Palaeoproductivity in the Ross Sea, Antarctica, during the last 15 kyr BP and its link with ice-core temperature proxies

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ABSTRACT. A detailed study of organic carbon content obtained from two sediment cores collected in the Joides basin, western Ross Sea, Antarctica, was carried out. The variations observed during the last deglaciation and the Holocene were compared to the high-resolution climatic records (EPICA DC and Taylor Dome) preserved in the ice. The importance of the carbon content as a proxy for palaeoclimatic and palaeoenvironmental changes was investigated. A dramatic decrease in the Ross Sea palaeoproductivity was observed during the Antarctic Cold Reversal (12.5–14 kyr BP). Another decrease in total organic carbon in the second half of the Holocene (after 5–6 kyr BP) confirms the climate worsening observed in previous studies.

INTRODUCTION

Determining climatic variations through the study of marine sediment cores in the Antarctic region, and in particular in the Ross Sea, is one of the aims of the 'Glaciologia e Paleoclima' project within the framework of the Italian 'Programma Nazionale di Ricerche in Antartide' (PNRA). During the last decade, several sediment cores have been collected in the central and western continental shelf of the Ross Sea which, together with the Weddell Sea, has been the object of numerous studies in recent years since the Late Pleistocene and Holocene sediments are well represented here and more widespread than in other Antarctic areas. Moreover, it is known that high-latitude areas, such as the Antarctic continent, are more sensitive to climatic changes because of their extreme environmental conditions (Frignani and others, 1998). The Ross Sea has long been recognized as a crucial area for testing glaciological models of ice-sheet dynamics and stability because a significant component of the West and East Antarctic ice sheet drains into the Ross Sea. The Ross Sea continental shelf has a mean depth of about 500 m and is characterized by deep troughs (up to 1500 m) and banks that document advance and retreat of ice streams coming from the Transantarctic Mountains and Marie Byrd Land (Hughes, 1977; Anderson and others, 1992).

Here we present geochemical (organic carbon) and sedimentological (grain-size analyses) data from sediment cores collected in the northern part of the Joides basin, which is located in the central sector of the Ross Sea. In particular, this study concerns two gravity cores selected from those collected during the 6th (1990/91) and 14th (1998/99) PNRA oceanographic cruises: cores ANTA91-19 and ANTA99-cJ5. Previous studies showed that the northern part of the Joides basin was free of grounded ice (Anderson and others, 1992; Licht and others, 1996; Domack and others, 1999; Shipp and others, 1999; Brambati and others, 2002b), with undisturbed sedimentary sequences, in particular for the Late Pleistocene and Holocene sediments (Brambati and others, 1999, 2002a).

The variations of organic carbon content in the cores, being related to the marine palaeoproductivity (Licht and others, 1996; Meyers, 1997; Frignani and others,1998; Cremer and others, 2003), may be an indicator of past climatic variations (sea-ice extent). For this reason, useful information can be derived from the comparison between this parameter and the stable-isotopic profiles from Antarctic ice cores. The high resolution of the organic carbon record in the Joides basin enables us to compare it with the high-resolution climate information preserved in the ice cores.

MATERIALS AND METHODS

The Joides basin has an elongate shape, with two troughs divided by a sill located near the 74°30′ parallel. The northern area of the basin, with a depth of 600 m, extends near to the continental-shelf break, while the southern part of the basin is deeper. During the 6th oceanographic cruise (1990/91) the 575 cm long gravity core ANTA91-19 (diameter of 10 cm) was collected (74°26′ S, 173°6′ E) at a water depth of 592 m, while during the 14th oceanographic cruise (1998/99) the 553 cm long gravity core ANTA99-cJ5 (diameter of 10 cm) was collected (73°49.42′ S, 175°39.01′ E) in the northern area of the Joides basin at a water depth of 598 m (Fig. 1).

The sediment cores were X-rayed, split, described and photographed. Subsamples, taken every centimetre, of about 10–15 g were used for grain-size analysis. Samples were rinsed with distilled water and wet-sieved to separate gravel (>2 mm), sand (2000–63 μm) and pelite (<63 μm) fractions (Wentworth, 1922). The sand fraction was analyzed on a Macrogranometer settling tube, and the mud fraction on a Sedigraph 5100 particle-size analyzer, using a 0.5% sodium hexametaphosphate dispersing solution. The total organic carbon (TOC) content was determined every cm in the uppermost part of both cores (up to 240 cm) and every 10 cm in the lower part. The organic carbon measurements were carried out using a Perkin–Elmer 2400 CHN Elemental Analyzer. About 10–20 mg of sediment was used and the carbonate fraction was previously eliminated using hydrochloric acid in silver capsules (Hedges and Stern, 1984).

The chronology of both cores is based on accelerator mass spectrometry (AMS) radiocarbon analyses (Table 1). These analyses were made on either foraminifera calcite or bulk organic carbon, depending upon the presence/absence of calcareous foraminifers within different intervals in the cores.

