PROGRESS IN NATURAL SCIENCE Vol. 14, No. 3, March 2004

Sedimentary environments of the Cenozoic sedimentary debris found in the moraines of the Grove Mountains, east Antarctica and its climatic implications*

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Received June 26, 2003; revised August 28, 2003

Abstract During the field work of the 1998 ~ 1999' s and 1999 ~ 2000' s Chinese National Antarctic Research Expedition (CHNARE) in the Grove Mountains, east Antarctica, some Cenozoic sedimentary debris are found in two terminal moraine banks over the blue ice near Harding Mount in the center of this region. All the debris are of characteristics of glaciogenic diamicton and belong to the products of the glacial movements of the East Antarctic Ice Sheet. In this paper, the authors make a detailed study on the sedimentary environments of the sedimentary debris through petrologic, sedimentological, mineralogical, and geo-chemical methods. Characteristics of their sedimentary textures and structures, grain size distributions, quartz grains' surface textures and features, together with their geochemical compositions all show that these sedimentary rocks are a kind of subglacial lodgement tills which are deposited in the ice sheet frontal area by reactions of glacial movements and glaciogenic melt water. Their palaeoenvironmental implications in revealing the retreat history of East Antarctic Ice Sheet are discussed. The authors draw the conclusion from current study that the glacial frontal of the East Antarctica Ice Sheet might have been retreated to this area during the Pliocene Epoch, which represents a warm climate event accompanied by a large-scale ice sheet retreat in Antarctica at that time.

Keywords: **Grove Mountains, east antarctica, diamicton, sedimentary environments, climatic change.**

Antarctic Ice Sheet and its dynamic evolution during the Cenozoic era are of great significance in understanding and predicting the global changes. Therefore, research subjects about how to reconstruct the glacial dynamic evolutionary history and its subsequent climatic changes in Antarctica have become one of the hottest scientific topics around the world nowadays. So far, studies upon this subject are mainly concentrated on records from ice cores and/or marine sediments[1~5] since most of the glacial records are absent in or around the Antarctic continent because of the extensive Ice Sheet cover. Evidence from the continental sedimentary records, especially from the glaciogenic sedimentary rocks in the inland of Antarctic continent, is very scarce. However, this kind of sedimentary rocks is the most important records which can provide direct evidence for the determination of the scale and time of the ice sheet expansion or retreat.

During the 15th and 16th CHNARE geological field survey upon the Grove Mountains in East Antarctica from 1998 to 2000, a certain quantity of Cenozoic sedimentary debris have been found in glacial moraine banks near the center of this area. These sedimentary rocks are of the characteristics of glaciogenic diamicton and were obviously formed by glacial movements of the East Antarctic Ice Sheet (EAIS)[6, 7]. Thus, they represented a new kind of materials in reflecting the evolutionary history of the ice sheet. In this paper, we report the preliminary results from the study on their sedimentary environments through petrologic, sedimentological, mineralogical, and geo-chemical methods, and its environmental implications are also discussed.

1 Regional backgrounds

The Grove Mountains (lat. 72°20′ ~ 73°10′S, long. 73°50′ ~ 75°40′E), about 450 km inland from the Zhongshang Station of China, is located in the east shore of the Lambert Rift. It covers an area of about 3200 km^2, in which the main part of the Grove Mountains, including Mt. Harding, Zakharoff and Wilson ridges, Davey and Black nunataks, Mason, Lambert and Bryse peaks, Gale Escarpment are dis-

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* Supported by the National Natural Science Foundation of China (Grant No. 40202034) and KOSEF, and the Ministry of Science and Technology of China (Grant No. 98-927-01-06)

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tributed within an area of about 2000 km^2. Totally, 64 isolated nunataks are exposed over the blue ice within the whole region[8] (Fig. 1), they were distributed as 5 parellel island chains extending in a direction from SSW to NNE. Generally, the geomorphic landform outline of this region dips from SE toward NW, and thus the East Antarctica Ice Sheet (EAIS) flows from the inland continent through this area in a direction of SE toward NW. It is divided into several branches in this area because of the holdback of the nunataks and subglacial mountains, and then incorporated into the Lambert Rift.

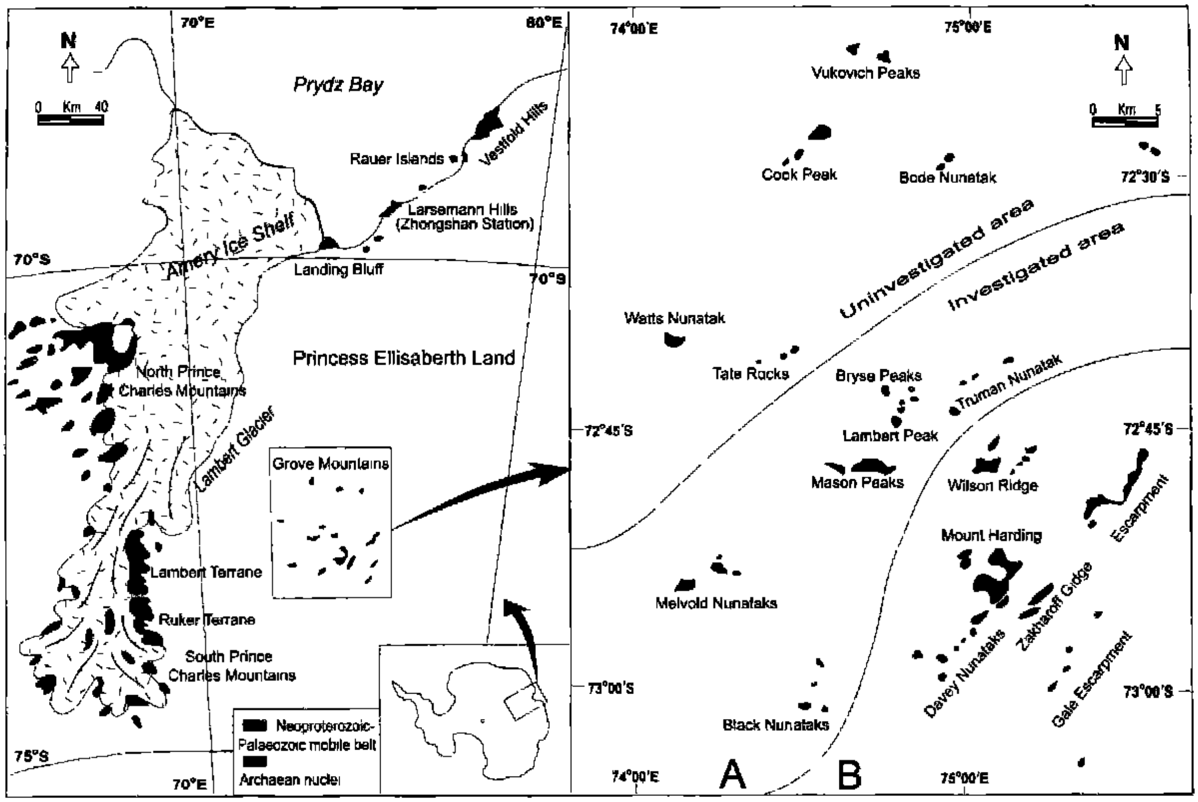

Fig. 1. The locality of Grove Mountains[8].

