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Environmental magnetic measurements of marine sediments from Antarctica: implications to paleoclimate changes during the past 15 ka[*]

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Abstract In this paper, authors report some results obtained from systematic rock magnetic measurements on Core NP95-1 and Core NG93-1 , which were collected from the Prydz Bay, Eastern Antarctica and Great Wall Bay (Maxwell Bay), Western Antarctica respectively during the 11th and 9th CHINARE and a sequence of paleoclimate variations is well established based on sediment rock magnetic properties. In Antarctica, the magnetic properties show a close linkage to paleoenvironmental variations. The Core NP95-1 well recorded several paleoclimatic events, such as Heinrich event 1, Bolling-Allerod warm period and Younger Dryas cold event. The Heinrich event 1 occurred at about 14.2 ka B. P. , Younger Dryas cold event occurred between 11.7 ka B. P. and 10.3 ka B. P. , and the boundary of Pleistocene and Holocene in Antarctica is 10.3 ka B. P.. In Holocene, two warm periods were recorded at about 10.0 ka B. P. and 6.0 ka B. P. with a little cold period between them. After 6.0 ka B. P. , two cores both recorded a cold climatic oscillation. Paleoclimate described by two cores rock magnetic measurements was simultaneously changed in Eastern and Western Antarctica during the same period two cores commonly covered.

Key words paleoclimatic variation, environmental magnetism, Younger Dryas, Heinrich event 1, marine sediment, rock magnetism, Antarctica.

1 Introduction

In 1970s, many researchers noted that the rock magnetic properties of deep sea sediments had somewhat relationship with paleoclimate changes and strove to probe the principles in them. Afterwards, many works concerning rock magnetic measure-

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ments show that there is a close linkage between magnetic parameters and paleoclimate variations, which are simply explained by co-variance of sedimentary source distribution, concentration of magnetic minerals, magnetic domain types and paleoclimate changes. Therefore, the variations of magnetic minerals and rock magnetic parameters are performed as proxies of paleoenvironmental variations and become a hotspot of marine Quaternary researches during the past a few decades. Recently, many environmental magnetic researches are done by geologists from many countries, covering deep-sea sediments, catchment sediments, loess, etc. (Robinson 1986; Oldfield and Robinson 1985; Oldfield and Yu 1994; Bloemendal *et al.* 1988; Versoub and Roberts 1995; etc.). The study of environmental magnetism during the past several years provided a specific theory and experimental procedures for understanding the paleoclimate changes using sediments' rock magnetic parameters (Versoub and Roberts 1995). With the advantages of convenience, rapidness, economy, effectiveness and non-constructive samples, rock magnetic measurements provide some new ideas and means to monitor Quaternary paleoenvironment and paleoclimate variations. Same approaches were extended to paleoenvironmental studies of terrigenous and lacustrine sediments and obtained a great number of achievements (Liu *et al.* 1994; Yu *et al.* 1995; Zhu *et al.* 1994; Han *et al.* 1995; Liu *et al.* 1995; etc.). In China, preliminary studies of correlating the paleoclimate changes with natural remanent magnetization (NRM) in the northern and southern of South China Sea were done by Chen *et al.* (1992) and Tang *et al.* (1993a). Hou *et al.* (1995, 1996a) also correlated the paleoclimate changes with proxies revealed by magnetic measurements of marine sediments taken from Northern and Southern South China Sea, and discussed the corresponding type between paleoclimate variations and environmental magnetic parameters. In the Prydz Bay, Antarctica, sediment magnetic fabric is effectively used for seeking the information of paleoenvironmental changes by Hou *et al.* (1996b). In this paper, based on rock magnetic measurements of Core NP95-1 and NG93-1, authors try to compare rock magnetic properties of marine sediments from Antarctica with past regional or global climate changes.