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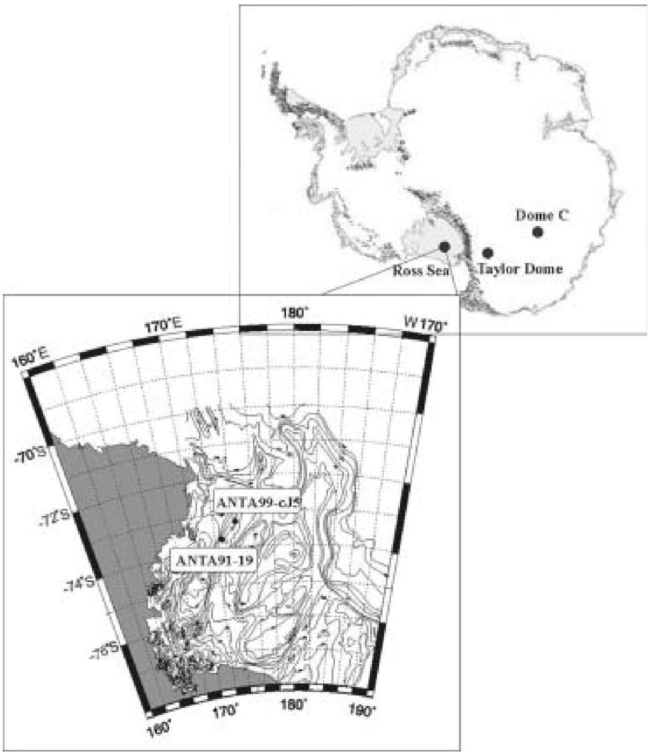

Fig. 1. Map of Antarctica, showing the location of the EPICA DC and Taylor Dome ice cores and the position of sedimentary cores in the Ross Sea.

For core ANTA99-cJ5, four AMS ^{14}C age determinations were made on bulk organic carbon at the Geochron Laboratories, Massachusetts, USA. For core ANTA91–19, five ^{14}C ages were determined on both bulk organic carbon and foraminiferal specimens (level 376–382 cm) using the AMS facility at the University of Groningen, The Netherlands.

Ages and sedimentation rates of the cores are reported in Table 1. The ^{14}C ages from the top of the cores are 4470 ± 70 years BP for core ANTA91-19 and 5000 ± 30 years BP for core ANTA99-cJ5. Such high values are common for Antarctic marine surface sediment (Domack and others, 1989; Domack, 1992; DeMaster and others, 1996; Licht and others 1996; Brambati and others, 1997; Frignani and others, 1998; Ingólfsson and others, 1998; Domack and others, 1999). Old surface ages may be due to different factors such as the loss of the core top during sampling, especially using gravity corers (Brambati and others, 1997; Frignani and others, 1998), or the reservoir effect, which is related to the antiquity of the carbon pool within the Southern Ocean (Domack and others, 1989, 1999; Bird and others, 1991; Gordon and Harkness, 1992; Leventer and others, 1993). The value of the reservoir effect in the Ross Sea is estimated to be 1200–1300 years (Licht and others 1996; Domack and others, 1999; Goodwin and Zweck, 2000; Cremer and others, 2003) but can also be higher (Taylor and McMinn, 2001, 2002).

In addition, significant reworking complicates the interpretation of radiocarbon dates derived from organic matter despite the absence of land-based organic detritus (Domack and others, 1995; Domack and McClennen, 1996; Leventer and others, 1996). However, previous micropalaeontological study of foraminifers taxa, on sediment cores collected in the Joides basin, and in particular on cores ANTA91-19 and ANTA99-cJ5 (Kellogg and others, 1979; Melis and others, 1998; Brambati and others, 1999), highlighted the presence of calcareous autochthonous foraminifers in the lower part of the cores. By contrast, the upper part of both cores is characterized by the occurrence of arenaceous foraminifers and the absence of calcareous faraminifers. These results, together with the qualitative and quantitative analyses of diatom associations (Bonci and others, 2000), highlighted the absence of reworking phenomenon in both cores.

The conventional ages were corrected using a conventional reservoir age of 1230 years and the calibration program CALIB 4.3 (Stuiver and Reimer, 1993) with $\Delta R = 830 \pm 40$ (Domack and others, 2001; Table 1). Calibrated ages are used below unless otherwise specified.

The sedimentation rate was calculated using a linear interpolation between ^{14}C dated levels (Table 1), and

Table 1. Radiocarbon ages and sedimentation rates for each gravity core

Core sample	Sample interval	Uncorrected age BP	Corrected age BP (Rt = 1230)	Calibrated age BP (ΔR = 830 ± 40)	Sedimentation rates cm kyr^{-1}
ANTA91-19	24–26	4470 ± 70	3240 ± 70	3543	
					30.08
	179–185	9070 ± 90	7840 ± 90	8762	
					5.83
	206–209	12 440 ± 100	11 210 ± 100	13 136	
					21.71
	376–382	19 020 ± 100	17 790 ± 100	21 036	
					20.71
	570–575	30 380 ± 600	29 150 ± 600	–	
ANTA99-cJ5	5–6	5000 ± 30	3770 ± 30	4237	
					38.60
	59–60	6120 ± 40	4890 ± 40	5636	
					30.40
	139–140	8620 ± 40	7390 ± 40	8268	
					15.61
	240–241	13 850 ± 50	12 620 ± 50	14 739	