Geologically, the Grove Mountains is located between the largest ice-free area in the east Antarctica of the Prince Charles Mountains (PCM) and the ice-free areas of the Larsemann Hills and the Vestfold Hills exposed along the coastal line of the Prydz Bay, so it belongs to one of the very few inland ice-free areas in East Antarctica. From a large scale, it is situated in the center part of the Lambert Glacier which is considered the largest and most important glacier in the east Antarctica continent. This glacier is originated from the center part of the east Antarctica, and terminated in the Amery Ice Shelf, and it drainages an area of about 1090000 km^2[9]. According to the results from physical modeling on its evolutionary process, the Lambert Glacier is one of the primitive continental ice sheets that have been formed in the Antarctic continent with a certain scale after the cooling of the continent in about 33 ~ 34 Ma ago[10,11], therefore, its developing history has lasted almost the same time with the EAIS. As a result, the study of its evolutionary history is of great help in reconstructing the origination and developing process of the EAIS.

In recent years, detailed investigations of the Cenozoic sedimentary rocks that were responsible for the reconstruction of regional ice sheet movements in the Prydz Bay and its inland basins have been carried out in those ice-free areas mentioned above, which greatly improved the understanding of the ice sheet evolutionary history of the Lambert Glacier as well as the EAIS[12~19]. However, there had been no formal scientific investigations in the Grove Mountains before CHNARE’s 1998 ~ 1999 first field trip, and it is still poorly known how the glaciers have evolved in this area. Furthermore, because of its special situation, the Cenozoic sedimentary rocks left by the ice sheet movements in Grove Mountains are very helpful to reflect the behavior of the EAIS, and that also provides good correlations between the Cenozoic sedimentary records found in the PCM and those in the Larsemann Hills and the Vestfold Hills.

2 Sample collecting and their field outcroppings

Total 35 blocks of sedimentary rocks were collected during the last two expeditions. Most of them are directly picked from the moraines over the blue ice, while several are collected from large ice sheet debris with a diameter of more than 1 m. The sedimentary debris found in the moraines varies in size from several centimeters to several meters in diameters, and are distributed sparsely among different kinds of metamorphic and/or igneous debris (Fig. 2 (a), (b)). According to different extent of lithofication and consolidation, these sedimentary samples can be subdivided into three kinds: the first one is well to half cemented hard sedimentary rocks, the second is weakly consolidated sediments and the third is loosely unconsolidated diamictons. All of these samples are of chaotic characteristics, showing typical features left by ice sheet reactions, and belonging to glaciogenic diamicts (including both lithified diamictite and unlithified diamictons). From their geometrical outlines, these samples have been weathered to some different extent so that their surfaces are fairly smoothed. Some samples have a kind of rock varnish, some have a cover of calcite or other inorganic salts in their bottom surfaces, and all of these features are resulted from the geological actions under a dry and desert condition. However, some samples have angular forms, showing that they have experienced little weathering, and may have been brought to the ground in a short time.

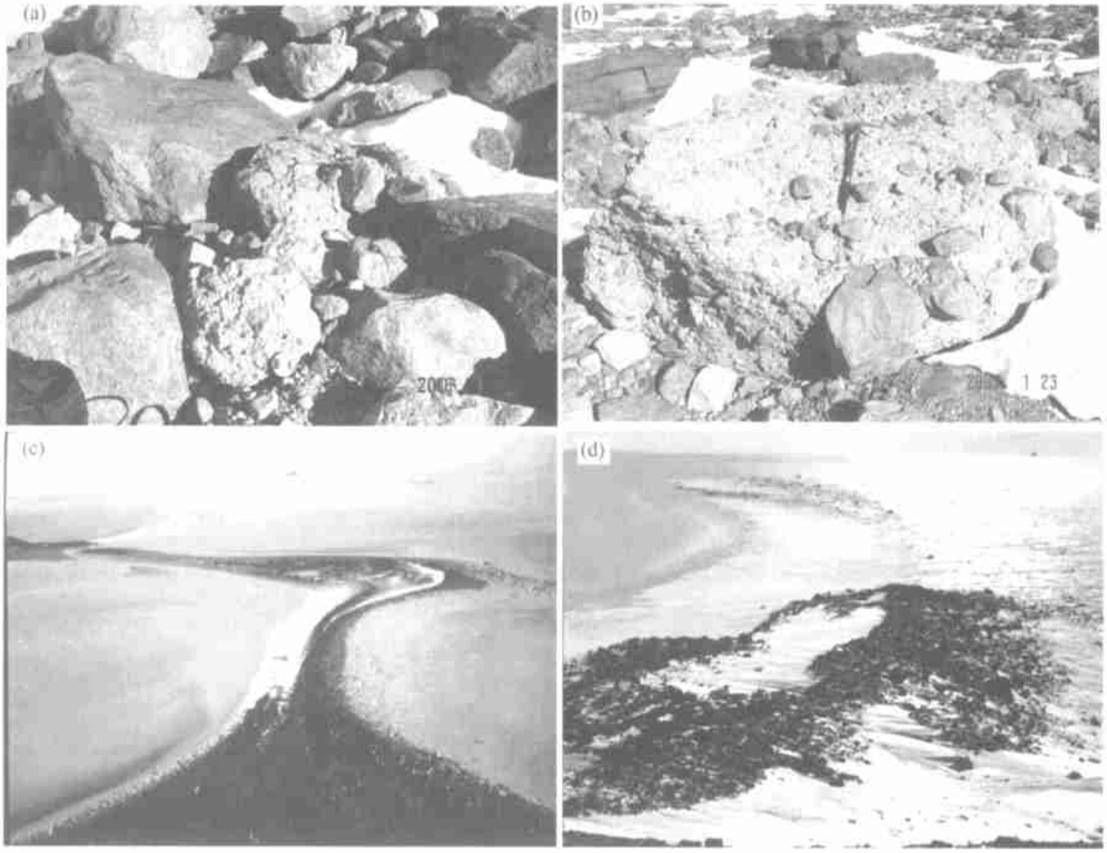

Fig. 2. The outcrops of the Cenozoic sedimentary debris and moraine banks in the Grove Mountains.

All the sedimentary samples were collected from the debris belts lying over the blue ice to the west of the Gale Escarpment and the Mt. Harding. These debris belts are composed of different kinds of iceboulders left by the movements of the Ice Sheet in this area from the Last Glacial Period. They look like moraine banks in geometrical shapes, while most of these debris belts are floating over the blue ice (Fig. 2(c)) instead of accumulating over the bedrocks as normal moraine banks. Obviously, the occurrence of large amounts of iceboulders in the Grove Mountains provides direct evidence for a much larger-scale ice sheet once happening in this area. According to the highest altitude at which the iceboulders occurred, it can be inferred that the thickness of the ice sheet at its largest scale (the Last Glacial Maximum) in this region is about 100 m higher than that of today.