2 Sample collection and rock magnetic measurements

The Core NP95-1 and Core NG93-1 are collected by piston core sampler from the Prydz Bay, Eastern Antarctica and Great Wall Bay (Maxwell Bay), Western Antarctica respectively during the 11th and 9th CHINARE. Core NP95-1 was taken from the outer slope of the Prydz Bay with water depth 1960 m. The Core NP95-1 (core length 170 cm) consists of brown to greyish silty clay except for two interlayers of middle to coarse sand and middle to coarse sand containing a little gravel at depth 79～89 cm and 136～143 cm; Core NG93-1 was sampled from Great Wall Bay with water depth about 50 m and core length 83 cm, which consists of dark grey silty clay all the core. Samples for rock magnetic measurements of two cores are continuously collected from the top of the cores with 2.5 cm × 2.5 cm transparent non-magnetic cylinder plastic sample containers at an interval of 2.5 cm. One or two specimens are collected at one depth, 77 and 32 specimens were totally obtained from Core NP95-1 and NG93-1 respectively.

Rock magnetic properties of all samples are systematically measured in Paleomagnetic Laboratory of South China Sea Institute of Oceanology, the Chinese Academy of Sciences. Susceptibility and magnetic fabric measurements were performed with KLY-1 bridge-type magnetic susceptibility meter. Remanent magnetization (Mr) measurements (both NRM and Mr) were carried out with DSM-1 digital spinner magnetometer system, which was improved by Tang *et al*. (1993b). Demagnetizer was employed with GSD-1 alternating demagnetizer system, which was reconstructed with a three-axis spinner system instead of the old one-axial system(Paleomagnetic results will be published in another paper). After demagnetizing under 100 mT alternating magnetic field and characteristic remanent magnetization (ChRM) measurements, samples were set into a high direct field of 20 mT, 200 mT and -100 mT and measured remanent magnetization respectively. High direct magnetic field for isothermal remanent magnetization (IRM) was produced by an electromagnet which was monitored by a high magnetic field meter with error 2% of applied field.

3 Rock magnetic properties

3. 1 Rock magnetic properties of Core NP95-1

That distinct difference detected by downcore rock magnetic measurements of bulk sediments provided us sensitive records of sedimentary paleoenvironmental changes(Fig. 1). From the full core magnetic measurements, the value of maximum magnetic susceptibility(K) is 1000 times more than the minimum one, indicating a giant environmental changes in Antarctica during the past 15 ka. A high magnetic susceptibility layer can be almost correlated with lithological variation of sediments, which abruptly changed from greyish silty to greyish middle to coarse sand. Isothermal remanent magnetization(IRM) at 20 mT($\mathrm{IRM}_{20\mathrm{mT}}$) and 200 mT ($\mathrm{IRM}_{200\mathrm{mT}}$) also gave a markedly high value at about 80 cm, but difference was evidently measured when correlating the $\mathrm{IRM}_{200\mathrm{mT}}$ and $\mathrm{IRM}_{20\mathrm{mT}}$ at layer between 126 cm to 80 cm. On the other hand, S ratio ($S=(\mathrm{IRM}_{200\mathrm{mT}}-\mathrm{IRM}_{20\mathrm{mT}})/\mathrm{IRM}_{200\mathrm{mT}}\times 100\%$) also suggested a distinct difference between the upper and low sections of 89 cm, indicating a large variation of sediments sources and sedimentary environment at depth 89 cm from the top of the core.

3. 2 Rock magnetic properties of Core NG93-1

Core NG93-1, collected from Great Wall Bay, Western Antarctica, consists of greyish silty clay all the core, indicating a relative steady sedimentary environment, and no giant environmental change was detected by downcore magnetic measurements. In view of full-core magnetic susceptibility, all values of sample bulk susceptibilities fluctuated at the range of $6\times10^{-4}\sim9\times10^{-4}$ SI. But, one layer at a depth of about 40 cm is measured characterized by a little lowering of values of magnetic susceptibilities. And there is a somewhat difference between upper and lower sections at