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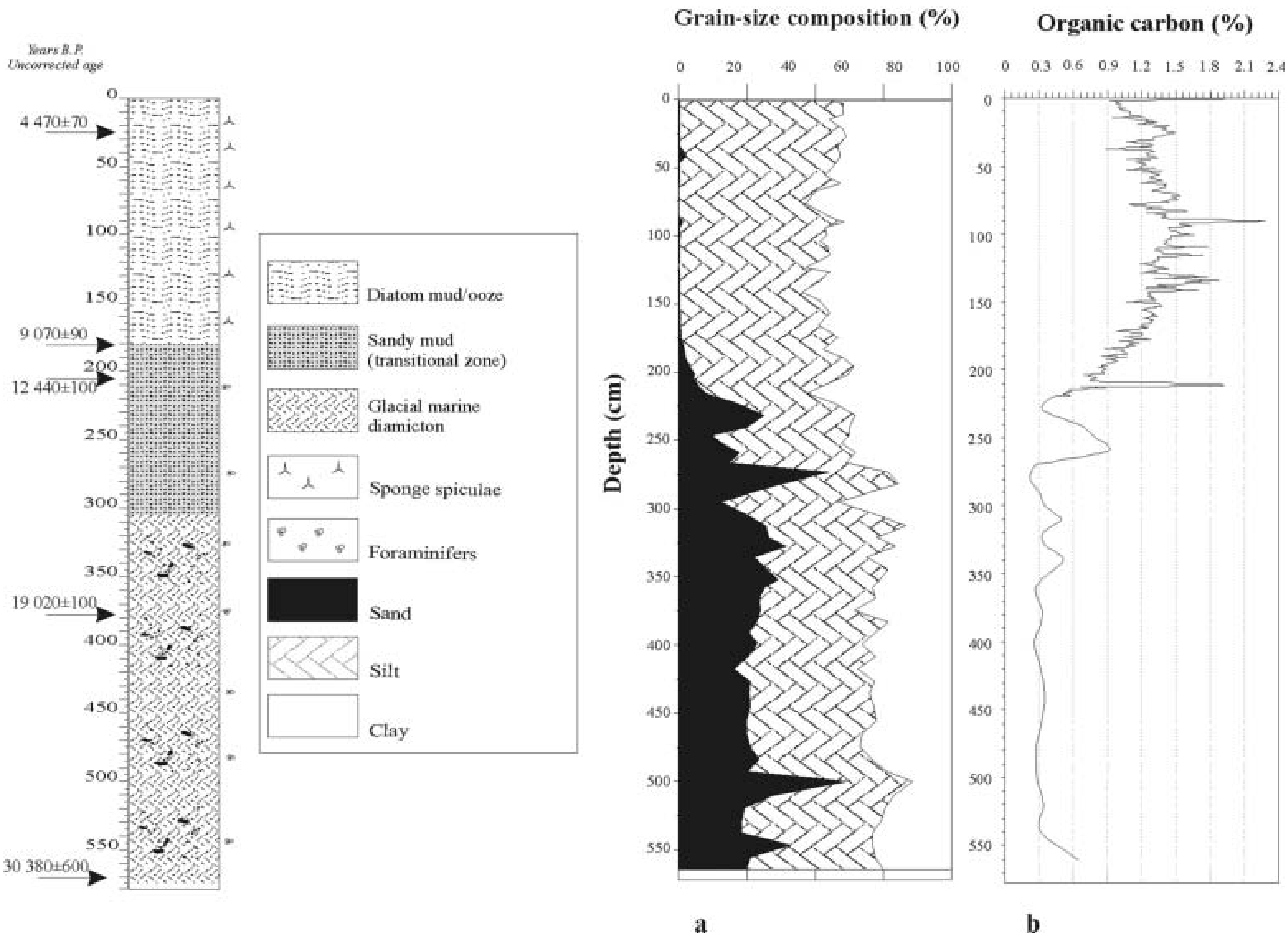

Fig. 2. Textural (a) and organic carbon (b) vertical distribution vs depth in the core ANTA91-19. Reported ^{14}C data are uncorrected.

assuming a constant sedimentation rate between them. The sedimentation rate of core ANTA99-cJ5 shows similar values from ~4200 to ~8200 years BP and lower values for older sediments. Core ANTA91-19 shows an abrupt decrease in sedimentation rate for the period between ~8800 and ~13 1001 years BP (Table 1). On the basis of these sedimentation rates and adopted sampling frequency, we obtained an age resolution of 26–64 and 33–171 years for cores ANTA99-cJ5 and ANTA91-19 respectively. Because of the low sedimentation rate found in core ANTA91-19, for ages older than ~8800 years BP, a high-resolution comparison with the ice-core records is not possible in this interval.

RESULTS

Previous sedimentological and micropalaeontological studies and $\delta^{13}C$ and $\delta^{18}O$ measurements (Brambati and others, 1999, 2002a, b) showed that the core ANTA91-19 sequence can be divided into three units. From the bottom to the top, the sedimentary section is formed by a fossiliferous diamicton, followed by a thin horizon of glacial marine sediment, with a marine siliceous mud in the topmost part of the core.

The fossiliferous diamicton of cores ANTA91-19 and ANTA99-cJ5 is characterized by the occurrence of quite well-preserved calcareous benthonic and planktonic foraminifers (Kellogg and others, 1979; Melis and others, 1998; Brambati and others, 1999) generally considered autochthonous. In both cores, the overlying deposits record the disappearance of the foraminifers; the beginning of such an event is contemporaneous. The uppermost part of both cores is characterized by the occurrence of agglutinated foraminifers. These findings indicate that the oceanic water circulation is more corrosive during the Holocene than the Last Glacial Maximum period, due to the rise of the carbonate compensation depth (CCD) level.

From a sedimentological point of view, core ANTA91-19 (Fig. 2) presents a lower unit (575–300 cm), characterized by a fine-grained matrix with the inclusion of gravel-sized clasts. The central unit, from 300 to 180 cm, shows a decrease in sand fraction while the mud component increases. The upper unit, from 180 cm to the top, is constituted by fine grain-size sediment with a low sand fraction.