There are many debris belts occurring in the whole Grove Mountain region, of which two groups can be divided according to their extending orientation (Fig. 3). One is extending almost along the flow lines of modern ice sheets in this area, while the other is perpendicular to the modern ice flows. The debris belts in the former group always begin at two flanks of some nunataks and then extend along stream lines of the ice sheets from SSW down to NNE. The iceboulders in debris belts of this group are mainly composed of the blocks of bedrocks that were scratched from the basement by the ice sheet movements as well as those dropped from surrounding nunataks. They included all kinds of the lithological components of the basement rocks in this area[8, 20]. From their geometrical shapes and moraine components, this kind of debris belts is similar to lateral moraine banks. The other group of debris belts is almost parallel to the nunatak chains of this area, i. e. approximately perpendicular to the modern ice flowing lines, and they are inevitably paved over the blue ice in the down stream areas of these chains. According to their outcroppings, the debris belts of this group can be corresponding to terminal moraine banks. Furthermore, it can be inferred from the distances between these debris belts and the exposed nunatak chains that these terminal moraine banks should have formed in different stages. The iceboulders in these debris belts are derived not only from the basement rocks found in the Grove Mountains, but also from some Cenozoic sedimentary rocks as well as some ultramafic rocks which have not been found outcropped in this area.

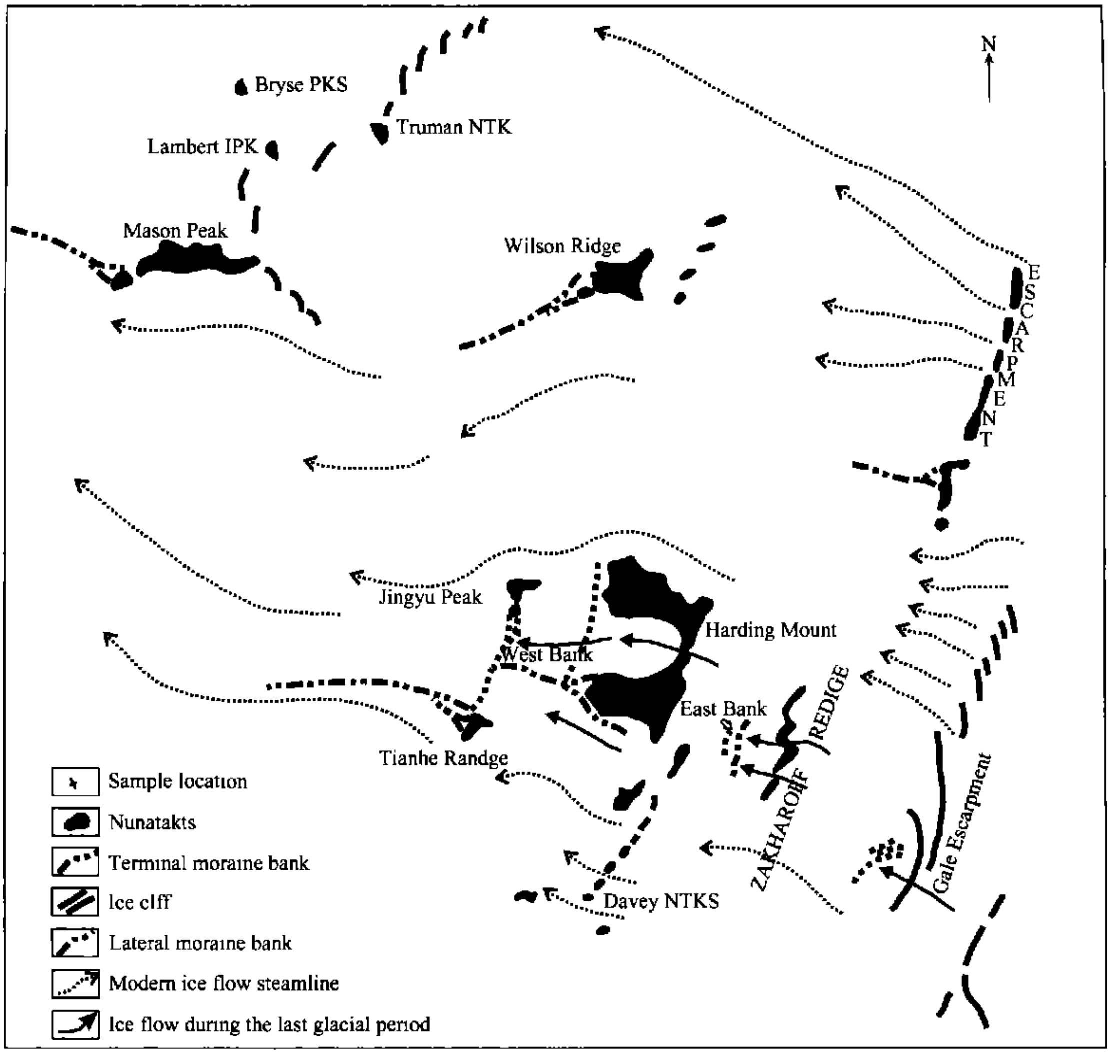

Fig. 3. The distributions of the debris belts and the modern ice flow lines in the Grove Mountains.

Near the Mt. Harding in the center part of the Grove Mountains, two debris belts were found lying over the blue ice, which was named "East-Dyke Detritus Strip" and "West-Dyke Detritus Strip", respectively. The "East-Dyke Detritus Strip" is situated between the Zhakroff Ridge and Mt. Harding, and it has a small scale compared with the "West-Dyke Detritus Strip". Geographically, its extensional orientation is almost the same as that of the Zhakroff Ridge, and it extends for about 1.5 km in length. The "West-Dyke Detritus Strip" is located to the west of the Mt. Harding, and it has a much larger scale than the "East-Dyke Detritus Strip", extending more than 10 km totally in length with an average width of about 10 m. According to its outline distributions, the "West-Dyke Detritus Strip" can be divided into three parts. The northern part is close to the Mt. Harding, and it extends for about 3 km along the west flanks of the Mt Harding in a direction from the NNE to SSW. The middle part begins from the southwestern foot of the Mt. Harding, and extends for about 2 km along the flow lines of modern ice sheet in this area in a direction from SE to NW. The southern part starts from the Jingyu Peak in the north and extends for about 2 km towards a subglacial rise of the Tianhe Ridge in the south with the same extensional orientation as the northern part. However, in the southern end of this part, the debris belts has been stretched by the movements of modern ice sheets, and it becomes one of the lateral moraine bank type debris belt extending toward the NW for more than 10 km.

Besides in some areas of the "East-Dyke Detritus Strip", the sedimentary iceboulders are mainly distributed in the sourthern part of the "West-Dyke Detritus Strip" near Jingyu Peak, where the debris belt looks like a complex ablation moraine belt, consisting of hummocky and multi-crested supraglacial moraine belts, about 500m wide and 30 m high above the blue ice surface (Fig. 2(d)). The blue ice under the moraines becomes immobile since its driving force has no longer existed because of the holdback of Mt. Harding. Therefore, the debris belt here must be a terminal moraine bank left by the ablation of an old ice sheet — most probably the ice sheet of the Last Glacial Maximum. The age dating by thermoluminescence1) shows that the subglacial tillites of this debris belt were formed about 50000 years ago, i.e. the main part of the moraine complex here was probably formed during a cold period before the Last Glacial Maximum, corresponding to stage D as Lorius et al.[21] subdivided according to the $\delta^{18}O$ curve of the ice core in Vostok.