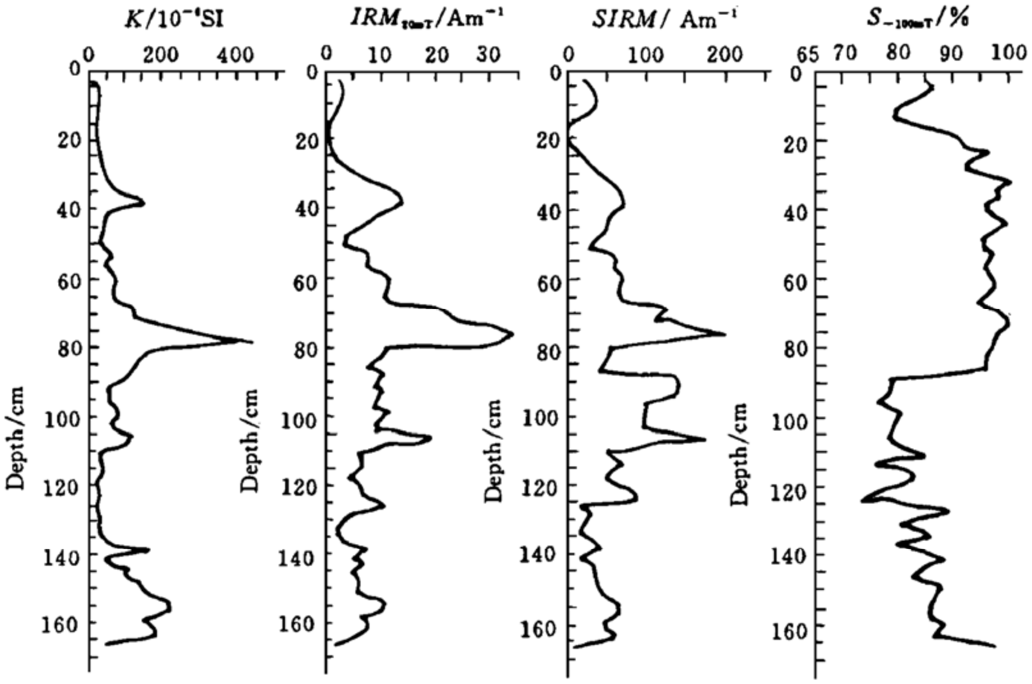

Fig. 1. Downcore rock magnetic parameters of Core NP95-1.

40 cm, that is, samples from the section above 40 cm have slightly lower magnetic susceptibilities than those from the section under the boundary of 40 cm. Although IRM_{20mT} and IRM_{200mT} have a general same trend all the core, difference is also measured in details. That the *S* ratios fluctuated in a small amplitude suggested a relatively steady sedimentary environment and sediments sources when the core was deposited(Fig. 2).