Using textural analysis (Fig. 3), core ANTA99-cJ5 was also subdivided into three units. The lower unit (553–340 cm) is a homogeneous diamicton with gravel in a clay–silt matrix; the sediment has almost equal proportions of sand, silt and clay. A sharp contact marks the base of a central unit, characterized by variable percentages of sand; pebbles of ~1 cm are present in this unit. The upper part of the core (180 cm to the top) is characterized by the highest mean percentage of silt, while the sand fraction is very low and the gravel component is absent.

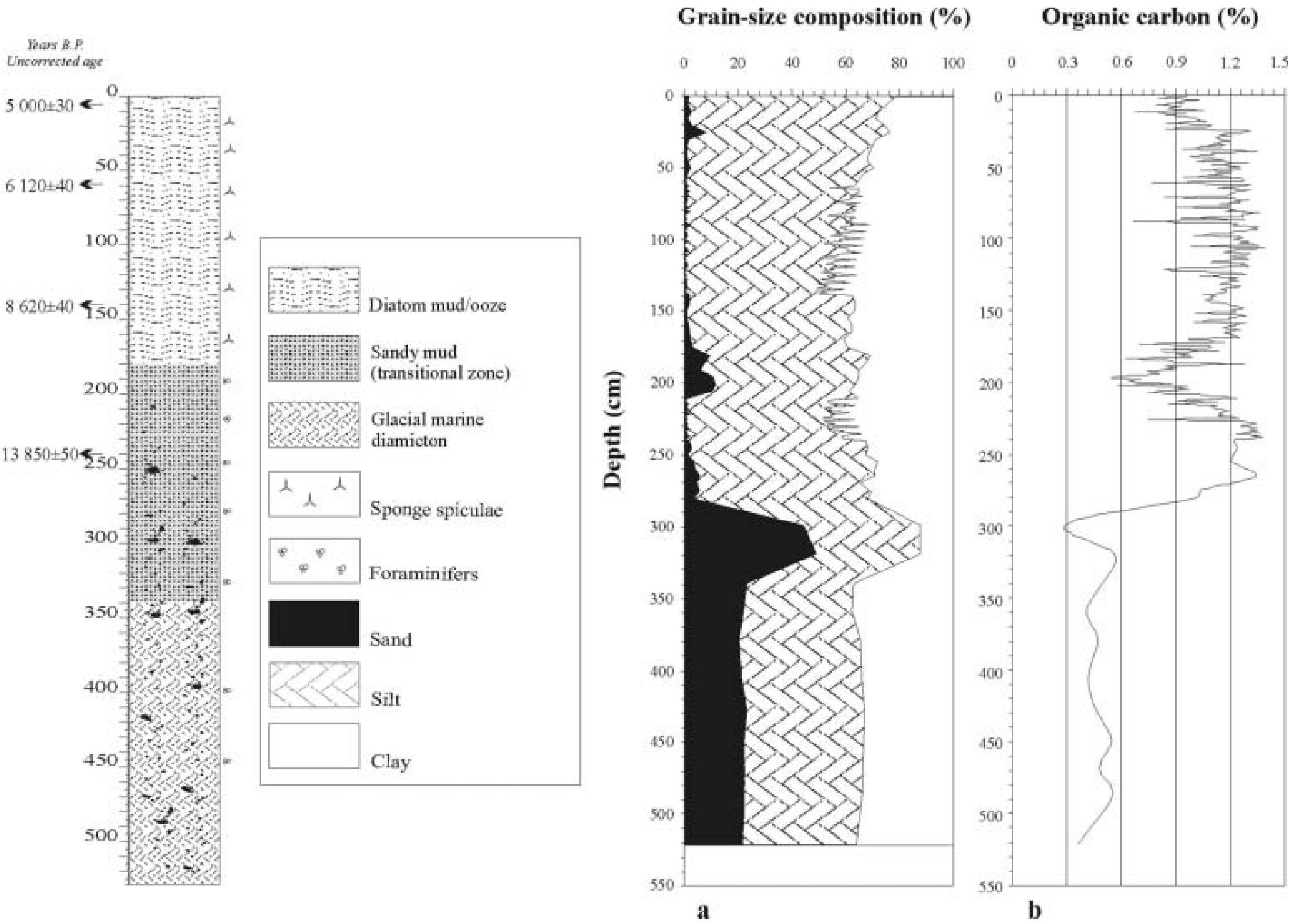

Fig. 3. Textural (a) and organic carbon (b) vertical distribution vs depth in core ANTA99-cJ5. Reported ^{14}C data are uncorrected.

The organic carbon contents of both cores (Figs 2 and 3) are in the range of those observed in other Antarctic sediments (Domack and McClennen, 1996; Brambati and others, 1997; Licht and others, 1999). In particular, the TOC content for core ANTA91-19 (Fig. 2) is generally low (<0.5%) from the bottom to 270 cm, with a mean value of 0.34 ± 0.10%; between 220 and 270 cm the mean value is 0.56 ± 0.25%, with a maximum of 0.91% at 260 cm and a minimum of 0.33% at 230 cm. The level from 220 cm to the top of the core is characterized by an increase in carbon content, with values generally >1% (mean value of 1.25 ± 0.27%). There are three peaks of 1.91%, 2.27% and 1.92% at 211 cm, 90 cm and the top respectively.

The organic carbon content in core ANTA99-cJ5 (Fig. 3) is also highly variable. From the bottom (553 cm) to 340 cm the values are generally low and relatively constant, with a mean value of 0.47 ± 0.06%. A minimum value of 0.30% is observed at 299 cm. Above this, there is an increase of TOC, with a mean value of 1.11 ± 0.21%, followed by another decrease at 197.5 cm with a value of 0.55%. From this level to the top of the core, the carbon values are generally >1% (mean of 1.11 ± 0.17%).