From their distributions and preservation conditions and the components of their surrounding iceboulders, these glaciogenic diamicton sediments were transported here in a short distance, and their primitive outcropping strata must exist in the upstream area of the glacier, probably near the Gale Escarpment. However, so far no original Cenozoic sedimentary strata have been found exposed in the Grove Mountains because of the thick ice cover as well as erosions by the ice sheet movements afterwards, which brings us big problems for a further detailed study on their stratigraphical sequences and facies analysis.

3 Components of the clasts and matrix

Observed from the specimens, all these samples are yellow grey diamicts consisting of non-sorted clasts of different sizes and sandy mud matrix and showing a massive texture. Estimated by eyes, they contain 4% ~40% gravel size (ranging from boulders to pebbles) clasts and a matrix comprising more than 50% of either sand or mud (including silt and clay). Statistically, clasts contained within the diamicts are predominantly of local origin, including all the major lithologies of the basement rocks exposed in the Grove Mountains, among which the metamorphic basement-derived clasts (mainly gneiss or granulites) are the most common and the igneous clasts of granite, hornblende and quartzite subordinate. Therefore, the sources of the diamicts should be local, i.e. these sedimentary rocks were formed *in situ*. Most of the clasts within the diamicts are subangular to angular, showing that they have experienced short distance transportation.

The matrix of the diamicts is mainly composed of mud and sands, and some samples contain certain quantity of calcite cements and veins. To petrologically and mineralogically study these diamicts under microscopes, we chose the matrix of 11 consolidated to half-consolidated samples making thin sections, and statistically counted the mineral components of their sandy particles. The results show that the min-

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1) Li Xiaoli, The soil in the Grove Mountains and its environmental implications. Doctoral dissertation, The Institute of Geology and Geophysics, Chinese Academy of Sciences, 2002.

eral constitutions in all the 11 samples are generally similar, in which the metamorphic and granitic detritus is predominant, accounting for about 50% ~ 70%; the feldspar and quartz are subordinate, accounting for about 15% ~ 50%; and a few amounts of dark minerals (hornblende and pyroxene) also occurred. According to the EMS analysis upon the compositions of the fine cementing minerals in the matrix, there are two kinds of cementation in these sedimentary debris. One is cemented by calcite, whose average chemical compositions are as follows: SiO_2 0.59wt%, Al_2O_3 0.14wt%, TiO_2 0.01wt%, FeO 0.22wt%, MnO 0.10wt%, MgO 0.52wt%, CaO 54.89wt%, totally 56.65wt%; the other is cemented by clay, whose average chemical compositions are: SiO_2 33.43wt%, Al_2O_3 10.36wt%, TiO_2 1.78wt%, Cr_2O_3 0.104wt%, FeO 8.47wt%, MnO 15.85wt%, MgO 3.58wt%, CaO 3.61wt%, Na_2O 0.83wt%, K_2O 2.99wt% and NiO 0.23wt%. The sedimentary rocks cemented by these two types of mineral are quite different in their consolidations: those that cemented by calcite are fairly hard and lithofied, the other are quite loose and unlithofied.

From the above analysis upon their textural characteristics, mineral components of their clasts as well as matrix, these sedimentary rocks show a very bad textural and compositional maturity, which is similar with the characteristics of typical glacial deposits. Furthermore, these sedimentary rocks may belong to several different lithological units formed at different time.

4 Geochemical compositions

Geochemical compositions of sedimentary rocks are not only controlled by their source materials, but also closely related to the climatic and environmental conditions under which they are formed. Therefore, we can get useful information from the geochemical compositions of sedimentary rocks to reflect their depositional environments and palaeo-climatic conditions[22,23]. Total 7 samples were selected from the sedimentary debris for geochemical analysis. Before measuring, we first picked out the gravel clasts, then powdered the matrix of each sample to less than 200 mesh, and disposed all the samples according to the routine processes in laboratories. The major elements and trace elements were measured in the Institute of Geology, Chinese Academy of Sciences by the XRF and ICP-MS, respectively. The results are shown in Table 1.

Table 1. The geochemical compositions of major elements (%) and some trace elements (WB/$\mu g \cdot g^{-1}$)

Sample	SiO_2	TiO_2	Al2O$_3$	FeO	Fe2O$_3$	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	LOI	Total	CIW
S1501	43.98	0.51	8.45	1.25	1.81	0.12	21.09	1.36	2.17	1.27	0.17	17.17	99.35	27.43
S1502	69.58	0.51	12.49	1.87	3.06	0.10	3.11	1.72	2.09	2.31	0.1	2.67	99.61	69.74
S1503	25.9	0.35	5.35	0.94	1.33	0.12	35.24	1.10	1.42	0.97	0.15	27.28	100.2	12.87
S1504	67.39	0.77	12.23	1.91	3.4	0.10	2.67	2.34	2.70	1.58	0.16	4.48	99.73	74.21
S1505	67.98	0.70	12.62	1.74	3.12	0.08	2.59	2.20	2.82	1.80	0.17	3.86	99.68	74.19
S1506	34.67	0.43	7.62	0.86	2.02	0.11	27.32	1.46	1.88	1.38	0.18	21.78	99.71	20.98
S1511	66.64	0.71	12.8	1.96	3.29	0.12	2.91	2.09	2.73	2.27	0.2	3.78	99.5	71.19

(continued)

Co	Ni	Cu	Rb	Sr	Cs	Ba	Zn	La	Ce	Pr	Nd	Sm	Eu	Th	Zr	Sr/Ba
9.46	17.56	18.89	83.95	267.19	0.72	754.91	45.41	107.68	116.30	19.57	35.91	11.75	1.74	23.80	177.74	0.35
18.31	28.46	30.71	66.15	217.45	1.15	639.48	68.02	37.60	80.76	9.27	55.25	7.57	1.33	16.35	104.79	0.34
6.26	13.31	13.46	59.94	1916.90	0.43	563.64	38.04	84.94	130.64	15.97	37.65	8.40	1.02	32.93	222.94	3.40
17.64	40.91	38.86	103.24	279.76	1.59	844.92	75.85	41.87	88.63	10.06	35.38	8.07	1.53	14.88	151.62	0.33
17.51	39.34	34.69	98.15	276.00	1.47	805.02	70.52	41.26	85.46	9.31	80.88	7.85	1.51	14.97	157.53	0.34
11.43	13.00	19.38	97.19	318.02	0.69	704.71	46.92	159.19	99.27	23.49	32.85	10.99	1.55	19.18	129.13	0.45
13.58	24.02	29.19	64.66	155.92	0.89	778.13	52.34	37.58	51.69	9.01	68.97	6.55	1.25	13.08	129.29	0.20

According to the major element contents in Table 1, 7 samples are quite different from each other, among which two groups can be subdivided. One group, including S1501, S1503, and S1506, has a high content in CaO, and is relatively low in SiO_2, Al_2O_3 and FeO, which are cemented mainly by calcite; while the other group has a contrary major element compositions, i.e. a low content in CaO and high SiO_2 and Al_2O_3 contents, which are cemented mainly by clay. Furthermore, the chemical index of weathering (CIW) calculated from these data (according to Harnouis[22]), which are used to reflect the different degrees of the weathering and erosion of the source rocks, is also quite different between these two groups. The results show that the first group has a much lower CIW value than the second one, which means that their source rocks have experienced a high degree of weathering and erosion compared with the other group.