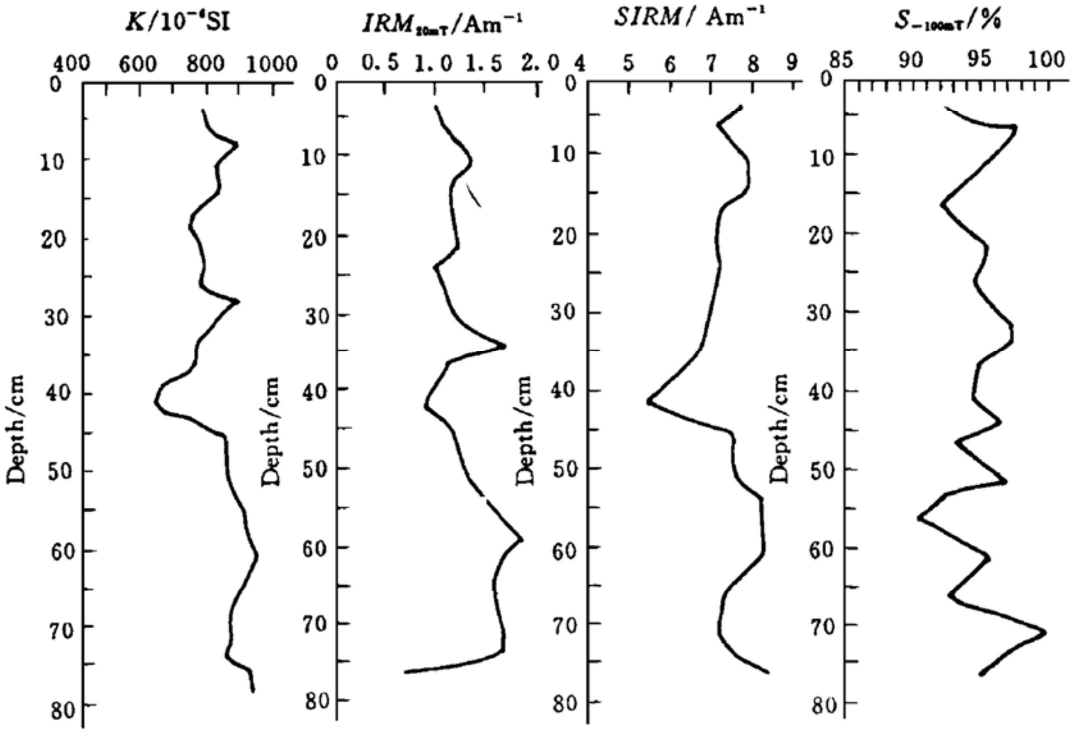

Fig. 2. Downcore rock magnetic parameters of Core NG93-1.

4 Magnetic mineral assemblage analysis

In order to determine the magnetic minerals assemblage of sediments, all samples from two cores are demagnetized progressively in GSD-1 alternating demagnetizer system with the peak alternating magnetic field of 100 mT, the remanent magnetization was measured at each step. In Core NG93-1, after systematically demagnetizing, the remanent magnetization of all samples decreased to less than 5% of NRM when they were demagnetized in 100 mT (Fig. 3), which indicated the magnetic minerals of samples were all magnetite-dominated. From that all samples have S ratios higher than 90%, it is inferred that the magnetic grains in sediments are evidently occupied by multidomain grains, which can be matched with the reducing environment in the Great Wall Bay.

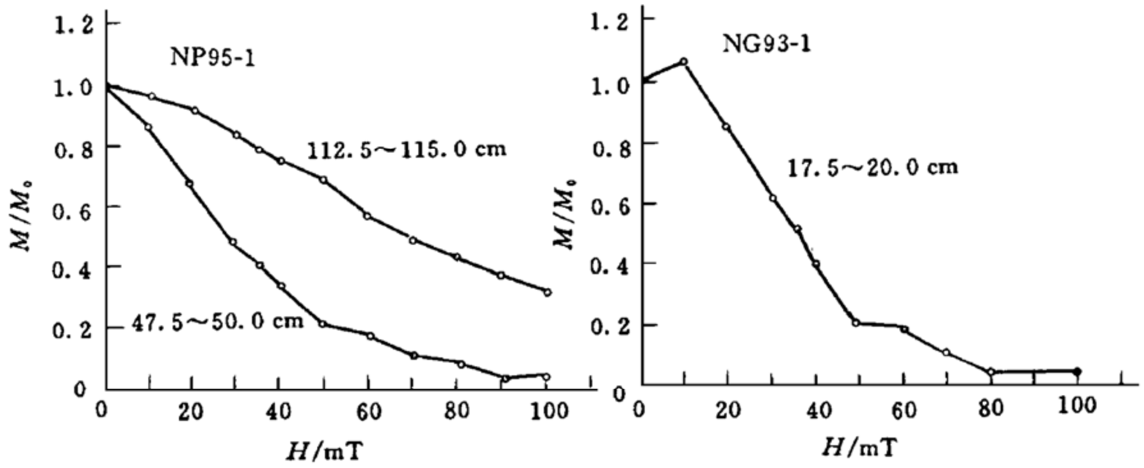

Fig. 3. Alternating field demagnetized curves of samples from Antarctica. H: Peak intensity of applied alternating magnetic field; M: Remanent magnetization; M_0: Natural remanent magnetization.