DISCUSSION

The study of sediment cores from the Joides basin highlights the environmental evolution of this area during the late Quaternary. Previous studies (e.g. Brambati and others, 1999, 2002a, b) on core ANTA91-19 and unpublished data on core ANTA99-cJ5 show that the Joides basin had a different history to other basins in the Ross Sea such as the Drygalski basin. In both cores the basal unit is characterized by a glacial marine diamicton (sensu Licht and others, 1996) with the presence of well-preserved foraminifers (both benthonic and planktonic).

It is hypothesized that in the deepest part of the basin, the West Antarctic ice sheet was not grounded during the LGM, but probably was grounded on the flanks of the basin (Corradi and others, 1997; Domack and others, 1999; Shipp and others, 1999; Brambati and others, 2002b).

The TOC content in the two cores is useful for palaeoenvironmental information, because, in Antarctic marine sediments, this is more closely related to productivity in the marine realm than to terrestrial sources of plant debris and of reworked organic particulates (Domack and others, 1995; Leventer and others, 1996; Licht and others, 1996; Meyers, 1997; Frignani and others, 1998). The variation of organic carbon content may be an indicator of past climatic variations (sea-ice extent: Domack and others, 1995; Meyers, 1997).

The palaeoclimatic information obtained from the organic carbon records was compared with two ice cores, one from the East Antarctic plateau located at Dome Concordia (DC) (European Project for Ice Coring in Antarctica (EPICA)), and one from a more coastal site, Taylor Dome, facing the Ross Sea (Fig. 1). The time period considered spanned the last 15 000 years BP.

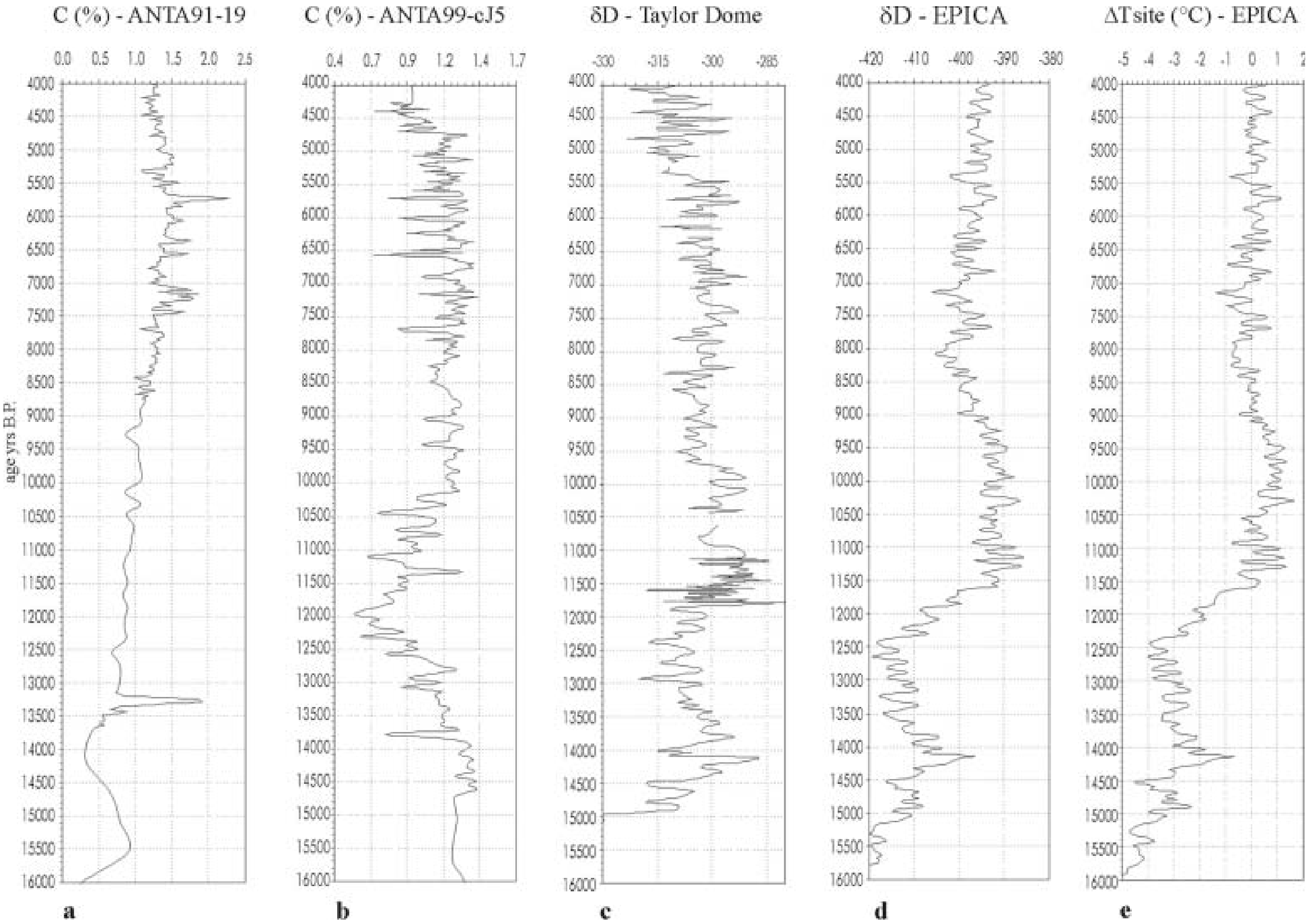

Fig. 4. Carbon content of cores ANTA91-19 (a) and ANTA99-cJ5 (b), δD of Taylor Dome (c) and EPICA DC (d), and ΔT_{site} of EPICA DC (e) vs age; the ages of the sedimentary records are calibrated ^{14}C data. The Taylor Dome data were obtained from the website http://www.sas.upenn.edu/~esteig/taylor.html.