Similar results can also be drawn from the characteristics of their trace element compositions shown in Table 1, of which two groups of samples cemented by calcite or clay, respectively are quite different in their mobile (e.g. Rb, Sr, and Cs), immobile (e.g. Co, Ni, Cu, Th, U, etc.) and rare earth trace elements contents.

All the geochemical compositional differences in the 7 samples shown above cannot be simply attributed to the differences in their source rocks, however, it may also result from the differences in their sedimentary environments and weathering conditions, i.e. they may come from different lithological units.

5 Surface textures of quartz sand grains

The surface textures and features of quartz grains are mainly controlled by different types of geological factors which act upon the particles during their transportation and sedimentation and the distances that they are transported before final deposition, therefore, they are useful markers in distinguishing different kinds of sedimentary environments[24~27].

Quartz grains of similar sizes (ranges from 0.25 to 0.5 mm in diameter) were picked out under a microscope, and then separated by chemical processes from two samples out of the two groups with different cementations, respectively. Observed under an electricity scanning microscope (ESM), their shapes and surface mechanical structures were subdivided and counted (see Table 2).

According to their roundness, the shapes of the quartz grains from the two samples can be subdivided into angular, subangular, sub-rounded and rounded ones, respectively. Of which the angular grains are the most common, with a frequency about 70% ~ 85%; the subangular ones are the second, accounting for about 10% ~ 20%; and the sub-rounded grains accounts for about 5% ~ 10%. The mechanical textures are very common in the surfaces of the quartz grains, among which such structures as the oriented striations, V-shaped pits, conchoidal fractures, etc., which are generally considered to be the markers of glacial actions, are very abundant, they occurred in more than 50% of the total particles in statistics. All these characteristics of the quartz grains show that the glacial movements play an important role in their formation, thus we can infer that these sedimentary rocks are formed in glacial environments.

Table 2. Shapes and surfacial characteristics of quartz grains in sedimentary rocks

Sample	Total grains	Particle shape				Surfacial features			Rock name
		Sharp angular	Angular	Subangular r	Subrounded	Fractures s	Striations	Hit pits	
S1502	23	13	7	2	1	19	19	11	Muddy gravel
S1505	11	5	3	2	1	7	6	4	Muddy gravel

6 Grain sizes characteristics

Grain size analysis is helpful in determining the sedimentary environments because the characteristics of grain sizes in sedimentary rocks are very sensitive to the dynamic conditions of the medium in which the sedimentary particles are transported or deposited[28, 29]. Therefore, four samples (S1501, S1502, S1503 and S1504) are selected from the above sedimentary debris, and their grain size distributions are analyzed under an IBAS-2000 image analysis instrument in the China University of Geology. All the grain size parameters are listed in Table 3, and their log-probability plots are shown in Fig. 4.

Table 3. Grain size distribution characteristics of the Cenozoic sedimentary rocks

Sample	Curve type	M_z(Φ)	σ_1(Φ)	Sk_1(Φ)	Kg(Φ)	Rock name	Gravel contents (%)
S1501	polymodal	3.24	0.88	−0.66	1.08	Gravel muddy sandstones	10
S1502	polymodal	3.46	0.89	−1.02	1.09	Gravel muddy sandstones	15
S1503	polymodal	3.32	0.88	−0.87	1.07	muddy sandstones	2
S1504	polymodal	3.48	0.63	−0.40	3.20	muddy sandstones	4

Note: The parameters are calculated according to Folk and Ward (1974)[29].

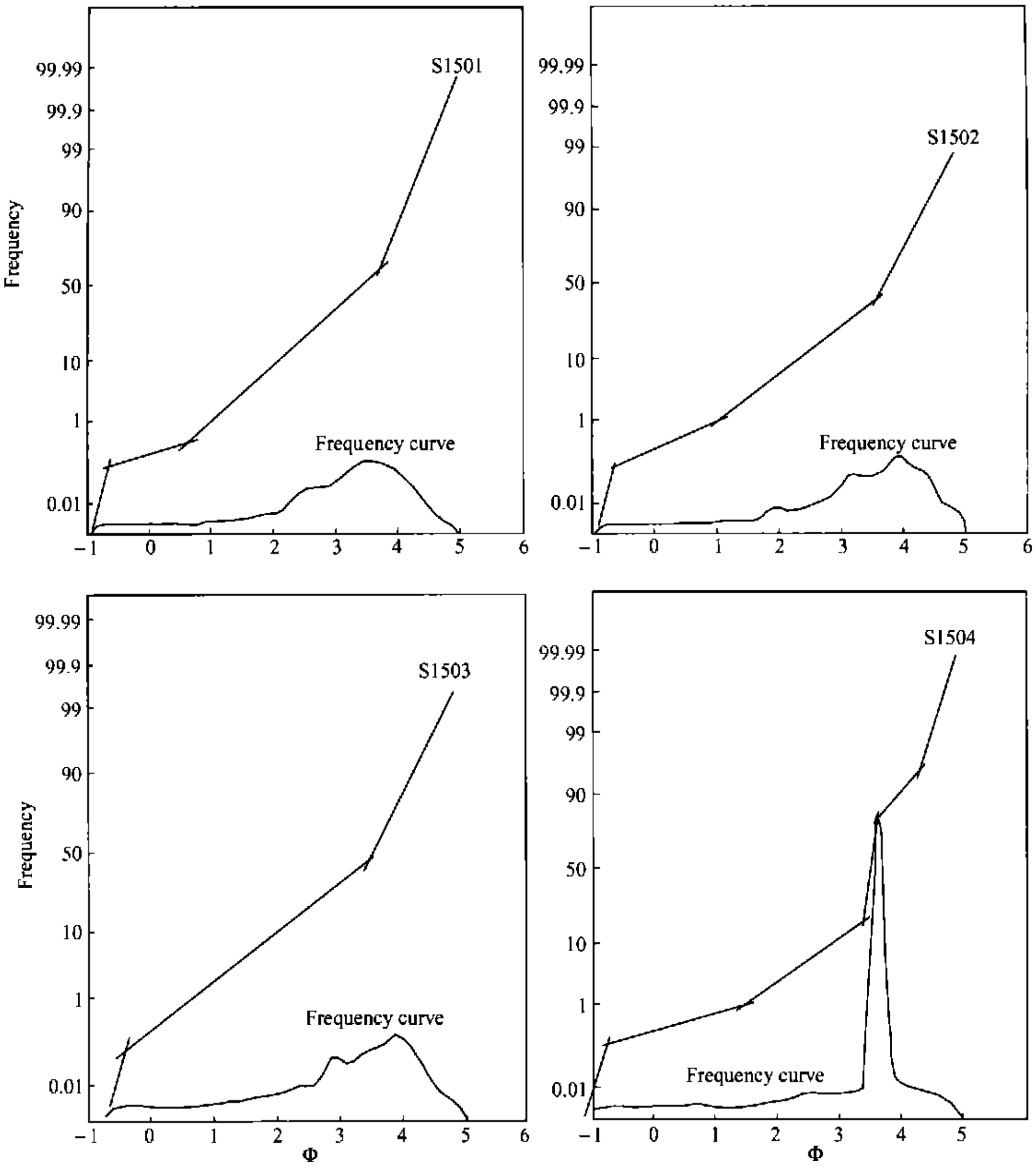

Fig. 4.