That downcore magnetic susceptibilities, $\mathrm{IRM}_{20\mathrm{mT}}$ and $\mathrm{IRM}_{200\mathrm{mT}}$ of Core NP95-1 all fluctuated in large amplitudes, indicating a large difference in magnetic mineral contents as well as in the types of magnetic minerals. The alternating field demagnetization curve (Fig. 3) shows a markedly difference of magnetic mineral properties in the upper and lower sections of NP95-1. Section above 80 cm was characterized by that the magnetization decreased to less than 3% of NRM after 100 mT alternating field demagnetized, but, by the same procedure section below 89 cm only lowered to 20%~30% of NRM. All these measurements implied that sedimentary source variations and paleoenvironmental changes occurred between the upper and lower sections of the core in the Prydz Bay. In the upper section, multidomain magnetite grains are the main magnetic mineral which bears the rock magnetic properties similar to Core NG93-1 from the Great Wall Bay. In the lower section (with depth larger than 89 cm), magnetic minerals are also mainly occupied by multidomain magnetite, but show obvious difference to the upper section, it is inferred that the proportion of high coercive magnetic minerals was high (such as single domain magnetite grains or high coercive hematite grains).

S ratios also suggested an abrupt change near 89 cm of the core, that is a sudden increase from 85% in the lower section to 95% in the upper section. At about 20 cm in depth, *S* ratios decrease to about 85% imply that a sedimentary source change occurred together with a paleoenvironmental change. Rock magnetic measurements of sediments of late Pleistocene in NP93-2 from the Prydz Bay by Tang *et al*. arrived a conclusion that the magnetic grains can be saturated magnetized in 150～160 mT direct magnetic field, and the magnetic mineral grains of sediments from the Prydz Bay are considered to be multidomain magnetite. Same experiments on 4 specimens of NP95-1 and 2 specimens of NG93-1 made by authors also came to same conclusion: that all specimens are almost saturated magnetized in 200 mT direct magnetic field illustrated the magnetic grains of two cores are all magnetite-dominated, and hematite only play a minor part to the magnetization. Consequently, the difference of sediments rock magnetic properties can be explained as difference of magnetic domain types of magnetic grains. Based on above descriptions and analysis, IRM_{200mT} can be roughly regarded as its saturation isothermal remanent magnetization(SIRM).

5 Paleoenvironmental significance of rock magnetic parameters

Many reports have been made on the relationship between rock magnetic parameters and paleoenvironmental changes(Robinson 1986; Chen *et al*. 1992; Oldfield and Robinson 1985; Bloemendal *et al*. 1988; Tang *et al*. 1993a; Hou *et al*. 1995, 1996a; etc.). Eight piston cores were obtained from Northern Atlantic of which systematically mineralogical magnetism was studied by Robinson(1986) , and some conclusions are drawn based on correlation between rock magnetic parameters and other proxies of paleoclimate: *K* (susceptibility), SIRM, ARM(Anhysteristic remanent magnetization) are of negative relations with paleoclimate variations described by $\delta^{18}O$ from foraminiferal shell with correlative coefficients of -0.704, -0.704 and -0.515 respectively, but *S* ratios are direct increased with $\delta^{18}O$. Same results are obtained by Tang *et al*. (1993a) and Hou *et al*. (1995) from South China Sea. Since sedimentary environment and geological background are different in different regions, rock magnetic parameter also bears a different physical significance in different areas. So it's natural that the relationship between rock magnetic parameter and paleoenvironmental changes is still in argument.

S ratio, as one of the most important paleoenvironmental indictors, reflects magnetic minerals assemblage , particularly the proportional composition of ferromagnetic minerals (magnetite-type) and antiferromagnetic minerals (hematite-type), but also exhibits the variations in the grain size of magnetic minerals. High *S* ratio implies a mineral assemblage of coarser (multidomain) ferromagnetic magnetite dominated. Intermediate *S* ratio give the information of either a fine magnetite dominant composition or an assemblage of small content of antiferromagnetic component, or both. Low *S* ratios are indicative of a magnetic minerals assemblage dominated by antiferromagnetic constituents (Robsinson, 1986).