The climate interpretation based on ice-core stable-isotope profiles relies on the empirical relationships between either δD or $\delta^{18}O$ and the condensation temperature (Dansgaard, 1964; Petit and others, 1999). The Dome C core provides a new high-resolution climate record for East Antarctica. We used EPICA DC δD data from Jouzel and others (2001), and Taylor Dome δD data from Steig and others (1998a, b, 2000).

The data obtained from analyses of the organic carbon content of cores ANTA91-19 and ANTA99-cJ5 are reported in Figure 4 along with the δD stable-isotope profiles of Taylor Dome and EPICA DC ice cores. All the records are reported on their own time-scale for the time interval covering the last deglaciation and the Holocene. Figure 4 also shows the temperature anomalies ΔT_{site} (as deviations from the present-day values; 50 year data) calculated using the method of Stenni and others (2001). These authors combined measurements of stable isotopes (δD and $\delta^{18}O$) from the EPICA DC ice core with a simple isotopic model, to reconstruct the variability of both the site temperature (East Antarctica) and the moisture source temperature (mainly the sub-Antarctic Indian Ocean) over the last 27 000 years. Jouzel and others (2001) suggested that all East Antarctic ice cores, including Taylor Dome, appear to have a similar deglaciation history characterized by a long gradual warming interrupted, between ~14 000 and 12 500 years, by the Antarctic Cold Reversal (ACR; Jouzel and others, 1995). The estimated surface temperature difference between the LGM and the early-Holocene optimum, calculated on the basis of the EPICA DC isotopic data (Stenni and others, 2001), is around 9°C.

The comparison between the organic carbon content and isotopic profiles, derived from the ice cores (Fig. 4), shows a high similarity, especially for core ANTA99-cJ5. Around 14 500–14 000 years BP, the high carbon contents observed in core ANTA99-cJ5 show values similar to those obtained during the middle Holocene (~7500–5500 years BP) in the same core. From 14 000 to 12 000 years BP, a dramatic decrease in the carbon content occurred. This decrease in productivity parallels a similar decrease in the δD values corresponding to the ACR period.

In core ANTA91-19 the organic carbon trend is different from that observed in core ANTA99-cJ5 for the lower part, whereas from ~8500 to ~4000 years it is similar. This discrepancy has not been explained. However, as stated above, the strong decrease in the sedimentation rate calculated between ~8800 and ~13 100 BP does not allow any comparison.

After the ACR, the TOC values gradually increase during the warming observed in the ice archive leading to the early-Holocene optimum. The high values observed between ~10 500 and 9000 years BP in core ANTA99-cJ5 are again in agreement with the high δD values. The small negative peak around 8500–8200 years BP in the TOC profile seems to

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correspond to a similar cold peak in the isotopic profile of EPICA DC. Afterwards, the isotopic profile of EPICA DC shows a slight increasing trend ending around 4500 years BP. By contrast, the organic carbon content in core ANTA99-cJ5 shows an increase up to ~7000 years BP and a decrease towards the top of the cores (up to 4500 years BP). A similar decreasing trend is well documented in the isotopic profile of the Taylor Dome ice core, which is located in a more coastal area than the EPICA DC ice core.

The isotopic record at Taylor Dome and diatom assemblages from Ross Sea sediment cores led Steig and others (1998b) to suggest: (i) warm climate conditions during the early Holocene; (ii) a rapid cooling at about 6000 years BP followed by continued cooling during the late Holocene; (iii) an increase in sea-ice cover at about 6000 years BP. This cooling is not evident in the more inland sites at EPICA DC, but seems to be restricted to coastal regions. Masson and others (2000) showed that the Holocene temperature trends inferred from Antarctic ice core might have been influenced by changes in both local ice-sheet elevation and climate.

The variations of the organic carbon content observed during the last deglaciation and the Holocene, pointed out in this study, suggest similar variations in productivity in this sector of the Southern Ocean, probably linked to sea-ice extent changes as suggested by Steig and others (1998b). Furthermore this study shows a dramatic decline in the Ross Sea productivity related to the cooling occurring during the ACR. It also confirms the cooling in the second half of the Holocene observed in the Taylor Dome ice core. Several studies have already highlighted the importance of the climate changes during the middle Holocene, recognizing a widespread climatic decline in the Southern Hemisphere, starting around 5000–6000 years BP (Heusser, 1998; Steig and others, 1998b; Porter, 2000; Hodell and others, 2001).

CONCLUSION

The variations of organic carbon content in the sediment core ANTA99-cJ5 collected in the Ross Sea embayment show a marked decrease during the ACR, a subsequent increase during the early-Holocene optimum and a decrease in the second part of the Holocene. These variations are probably linked to oceanic productivity fluctuations in the Ross Sea induced by variation in sea-ice extent. The correlation established between the climatic information obtained from the ice cores and ocean productivity from the sediment cores underlines the importance of the TOC as an indicator of palaeoclimatic and palaeoenvironmental changes.