It should be pointed out that the contents of gravel size clasts are separately estimated in specimens before making thin sections for grain size analyses under the instrument because they are too large to be measured by this method. Therefore, only sand and clay sizes of the grains in the matrix are measured and counted by the instrument, i.e. the above parameters and plots only reflect the grain size distributions of the matrix of these samples. For subglacial tills, their sedimentary grains are normally composed of three distinct populations: the coarse particles of lithic or rock fragments, the mineral grains produced by crushing of the rock fragments, and the fine particles produced by the abrasion of individual minerals[30]. In this paper, however, the grain size distribution plots mainly reflect the later two populations of the grains.

From the parameters shown in Table 3, the values of mean size (M_z) of the four samples are very similar, all at about $3\Phi \sim 4\Phi$ (0.063 mm ~ 0.125 mm); the skewness (SK_1) of the samples all belongs to minus one, indicating fine particles as the dominative ones. As for the standard deviation (σ_1) and kurtosis (Kg), which represent the degree of sorting and the dynamic conditions of the medium, respectively, there are some differences between S1504 and the other three samples: the former has a much higher degree of sorting than the latter (similar characteristics can also be observed from some other samples in specimen), which is probably caused by post-depositional modifications of the grain size distribution by flowing water or changes of their medium dynamics during the processes of transportation and sedimentation. The frequency curve and Log-probability plot of S1504 in Fig. 3 also show the same characteristics of a post-depositional modification by flow water which may be related to glacieofluvial actions upon it.

From the frequency curves shown in Fig. 4, all the four samples have a wide range of polymodal grain size distribution, which shows multi-source originations of the sedimentary particles. If taken into account the contents of gravel clasts in the rocks, the characteristics of their polymodal distributions are more obvious, which is similar to those of typical subglacial tillites.

The Log-probability plots in Fig. 4 are all composed of several gently sloped segments, showing similar characteristics as some typical tillites[25] around the world. In general, they can be subdivided into three or four segments, with a coarse truncation point at -0.5Φ, and a fine one between $3\Phi \sim 4\Phi$, which indicates that all the three kinds of particle movements (traction, saltation and suspension) exist together during their transportation while suspension is the dominative transporting mode. The polymodal grain size distributions of all the samples reflect multi-sources as well as multi-medium reactions to their sedimentary particles in transport by the glacier. To be more concrete, sedimentary grains in these samples might be carried by flowing water melted from the ice sheet, high density currents of traction carpets formed at the base of ice sheets, or within or on the surface of the solid bodies of ice sheets. All these particles in transport by the glacier may be finally deposited within, beneath or beyond of the glacier. However, the occurrence of post-depositional modifications as shown in S1504 indicates that glaciofluvial actions may also exist in this system. Such a complex multi-medium dynamic conditions should be existed only in the margin of a warm-based glacier. Therefore, it can be inferred that these diamicts are formed in glacial frontal environments.

7 Implications and discussion

7.1 Sedimentary environments

Because of the limitation by the very rigorous geographic conditions in the Grove Mountains, it is impossible to systematically study the sedimentary environments of these diamicts from stratigraphic sequences in the field. Instead, we have tried to obtain as much information as possible from the studies upon the samples collected and the large debris found in this area, esp. the study from view points of their microscopic characteristics, to reflect their sedimentary environments as well as the climatic conditions. However, some basic conclusions as follows can be drawn from the above studies: (1) the sedimentary debris found in the Grove Mountains are of typical characteristics of glaciogenic diamicts, although they may be formed at different stages during the glacial movements of the ice sheet since they have different degrees of lithofication and different geochemical compositions; (2) the clasts in these diamicts are mainly from subglacial tills, whose lithologies are similar to those exposed in the Grove Mountains, therefore, their source rocks are supposed to be mainly from local; however, it cannot be excluded that there are some extraneous debris as part of their sources since the samples we studied are not enough; (3) disclosed by the grain size analysis together with quartz grain surface features, the sedimentary particles of these diamicts are transported and deposited by multi-media which include flowing water melted from the ice sheet, high density currents at the base of ice sheets and the solid bodies of ice sheets with complex dynamic conditions from different parts of the ice sheet; furthermore, some post-depositional modifications by flowing water might happen as shown in S1504; and (4) the depositional environments of these sedimentary debris should be in glacial marginal areas.

In general, these glaciogenetic diamicts are formed by rock fragments or mineral detritus plucked and entrained by the glacier during its development, and then deposited by the melt out of the glacier during the warm period of time in the ice sheet frontal depositional environments.

According to Reading[29], the glacial depositional environments can be subdivided into 3 types: (1) the subglacial environments; (2) on or within the glacier to the glacial frontal environments; and (3) subaqueous environments; whose sedimentary units are massive tillites, layered sandstones and fine particle sedimentary rocks, respectively. Among which the massive diamicts formed in the subglacial environment are the typical products of a glacier sedimentation, and they have such characteristics as follows:

(1) a kind of diamicts with massive block textures; (2) without any bedding or stratification structure; (3) it can be traced for several kilometers long in the field; (4) about several to tens of meters in thickness; and (5) it includes all kinds of rock fragments and mineral detritus with some typical structures left by glacial abrasion. Therefore, most of the sedimentary debris found in the Grove Mountains are similar with the massive diamicts formed in the subglacial environment; however, some fine particle sedimentary rocks such as sandstones modified by post-depositional flowing water may belong to layered sandstone unit. The association of such lithological units found in these samples indicates that they should be formed in subglacial and glacial marginal environments located in the glacial frontal area.

7.2 Geological and palaeoenvironmental implications

Although many achievements about the ice sheet and climatic evolution in Antarctica have been obtained during the past 4 decades, the systematical stratigraphic frameworks of the Cenozoic strata in Antarctica have not been completely set up so far because all the marine and terrestrial sedimentary records related to this subject are dispersedly distributed in or around the continent. Therefore, some key problems about the evolution of the ice sheet are still in great dispute, among which there are some basic controversies such as when the incipient Cenozoic ice sheet began to develop[31, 32], if the evolutionary processes of the ice sheet were dynamic or stable[32, 33], and if there was a large-scale warm climatic event during the Pliocene[34, 35]. Those problems have greatly constrained a deeper understanding of the subject and brought great limitations on how to reconstruct the glacial evolutionary history.