In marine environment, factors, which have effects on magnetic minerals of marine sediments mainly include : terrigenous detrital deposition, volcanic actions, lithogenesis (transition from goethite to hematite), biological actions, warm water actions, etc.. Since two cores for this study are short both in length and time and no evident volcanic ash layers are detected by mineral analysis. In view of grain size and mineral composition, two cores are mainly composed of terrigenous clastics and thus magnetic materials of continental detritus input directly, so variations of magnetic properties of sediments can be regarded as representing paleoenvironment changes in two bays.

Although it has been reported in many areas that there is a good response between sediments rock magnetic properties and paleoenvironmental changes, many magnetic parameters are simply controlled by both contents and types of magnetic minerals. Consequently, many abnormal records can not be well constrained only by magnetic measurements when an abrupt changes in sedimentary lithology occurred. It's obvious that large differences of lithological properties of Core NP95-1 have added a lot of unfaithful information to paleoclimatic proxies. In order to get rid of the untrue information caused by different sedimentation rates and contents of magnetic minerals, authors chose a proportional parameter SIRM/*K* as the effective proxy of paleoenvironmental changes in these areas. For effectively eliminating the abnormal information caused by different contents of magnetic minerals, particularly, the layer when lithology was abruptly changed, SIRM/*K* is proved as a ideal proxy of past climatic changes in Antarctic.

6 Paleoclimatic variations during the past 15 ka in Antarctica

Core NP95-1 was collected at a site where water depth is 1960 m, which is larger than calcite carbonate compensate depth (CCD) in Southern Ocean. Also previous studies have shown that the paleotemperature estimated by benthic paleontological studies did not parallel to the sea-surface paleotemperature change loyally in Antarctica, for instance, the temperature of Antarctic Deep Water was a little higher in glacial period than that in deglacial period (Haowen and Jiansan , 1983), which could not response to the real paleo-situation and provide the accurate results. Therefore, rock magnetic measurement became an important and effective method to trace the paleoenvironmental information from marine sediments in areas, such as the Prydz Bay and other high-latitudinal areas in Antarctica.

Radiocarbon dating is used for effectively determining the sediments ages, 4 samples from Core NP95-1 and 2 samples from Core NG93-1 are measured in ^{14}C Laboratory, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Age results are tabulated in Table 1. But, that radiocarbon ages older than 5 ka from coretops of two cores brought many arguments about the confidence of bulk sample ^{14}C ages and a possibility of core top erosion in both two cores, though the constant ^{14}C Reservoir effect is considered to be about 400 a old in Antarctica(Zale 1994). Since the ages from top samples are older greatly than the ^{14}C reservoir effect in the global mean value (400 a), sediments erosion was taken into consideration in both top sections of two cores.

Paleoclimatic variations are obviously displayed through the paleoclimate proxies of bulk sediments *S* ratios and SIRM/*K* curves of two cores rock magnetic

Table 1. Bulk samples radiocarbon ages from Core NP95-1 and Core NG93-1*

NP95-1		NG93-1	
Depth/cm	Age/a B. P.	Depth/cm	Age/a B. P.
2. 5～5. 0	5540±720	0～2. 5	5390±500
57. 5～60. 0	7560±1900	80. 0～82. 5	7230±530
117. 5～120. 0	13810±2180		
167. 5～170. 0	15010±2100		

*:Radiocarbon ages were measured in Guangzhou Institute of Geochemistry, CAS.

