected by a grounded ice sheet

Unit III at the three sites has the same characteristics; high consolidation, lithologies of sandy silt with pebbly gravels, high sand content, low water content, and low organic carbon content. This unit is correlated with so-called diamicton, sandy basal tills widely distributed on the Ross Sea continental shelf (ANDERSON *et al.*, 1991), and the lower unit of semiconsolidated silt with pebble gravels of continental shelf type (NISHIMURA *et al.*, 1996; Fig. 5). The occurrence of diatoms and organic carbon suggest that most sediments of the unit are of marine origin. The normal stratigraphic order of the AMS ages, taking error into consideration, suggests that the sediments had not been intensively deformed. Consolidation was probably occurred by the loading of a grounded ice sheet. The diatoms with fragile tests in the unit may have been destroyed through the loading, so the ecological significance of the diatom assemblage cannot be discussed. The organic carbon dates of the unit show marine deposition ages prior to deformation, followed by the advance of a grounded ice sheet In this view, ice

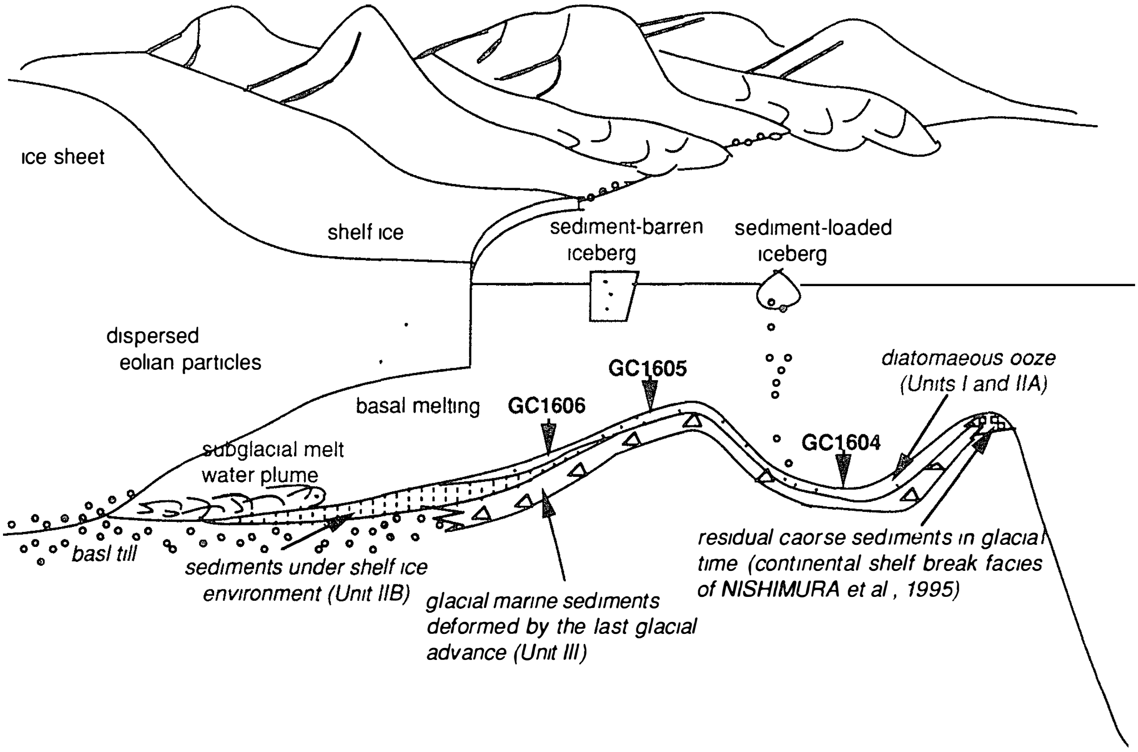

Fig 5 Schematic section along the sampling sites on the western Ross Sea Continental Shelf Ross Island is excluded in the section showing the sedimentary environment around the shelf ice

sheet advance occurred during the time shown by the time gaps above the unit, between 30 and 25 ka BP at the southern site and between 35 and 21 ka BP at the northern site

(2) Environment under floating ice

Unit IIB is composed of alternating clay and laminated silt with little terrigenous coarse sand grains The magnetic susceptibility and frequency dependence of the clay part suggest that magnetic minerals are present in only small amounts and that smaller magnetic grains are dominant, implying an environment with little supply of terrigenous coarse materials This unit may have been deposited under floating ice (probably an ice shelf), which prevented deposition of terrigenous coarse materials by icebergs and allowed supply of diatom tests and organic carbon There are a few observations of sediments under the present day ice shelf. Webb *et al.* (1979) reported surface sediments with diatom tests from beneath the Ross Ice Shelf. However, the mechanism of transportation of diatom tests and organic carbon of marine origin to the sea bottom under the ice shelf is unknown, and we need to consider the extent of shelf ice and sedimentation model under the ice shelf The silts of the unit with current derived laminations can be correlated with production of sediment-loaded melt water plumes induced from the ice sheet grounding line (Anderson *et al.*, 1991, Fig 5) This environment probably persisted from 25 to 20 ka BP at this site. Minor normal fault structures in the unit suggest that an ice sheet or icebergs grounded and deformed sea bottom sediments between 20 and 9 ka BP at the southern site