For a long time, the Sirius Group, which is widely distributed in Trans-Antarctic Mountains and its surrounding basins, has been considered the most famous as well as the most controversial Pliocene strata[35~39] in Antarctic continent. This group is composed of a series of glaciogenic and nonglaciogenic units of compact sedimentary rocks overlapped the older Tertiary strata with a unconformity surface. Special focus upon its depositional environments, formation time and the sources of the re-deposited microfossil assemblages found in these strata and its climatic implications (in review by Stroven et al.[33]) are greatly disputed after the finding of the reworked microfossil assemblages inside them by Harwood[36, 37]. In general, the significance of the finding of this Group lies in the followings: (1) it confirmed that Pliocene glaciogenic sedimentary strata do exist in the inland of the Antarctic continent, and furthermore, the wide distributions of this group indicate that they are products of a large-scale ice sheet instead of the local alpine glaciers, therefore, they can reflect the evolutionary history of the whole ice sheet; (2) the microfossil assemblages of the diatom and pollen found in these strata provided not only some definite constraints on the depositional time of these strata, but also provide good materials for the analysis on its sedimentary environments; and (3) the palaeoclimate reflected by the fossil of *Nathofagus* found in this strata shows that the temperature at that time is much higher than that of today[40], which presented a warm climatic event and a large-scale ice sheet retreat.

Recently, a lot of geological field surveys have been carried out in the areas around the Lambert Glacier and Amery Ice Shelf to disclose the evolutionary history of the East Antarctic Ice Sheet. In Northern Prince Charles Mountains, thick Cenozoic glaciomarine sequences — the Pagodroma Group have been well studied in the Amery Oasis and on Fisher Massif[15, 16]. These strata were deposited in Fjordal environments in the Lambert Graben during a time period from Miocene to Pleistocene[12, 17, 18]. The Pangodroma Group was considered as a firm recorder for a much reduced East Antarctic Ice Sheet[15, 16, 19].

The Sorsdal Formation found in the coastal areas of the Prydz Bay is proved to be another notable Pliocene strata which are closely related to the dynamic evolution of the East Antarctic Ice Sheet[13~15]. In Vestfold Hills, an *in situ* 9-m-thick section of horizontally bedded sequence of marine diatomaceous siltstones and sandy diamictites with abundant and diverse marine faunas from the interval 4.2 to 3.5Ma is outcropped in the Marine Plain area. At Stornes Peninsula in Larsemann Hills, a small area containes a 40-cm-thick unit containing well-preserved Pliocene benthic foramininifera and diatoms which indicate that this deposit is 3~2Ma old. Sediments near Casey Station in Windmill Islands formed 2~1Ma according to the diatoms found in it. These coastal sequences of Cenozoic sediments are supposed to be deposited in a shallow marine to intertidal environment during intervals of relatively warm climatic conditions[13].

A large amount of reworked micro-fossils are found in the Pagodroma Group and Sorsdal Formation[14, 15], which make them the same important Pliocene strata as the Sirius Group in Trans-Antarctic Mountains and thus much attention has been paid to them recently[38, 39].

In Southern Charles Mountains, recent field works by Australian National Antarctic Research Expedition (ANARE) have shown that thick Cenozoic glaciogenic strata consisting largely of matrix-rich diamicts with interbedded sands occurred in several places of this area[41, 42]. These sedimentary rocks are supposed to be deposited at terrestrial environments by glacial movements. Although the interpretation of the definite sedimentary environments and formation time of these lithostraigraphical Cenozoic strata is not so clear, the implications from these sedimentary records are apparently of great significance in reconstructing of the glacial history of the east Antarctic Ice Sheet.

Therefore, in such a geological section from the continental shelf of the Prydz Bay through coastal areas of Larsemann Hills and Vestfold Hills to the inland Charles Mountains, the Pliocene sedimentary facies are gradually changed from deep sea pelagic marl (the distal facies) through fjord or intertidal to terrestrial glacial environments (proximal facies). The spatial distribution of these sedimentary facies shows that the frontal of the EAIS should be located in the far inland areas of the continent, which implies a much smaller ice sheet accompanied with a warm climatic event together with a large-scale ice sheet retreat at that time.

No matter from the degrees of lithofication or the sedimentary characteristics of the sedimentary rocks found in the Grove Mountains, they are similar to those Pliocene strata mentioned above. Furthermore, the pollen assemblages (another paper in preparing) separated from these sedimentary samples contain the same components of *Nothofagus* as found in the Sirius Group in Trans-Antarctic Mountains. Therefore, these sedimentary rocks may also be formed in Pliocene, and if so, the extensive glaciogenic strata also exist in Lambert Glacier drainage area as the Sirius Group in Trans-Antarctic Mountains, which confirms a large-scale ice sheet retreat event in the Antarctica.

According to the available data observed at present time, the average daily temperature in the Grove Mountains is −18.5 ℃ in January, ranging from −13.1 to −22.6 ℃, and the average daily snow temperature is −17.9 ℃, i.e. the highest temperature in summer is far below zero, therefore, it is impossible to form sedimentary rocks in such a condition. If the ice sheet had been melt for the formation of the diamicts, it should be 15 ℃ higher than the temperature of today, that means that a very obvious warm event must happen, which will result in great impacts for the sea level rising. Therefore, the implications of the sedimentary rocks found in the Grove Mountains represent a giant scale of ice sheet retreat as well as a big warm climatic event during the Pliocene era.

As we know, the Grove Mountain area is located about 500 km inner to the south polar from the boundary of the Ice Sheet now days. If the sedimentary rocks found here are formed *in situ*, it can be inferred that the Ice Sheet must have retreated to this area in the Cenozoic era, which means that once the Ice Sheet frontal zone has retreated at least more than 500 km from its present location. Under this situation, the ice sheet of the Antarctic might either be totally collapsed or greatly reduced, which will give rise to at least tens of meters sea-level arising. Such an effect to the global environments is enormous.

Acknowledgement The field work was carried out during the 1998 ~ 2000 Chinese National Antarctic Research Expedition. Logistical support by the Antarctic Administration of China and the Chinese Academy of Sciences. We thank Ju Yitai, Yu Liangjun and Li Jinyan for sample collecting.

References

1 Petit, J. R. et al. Climate and atmospheric history of the past 420, 000 years from the Vostok ice core, Antarctica. Nature. 1999, 399: 429 ~ 436.

2 Domack, E. et al. Late Quaternary sediment facies in Prydz Bay, East Antarctica and their relationship to glacial advance onto the continental shelf. Antarctic Science, 1998, 10(3): 236 ~ 246.

3 Pope, P. G. et al. Late Quaternary glacial history of the northern Antarctic Peninsula's western continental shelf: Evidence from the marine record. In: Elliot, D. H. (ed.), Contributions to Antarctica Research III. Washington D. C.: American Geophysical Union, Antarctic Research Series, 1992, 57: 63 ~ 91.

4 Anderson, J. B. et al. Radiocarbon constraints on ice sheet advance and retreat in the Weddell Sea, Antarctica. Geology, 1999, 27(2): 179 ~ 182.

5 Labeyrie, L. D. et al. Melting history of Antarctic during the past 60000 years. Nature, 1986, 322: 701 ~ 706.

6 Liu, X. H. et al. The first discovery of the Cenozoic sedimentary rocks in the modern moraines of the Grove Mountains, East Antarctica. Geologic Scientia (in Chinese), 2001, 36(1): 119 ~ 121.