measurements from both Eastern and Western Antarctica (Fig. 4), which suggested that three remarkable paleoclimate change events are recorded at depth 19 cm, 90 cm and 130 cm from Core NP95-1 respectively, particularly two cold events are presented with peak values of SIRM/K at about 95 cm and 125 cm. Interpolating radiocarbon ages on average sedimentation rates in each periods of sedimentation, two cold events were recorded at 14. 2～13. 6 ka B. P. and 11. 7～10. 3 ka B. P. In consideration with other global changes data (Keigwin and Lehman 1994; Heinrich 1988; Maslin and Shackleton 1995; etc.), they could be correlated with Heinrich event 1 and Younger Dryas cold event. Heinrich event 1 is also named Oldest Dryas Cold Event in European continent. Bolling-Allerod warm period(BAWP) (Zhang 1995) was between these cold events also with a little paleoclimatic oscillations, which was coincided with the results from Hou *et al*. (1996b) who concluded that the Younger Dryas cold event ended at 10. 2 ka B. P. in Antarctica through sediments magnetic fabric measurements of Core NP93-2 from the Prydz Bay. The Heinrich event 1 was well recorded in marine sediments of Antarctica, particularly indicating that global paleoclimate changes happened simultaneously and the Dansgaard-Oeschger (DO) cycles which had lasted for a few hundred years occurred at the same time, though absolute age errors could be brought by bulk sample radiocarbon measurements. Liu *et al*. (1996) also concluded that paleoclimate changed simultaneously in both northern and southern hemisphere through correlating the paleoclimatic proxies from Chinese Loess Plateau and Australia. Some age errors of paleoclimatic events could be seen from other authors, which are due to dating method. Warm periods occurring after 10. 3 ka B. P. served as effective indicators of the commence of Holocene and paleoclimate changed from cold period to warm one. As the results from Zhang (1990), cold period responded to an arid climate and warm period is characterized by high humidity in Antarctica. Consequently, the variations of paleotemperature and paleoprecipitation could alter the content of terrestrial materials in marine sediments, with high sedimentation rate in warm period and low sedimentation rate in cold condition in the Prydz Bay. In this study, sedimentation rates also gave evidence for the division of paleoclimatic periods. In view of the grain size of magnetic particles, high temperature divergence between equatorial and polar areas raised the atmosphere circulation and content of aeolian dust particles which in little ice age is 8 times than at present and even 20 times in last glacial maximum(Zhang, 1990). The large quantities of aeolian origin particles in sediments increased the single domain and pseudo-single domain(PSD) crystals causing low S ratios, which supports the reasonable explanations of rock magnetic measurements to paleoclimate changes. At same time, lithologic features also supported the paleoclimatic explanations, two cold events are both revealed by lithologic changes, indicating that these paleoclimatic events recorded marine sediments, also the sediments dominated by terrestrial materials are sensitively responded to the paleoclimate changes in the Prydz Bay.