(3) Open marine environment with moderate productivity influenced by shelf ice/ice

sheet

Unit IIA of GC1604 is mud with ages between *ca.* 20 and 9 ka BP. Average sedimentation rate is smaller than that of the upper unit at this site. The carbon contents of this unit are 0.3% to 0.4%, which are smaller than those of Unit I and suggest lower productivity than under modern conditions. This was possibly due to the influence of an ice shelf or an ice sheet near the site.

(4) Open marine environment with high productivity

Unit I, including the surface sediments at the three sites, is composed of diatomaceous mud with high organic carbon contents exceeding 0.6%, suggesting high productivity. The diatomaceous mud contains sand grains, which are thought to be of ice-rafted origin, inferred based on the heavy mineral composition including continental origin (TOKUHASHI *et al.*, 1996). *Nitzschia curta*, which is the dominant species of this unit, is found in surface sediments of the southwestern McMurdo Sound with high content and thought to be an indicator of sea ice influence and high productivity (LEVENTER and DUNBAR, 1988). In summer, high and variable biogenic fluxes result in high sediment accumulation in the Ross Sea (DEMASTER *et al.*, 1992). Sedimentation under modern conditions started at 9 ka BP at Sites GC1604 and GC1606. The sedimentary environment of Unit I has been continued to the present.

The ice sheet is thought to have covered the Ross Sea continental shelf at the Last Glacial Maximum (ANDERSON *et al.*, 1991), but recent studies suggest that the ice sheet in the western Ross Sea was restricted south of 74°S in the Last Glacial Maximum (LICHT *et al.*, 1996). In this study, we recognize that an ice sheet covered the three coring sites south of 74°S, and that the advance and retreat of the ice sheet occurred between 30 and 25 ka BP at the southern site, 20 and probable 9 ka BP at the central site, and 35 and 21 ka BP at the northern site. It is suggested that the ice sheet retreat occurred prior to the Last Glacial Maximum with an age of *ca.* 18 ka BP, except at the central site. At the southern site, shelf ice possibly covered the site between 25 and 20 ka BP. At the northern site, an open marine environment has existed since 20 ka.

ANDERSON *et al.* (1991) classified the sediments of the Ross Sea into basal tills, transitional facies, and glacial marine compound in their ice shelf facies model. Moreover, they pointed out that the sharp boundaries between the basal till and the diatomaceous mud are widely distributed without transitional facies, and that the boundary had been formed after the retreat of the ice sheet under shelf ice condition, where no sediment had been deposited. Unit IIB at the southern site may consist of sediments deposited under ice shelf. This is a possible good example of sedimentation under a shelf ice, therefore, it raises a problem of the cause of the sharp boundary. The boundary was possibly formed by an other mechanism, such as erosion by bottom currents.

More detailed study is needed on the relation between sedimentation and glacier drainage in this region. Advance and retreat times of a series of Ice sheet covering the three sites cannot be easily determined based on the positions and dating data of the cores. It is possible that the ice sheets which influenced our three sites belonged to different drainage streams. Moreover, our ^{14}C ages are based only on correction for isotopic precipitation, but large reservoir effects are known in Antarctica, and estimated dates may be altered by addition of ^{14}C-dead carbon, as indicated by reworked diatoms and terrigenous compositions in sediments

7. Concluding Remarks

The AMS radiocarbon ages of organic carbon in sediment cores from the western margin of the Ross Sea give important time constraints for the reconstruction of the sedimentary environments in the latest Quaternary, as follows.

(1) Since 38 ka BP at the latest, this area was possibly under a marine environment

(2) A grounded ice sheet advance is thought to have occurred between 30 and 25 ka BP at the southern site (*ca.* 76°46′S), 20 and 9 ka BP at the central site (*ca.* 76°00′S), and 35 and 21 ka BP at the northern site (*ca.* 74°33′S), forming a consolidated sandy silt unit The length and timing of duration of a single ice sheet advance cannot be determined to explain the lithologic changes and radiocarbon dating results at the three sites

(3) After 25 ka BP, the southern site was possibly covered by shelf ice, preventing deposition of terrigenous coarse materials and maintaining of supply of diatom tests and organic carbon to *ca.* 20 ka BP.

(4) The northern site was under a marine environment with moderate productivity influenced by a shelf ice/ice sheet from *ca.* 20 to 9 ka BP

(5) The modern open marine environment with high productivity began around 9 ka BP This condition has continued to the present

In the ages used above, two to three thousand years correction is needed in the upper unit at least. As to age data for lower units, we have no data to use for correction. The ages are possibly older than the true sedimentary ages because of their older carbon contamination, adding the reservoir effect Further research of age data is needed

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