The high-resolution TOC analyses carried out in this study allowed comparison of climatic events recorded in different climatic proxies such as ice and sediment cores. In particular, this methodology seems able to extract and at the same time explain Late Pleistocene and Holocene palaeoenvironmental and/or climatic variations which have occurred in the sedimentary sequences in the Ross Sea continental shelf.

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REFERENCES

Anderson, J.B., S.S. Shipp, L.R. Bartek and D.E. Reid. 1992. Evidence for a grounded ice sheet on the Ross Sea continental shelf during the Late Pleistocene and preliminary paleodrainage reconstruction. *In* Elliot, D.H., *ed. Contributions to Antarctic research III*. Washington, DC, American Geophysical Union, 39–62. (Antarctic Research Series 57.)

Bird, M.I., A.R. Chivas, C.J. Radnell and H.R. Burton. 1991. Sedimentological and stable-isotope evolution of the lakes in the Vestold Hills, Antarctica. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* **84**(1–4), 109–130.

Bonci, M.C., N. Corradi, R. Ivaldi and C. Pirini. 2000. Paleoenvironmental characteristics of the Northern Joides basin (Ross Sea): sedimentological and micropalaeontological findings (diatoms and forarms). *Terra Antarct. Rep.,* **4**, 111–124.

Brambati, A. *and 6 others*. 1997. Paleoenvironmental record in core ANTA91-30 (Drygalski Basin, Ross Sea, Antarctica). *In* Barker, P.F. and A.K. Cooper, *eds. Geology and seismic stratigraphy of the Antarctic margin 2*. Washington, DC, American Geophysical Union, 137–151. (Antarctic Research Series 71.)

Brambati, A. *and 6 others*. 1999. Some paleoecological remarks on the Ross Sea shelf, Antarctica. *In* Faranda, F.M., L. Guglielmo and A. Ianora, *eds. Ross Sea ecology*. Berlin, Springer-Verlag, 51–61.

Brambati, A., R. Melis, T. Quaia and G. Salvi. 2002a. Late Quaternary climatic changes in the Ross Sea area, Antarctica. *Bull. R. Soc. N.Z.,* **35**, 359–364.

Brambati, A., N. Corradi, F. Finocchiaro and F. Giglio. 2002b. The position of the Last Glacial Maximum grounding line in the Joides Basin: an interpretation based on sedimentological and geotechnical data. *Bull. R. Soc. N.Z.,* **35**, 365–372.

Corradi, N., G. Fierro, L. Mirabile, M. Ferrari and R. Ivaldi. 1997. Geotechnical, sedimentological characteristics and seismic stratigraphy of northern Joides Basin (Ross Sea, Antarctica): preliminary results. *In* Ricci, C.A., *ed. The Antarctic region: geological evolution and processes*. Siena, Museo Nazionale dell’ Antartide, 885–887. (Terra Antarctica Publication.)

Cremer, H., D. Gore, M. Melles and D. Roberts. 2003. Paleoclimatic significance of late Quaternary diatom assemblages from southern Windmill Islands, East Antarctica. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* **195**(3–4), 261–280.

Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus,* **16**(4), 436–468.

DeMaster, D.J., O. Ragueneau and C.A. Nittrouer. 1996. Preservation efficiencies and accumulation rates for biogenic silica and organic C, N and P in high-latitude sediments: the Ross Sea. *J. Geophys. Res.,* **101**(C8), 18,501–18,518.

Domack, E.W. 1992. Modern carbon-14 ages and reservoir corrections for the Antarctic Peninsula and Gerlache Strait area. *Antarct. J. U.S.,* **27**(5), 63–64.

Domack, E.W. and C. McClennen. 1996. Accumulation of glacial marine sediments in fjords of the Antarctic Peninsula and their use as Late Holocene paleoenvironmental indicators. *In* Ross, R.M., E.E. Hofmann and L.B. Quentin, *eds. Foundations for ecological research west of the Antarctic Peninsula*. Washington, DC, American Geophysical Union, 135–154. (Antarctic Research Series 70.)

Domack, E.W., A.J.T. Jull, J.B. Anderson, T.W. Linick and C.R. Williams. 1989. Application of tandem accelerator mass-spectrometer dating to Late Pleistocene–Holocene sediments of the East Antarctic continental shelf. *Quat. Res.,* **31**(2), 277–287.

Domack, E.W., S.E. Ishman, A.B. Stein, C.E. McClennen and A.J.T. Jull. 1995. Late Holocene advance of the Müller Ice Shelf, Antarctic Peninsula: sedimentological, geochemical and palaeontological evidence. *Antarct. Sci.,* **7**(2), 159–170.

Domack, E.W., E.K. Jacobson, S.S. Shipp and J.B. Anderson. 1999. Late Pleistocene–Holocene retreat of the West Antarctic ice-sheet system in the Ross Sea: Part 2 – sedimentologic and stratigraphic signature: geophysical results. *Geol. Soc. Am. Bull.,* **111**(10), 1517–1536.

Domack, E.W. *and 6 others*. 2001. Chronology of the Palmer deep site, Antarctic Peninsula: a Holocene paleoenvironmental reference for the circum-Antarctic. *Holocene,* **11**(1), 1–9.

Frignani, M., F. Giglio, L. Langone, M. Ravaioli and M. Mangini. 1998. Late Pleistocene–Holocene sedimentary fluxes of organic carbon and biogenic silica in the northwestern Ross Sea, Antarctica. *Ann. Glaciol.,* **27**, 697–703.

Goodwin, I. D. and C. Zweck. 2000. Glacio-isostacy and glacial ice load at Law Dome, Wilkes Land, East Antarctica. *Quat. Res.,* **53**(3), 285–293.