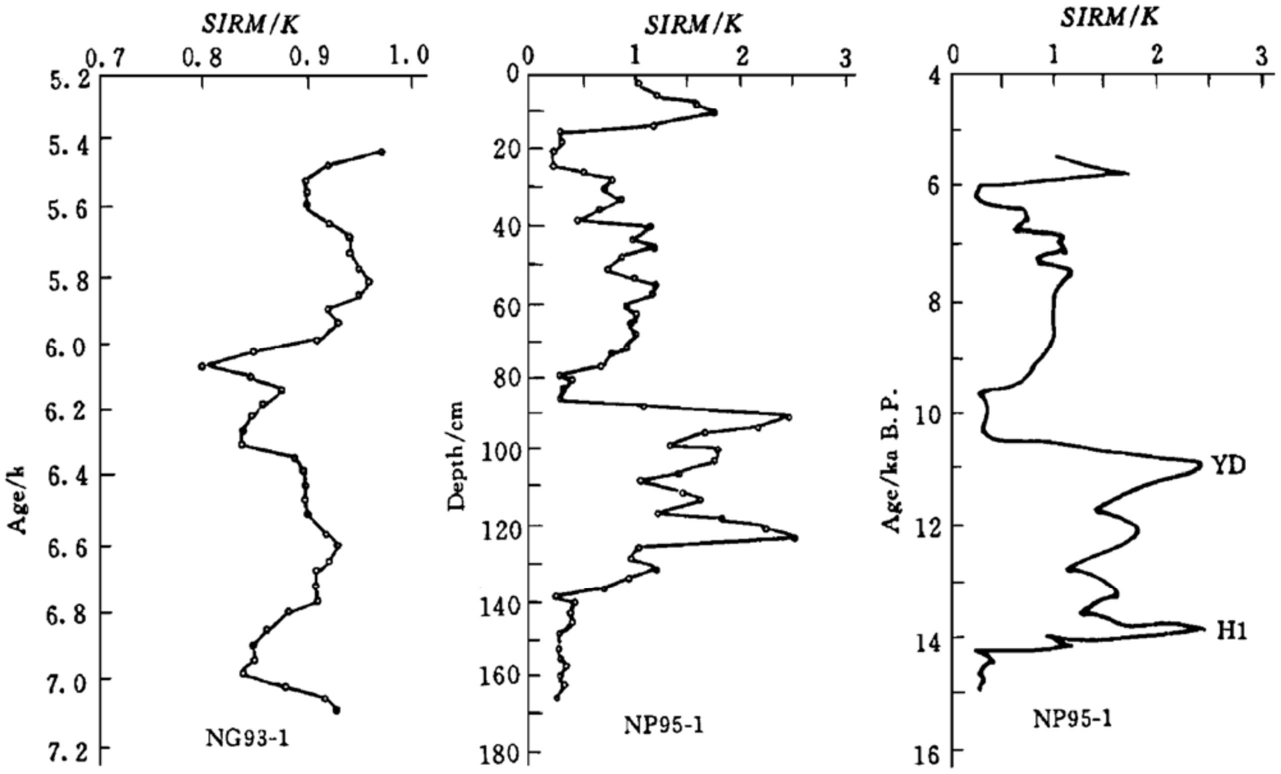

Fig. 4. Variations of rock magnetic parameters and take as the proxies to paleoclimatic changes in Core NP95-1 and Core NG93-1 from Antarctica.

Although the resolutions of two cores are largely different (the time resolution of Core NG93-1 is 50 a/sample), paleoclimatic records in Holocene from two cores both gave the same performances in the same recorded periods, i. e. , high temperatures were detected between 6. 0 ka B. P. and 6. 4 ka B. P. and a cold oscillation occurred just after 6. 0 ka B. P. , which indicated that the paleoclimate in Western and Eastern Antarctica is simultaneously changed in the same covered period of two cores. Also a temperature decrease after 9. 6 ka B. P. was recorded in Core NP95-1.

High resolution paleoclimatic curves of Core NG93-1 from the Great Wall Bay illustrated a warm period between 5. 5 ka B. P. and 7. 2 ka B. P. in which some small-scaled paleoclimatic oscillations were mixed with the cycles of several hundred years. But the dynamic background of these cycles still need to be intensely studied.

7 Conclusive remarks and discussions

Detailed rock magnetic measurements of marine sediments of Core NP95-1 and Core NG93-1 from Eastern and Western Antarctica outlined a series of paleoclimatic variations in bulk sample radiocarbon time scale from 15.0 ka B.P. to 5.5 ka B.P., which revealed the Heinrich event 1(Oldest Dryas in Europe), Younger Dryas cold event, Bolling-Allerod warm period and two short warm periods at about 10.0 ka B.P. and 6.0 ka B.P. No obvious age difference of paleoclimate changes was detected in both Eastern and Western Antarctica. That Heinrich event 1 and Younger Dryas cold event occurred at the same time as compared with results from other authors and research areas indicates the paleoclimate changes occurred globally and simultaneously.

Environmental magnetism aimed at revealing the paleoclimate changes through rock magnetic measurements, which is proved effectively, particularly in describing the outline of paleoclimate changes since Quaternary in Chinese Loess Plateau and some deep ocean sediments. But it's still difficult now to give accurate quantities of paleoclimate variation only through correlating environmental magnetic parameters with other paleoclimatic parameters because of the presence of nonlinear response of parameters to paleoclimate changes and some theoretical problems, such as the concentration of different kinds of magnetic particles and different types of magnetic crystals and their paleoenvironmental significance. Also this work is a preliminary one and more tests are still needed so as to give a more practical result.

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