7 Fang, A. M. et al. The preliminary study upon the Cenozoic sedimentary rocks found in the tills of the Grove Mountains, east Antarctica. In: (eds.) Hong, S. et al. The role of Antarctic Sciences in the Global Environmental Research-The 8th International Symposium of on Antarctic Science, 2001, Seoul, Korea, 2001, 65~66.

8 Liu, X. H. et al. Geology of the Grove Mountains in East Antarctica. Science in China (Series D), 2003, 46 (4): 305~316.

9 Allison, I. F. The mass budget of the Lambert Glacier drainage basin, Antarctica. J. Glaciol., 1979, 22: 223~235.

10 Budd, W. et al. Results from the Amery Ice Shelf project. Ann. Glaciol., 1982, 3: 36~41.

11 Barker, P. F. et al. Ice sheet history from Antarctic continental margin sediments: the ANTOSTRAT approach. Terra Antarctica, 1998, 5: 737~760.

12 Labia, A. A. et al. Cenozoic Glacial-Marine Sediments from the Fisher Massif (Prince Charles Mountains). In: The Antarctic Region: Geological Evolution and Processes (ed. Ricci C. A.). In: Proceedings of 7th International Symposium on Antarctic Earth Science. Siena: Terra Antarctica Publishers, 1997, 977~984.

13 Quilty, P.G. Late Neogene sediments of coastal east Antarctica-an overview. In: Recent Progress in Antarctic Earth Science (ed. Yoshide, Y.). Tokyo: Terra Scientific Publishing Company, 1992, 699~705.

14 Harwood, D. M. et al. Diatom biostratigraphy and age of the Pliocene Sorsdal formation, Vestfold Hills, east Antarctica. Antarctic Science, 2000, 12(4): 443~462.

15 Whitehead, J. M. et al. The stratigraphy of the Pliocene-lower Pleistocene Bardin Bluffs Formation, Amery Oasis, northern Prince Charles Mountains, Antarctica. Antarc. Sci., 2001, 13(1): 79~86.

16 McKelvey, B.C. et al. A geological reconnaissance of the Rodak Lake area, Amery Oasis, Prince Charles Mountains. Antarctic Science, 1990, 2(1): 53~66.

17 McKelvey, B. C. et al. The Dominion Range Sirius Group - A record of the Late Pliocene-Early Pleistocene Beardmore Glacier. In: (eds. Thomson, M. R. A. et al.). Geological Evolution of Antarctica, Cambridge: Cambridge University Press, 1997, 675~682.

18 Hambrey, M. J. et al. Neogene fordal sedimentation on the western margin of the Lambert Graben, East Antarctica. Sedimentology, 2000, 47: 577~607.

19 Hambrey, M. J. et al. Major Neogene fluctuations of the East Antarctic Ice Sheet: Stratigraphic evidence from the Lambert Glacier region. Geology, 2000, 28(10): 887~892.

20 Yu, L. J. et al. Geochemical characteristics of meta-mafic rocks of the Grove Mountains, East Antarctica. Acta Petrological Sinica (in Chinese), 2002, 18(1): 91~99.

21 Lorius, C. et al. A 150, 000-year climatic record from Antarctic ice. Nature, 1985, 316: 591~596.

22 Harnouis, L. The CIW index: A new chemical index of weathering. Sed. Geol., 1988, 55: 319~322.

23 Xie, Y. Y. et al. Some geochemical features of Quarternary sediments from the Vestfold Hills, Antarctica. In: (ed. Zhang, Q. S.), Studies of Late Quaternary Geology and Geomorphology in the Vestfold Hills, East Antarctica (in Chinese). Beijing: Science Press, 1985, 180~195.

24 Wang, Y. et al. Atlas of Structural Features of the Quartz Grains. (in Chinese). Beijing: Science Press, 1985, 4~10.

25 Pye, K. Grain surface textures and carbonate content of Late Pleistocene Loess from western Germany and Poland. Journal of Sediment Petrology, 1983, 53: 973~980.

26 Xie, Y. Y. The surface structures of the quartz grains under electricity scanning microscope and their geological interpretation. Petroleum and Natural Gas Geology (in Chinese), 1981, 2(1): 66.

27 Xie, Y. Y. (ed.). Atlas of the Surface Structures of the Quaternary Quartz Grains Under ESM in China (in Chinese). Beijing: Ocean Press, 1983, 3~10.

28 Friedman, G. M. et al. The Principle of Sedimentology (translated by Xu, H. D. et al.), Beijing: Science Press, 1986, 80.

29 Reading, H. C. Sedimentary Environments and Facie. (translated by Zhou, M. J. et al.). Beijing: Science Press, 1986, 528~529.

30 Bennett, M. R. et al. Glacial Geology: Ice Sheets and Landforms. Chichester: Baffins Lane, John and Wiley & Sons Ltd, 1996, 148~166.

31 Abreu, V. S. et al. Glacial eustacy during the Cenozoic: sequence stratigraphic implication. AAPG Bull., 1998, 82: 1385~1400.

32 Webb, P. N. The Cenozoic history of Antarctica and its global impact. Antarctic Science, 1990, 2(1): 3~21.

33 Stroeven A P. The Sirius Group of Antarctica: age and environments. In: The Antarctic Region: Geological Evolution and Processes. Siena: Terra Antarctica Publishers. 1997, 747~761.

34 Marchant, D. R. et al. Miocene and Pliocene paleoclimate of the Dry Valleys region, Southern Victoria land: a geomorphological approach. Marine Micropaleontology, 1996, 27(2): 253~271.

35 Mercer, J. H. Some observations on the glacial geology of the Beardmore glacier area. In: Antarctic Geology and Geophysics. Oslo: Universitesforlaget, 1972, 427~433.

36 Harwood, D. M. Diatoms from the Sirius Formation, Transantarctic Mountains. Antarctica Journal of the USA, 1983, 18(5): 98~100.

37 Harwood, D. M. Recycled siliceous microfossils from the Sirius Formation. Antarctic Journal of the United States, 1986, 21(5): 101~103.

38 Webb, P. N. et al. A marine and terrestrial Sirius Group succession, middle Beardmore Glacier-Queen Alexandra Range, Transantarctic Mountains. Marine Micropaleontology, 1996, 27 (3): 273~297.

39 Burckle, L. H. et al. Deficiencies in the diatom evidence for a Pliocene reduction of the East Antarctic ice sheet. Paleoceanography, 1996, 11(4): 379~389.

40 Hill, R.S. et al. Nothofagus beardmorensis (Nothofagaceae), a new species based on leaves from the Pliocene Sirius Group, Transantarctic Mountains, Antarctica. Reviews of Palaeobotany and Palynology, 1996, 94: 11~24.

41 Whitehead, J. M. et al. Cenozoic glacial deposits in the Southern Prince Charles Mountains of East Antarctica. Terra Antarctica, 2000, 7(5): 655~656.

42 Whitehead, J. M. et al. Cenozoic glacigene sedimentation and erosion at the Menzies Range, Southern Prince Charles Mountains, Antarctica. Journal of Glaciology, 2002, 48 (2): 207.