Gordon, J. E. and D. D. Harkness. 1992. Magnitude and geographic variation of the radiocarbon content in Antarctic marine life: implications for reservoir corrections in radiocarbon dating. *Quat. Sci. Rev.,* **11**(7–8), 697–708.

Hedges, J. and J. Stern. 1984. Carbon and nitrogen determinations of carbonate-containing solids. *Limnol. Oceanogr.,* **29**(3), 657–663.

Heusser, C.L. 1998. The glacial paleoclimate of the American sector of the Southern Ocean: Late Glacial–Holocene records from the latitude of Canal Beagle (55° S), Argentine Tierra del Fuego. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* **141**(3–4), 277–301.

Hodell, D.A., S.L. Kanfoush, A. Shemesh, X. Crosta, C.D. Charles and T P. Guilderson. 2001. Abrupt cooling of Antarctic surface water and sea-ice expansion in the South Atlantic sector of the Southern Ocean at 5000 cal yr B.P. *Quat. Res.,* **56**(2), 191–198.

Hughes, T. 1977. West Antarctic ice streams. *Rev. Geophys. Space Phys.,* **15**(1), 1–46.

Ingólfsson, O. *and 10 others*. 1998. Antarctic glacial history since Last Glacial Maximum: an overview of the record on land. *Antarct. Sci.,* **10**(3), 326–344.

Jouzel, J. *and 11 others*. 1995. The two-step shape and timing of the last deglaciation. *Climate Dyn.,* **11**(3), 151–161.

Jouzel, J. *and 12 others*. 2001. A new 27 kyr high resolution East Antarctic climate record. *Geophys. Res. Lett.,* **28**(16), 3199–3202.

Kellogg, T.B., L.E. Osterman and M. Stuiver. 1979. Late Quaternary sedimentology and benthic foraminiferal paleoecology of the Ross Sea, Antarctica. *Journal of Foraminiferal Research,* **9**, 322–335.

Leventer, A., R.B. Dunbar and D.J. DeMaster. 1993. Diatom evidence for the late Holocene climatic events in Granite Harbour, Antarctica. *Paleoceanography,* **8**(3), 373–386.

Leventer, A., E.W. Domack, S.E. Ishman, S. Brachfield, C.E. McClennen and P. Manley. 1996. Productivity cycles of 200–300 years in the Antarctic Peninsula region: understanding linkages among the sun, atmosphere, oceans, sea ice, and biota. *Geol. Soc. Am. Bull.,* **108**(12), 1626–1644.

Licht, K.J., A.E. Jennings, J.T. Andrews and K.M. Williams. 1996. Chronology of the late Wisconsin ice retreat from the western Ross Sea, Antarctica. *Geology,* **24**(3), 223–226.

Licht, K.J., N.W. Dunbar, J.T. Andrews and A.E. Jennings. 1999. Distinguishing subglacial till and glacial marine diamictons in the western Ross Sea, Antarctica: implications for a Last Glacial Maximum grounding line. *Geol. Soc. Am. Bull.,* **111**(1), 91–103.

Masson, V. *and 13 others*. 2000. Holocene climate variability in Antarctica based on 11 ice-core isotopic records. *Quat. Res.,* **54**(3), 348–358.

Melis, R., G. Salvi, M. Dini, S. D'Onofrio and N. Pugliese. 1998. Micropaleontological aspects of some cores from the western Ross Sea (Antarctica). *Terra Antartica Reports,* **1**, [1997], 97–101.

Meyers, P.A. 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic and palaeoclimatic processes. *Organic Geochemistry,* **27**(5–6), 213–250.

Petit, J.-R. *and 18 others*. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature,* **399**(6735), 429–436.

Porter, S. C. 2000. Onset of Neoglaciation in the Southern Hemisphere. *J. Quat. Sci.,* **15**(4), 395–408.

Shipp, S.S., J.B. Anderson and E.W. Domack. 1999. Late Pleistocene–Holocene retreat of the West Antarctic ice-sheet system in the Ross Sea: Part 1 – geophysical results. *Geol. Soc. Am. Bull.,* **111**(10), 1486–1516.

Steig, E.J., C.P. Hart, J.W.C. White, W.L. Cunningham, M.D. Davis and E.S. Saltzman. 1998a. Changes in climate, ocean and ice-sheet conditions in the Ross embayment, Antarctica, at 6 ka. *Ann. Glaciol.,* **27**, 305–310.

Steig, E.J. *and 8 others*. 1998b. Synchronous climate changes in Antarctica and the North Atlantic. *Science,* **282**(5386), 92–95.

Steig, E.J. *and 7 others*. 2000. Wisconsinan and Holocene climate history from an ice core at Taylor Dome, western Ross Embayment, Antarctica. *Geogr. Ann.,* **82A**(2–3), 213–235.

Stenni, B. *and 7 others*. 2001. An oceanic cold reversal during the last deglaciation. *Science,* **293**(5537), 2074–2077.

Stuiver, M. and P.J. Reimer. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon,* **35**(1), 215–230.

Taylor, F. and A. McMinn. 2001. Evidence from diatoms for Holocene climate fluctuations along the East Antarctic margin. *Holocene,* **11**(4), 455–466.

Taylor, F. and A. McMinn. 2002. Late Quaternary diatom assemblages from Prydz Bay, Eastern Antarctica. *Quat. Res.,* **57**(1), 151–161.

Wentworth, C.K. 1922. A scale of graded clasters for clastic sediments. *J. Geol.,* **30**(5), 377–392.