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Cenozoic terrestrial palynological assemblages in the glacial erratics from the Grove Mountains, east Antarctica

Aimin Fang [a,*], Xiaohan Liu [b], Weiming Wang [c], Feixin Huang [b], Lianjun Yu [a]

[a] *Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*
[b] *Institute of Tibet Plateau Research, Chinese Academy of Sciences, Beijing 100029, China*
[c] *Nanjing Institute of Geology and Palaeontology, Chinese Academy of Science, Nanjing 210008, China*

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Abstract

Fossiliferous glacial erratics have been found in moraines of the Grove Mountains, east Antarctica since 1998 by Chinese National Antarctic Research Expedition (CHNARE) teams. These erratics were derived from a suite of glaciogene strata hidden beneath the Antarctic Ice Sheet in the Lambert glacier drainage system, and thus provide a record of Cenozoic paleoenvironmental conditions and fossil biotas that are so far unknown from outcrops and drill cores in this region. By microfossil analysis, sparse Neogene spores and pollen grains are revealed, including: *Toroisporis* (Lygodiaceae), *Granulatisporites* (Pteridaceae?), *Osmunda* (Osmundaceae), Polypodiaceae, *Magnastriatites* (Parkeriaceae), *Deltoidospora*, Araucariaceae, Taxodiaceae, *Podocarpus* (Podocarpaceae), *Dacrydium* (Podocarpaceae), *Pinus* (Pinaceae), *Keteleeria* (Pinaceae), *Picea* (Pinaceae), *Tsuga* (Pinaceae), Chenopodiaceae, *Artemisia* (Asteraceae), Asteraceae, Gramineae, *Fraxinoipollenites* (Oleaceae), *Oleoidearumpollenites* (Oleaceae), Oleaceae, *Operculumpollis*, *Nothofagidites* (*Nothofagus*), *Rhus*, *Quercus* (Fagaceae), *Juglans* (Juglandaceae), *Pterocarya* (Juglandaceae), *Liquidambar* (Hamamelidaceae), *Ulmus* (Ulmaceae), *Ulmoideptes* (Ulmaceae), *Tilia*, *Proteacidites* (Proteaceae) and *Tricolpopollenites*; but without any marine diatoms. Most of the spores and pollen grains in the erratics are considered to originate from local sources except for some older exotic components that might be recycled from the basement sedimentary rocks by the ice sheet, so they are *in situ* sporo-palynological assemblages. Furthermore, since the source areas of the glaciogenic sedimentary rocks are assumed to be local or in the up glacier areas, the palynological assemblages in these erratics represent an inland terrestrial flora during a warmer period of the ice-sheet evolutionary history. The ages of these erratics are also discussed based on the occurrence of some diagnostic pollens such as the *Artemisia,* Chenopodiaceae and *Nothofagus*, which implies Neogene (most probably Pliocene). As a preliminary conclusion, we think that the existence of the Cenozoic glaciogenic rocks and their palynological assemblages present new evidence for a large scale glacial retreat event in the Grove Mountains of east Antarctica, and thus support a dynamic East Antarctic Ice Sheet (EAIS). Furthermore, the absence of marine fossils in the samples analyzed not only provides additional evidence for a terrestrial sedimentary environment of these erratics, but also indicates that there is no transportation of Cenozoic marine fossils from the adjacent areas of the Grove Mountains.
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1. Introduction

The dynamic evolution of the Antarctic Ice Sheet during the Cenozoic era and the subsequent global climatic changes have always been one of the most important subjects in Antarctic studies, while the evidence revealing this process was mainly contained in sediments and ice cores inside the Antarctic continent and its surrounding regions. Among these different kinds of evidence, fossils preserved in sedimentary sequences are of particular significance in determining the age of the strata and inferring their paleo-

* Corresponding author.
E-mail address: fam@mail.igcas.ac.cn (A. Fang).

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environmental and paleoclimatic conditions. However, Cenozoic strata that contain fossils are very scarce and they are only sporadically outcropped in Antarctica because of the extensive coverage of the ice sheet in this region. As a result, reconstruction of the biostratigraphic frameworks of the Cenozoic sedimentary units is greatly constrained and more biostratigraphic data are needed to solve these problems.

During the field surveys made by the Chinese National Antarctic Research Expedition (CHNARE) team in the Grove Mountains, east Antarctica (Fig. 1), large quantities of glacial erratics of Cenozoic sedimentary rocks were found in the moraine banks in this area. Lithologically, most of the erratics are glaciogenic diamictons, so they are supposed to be derived from a suite of glaciogene strata hidden beneath the Antarctic Ice Sheet in the Lambert glacier drainage system [1]. Furthermore, they bear some similarities with Cenozoic strata of the Sirius Group in the Transantarctica Mountains [2–4], the Sørsdal Formation in Riiser-Larsen Hills and Vestfold Hills [5,6], and the Pagodroma Formation in the northern Prince Charles Mountains [7–10] on their lithologic assemblages and sedimentary features. By micropalaeontological analyses, it was found that these sedimentary erratics contain some Cenozoic spores and pollen grains, and especially, the *Nothofagus* and *Artemisia*, which are very important in inferring their ages and paleoclimatic conditions. As a result, these glacial erratics may provide crucial evidence in reconstructing the evolutionary histories of the Lambert Glacier system and the East Antarctic ice sheet in the Cenozoic era. This paper reports the preliminary results from the sporopollen study on the samples collected during the last geological field surveys made by CHNARE.

2. Regional backgrounds

The Grove Mountains (72′20″–73′l0″S, 73′50″–75′40″E) is located about 400 km to the south of the Zhongshang Station of China within the largest ice sheet drainage system of the Lambert-Amery ice shelf in east Antarctica (Fig. 1(a)). It is composed of 64 isolated nunataks that are distributed as five parallel island chains extending from SSW to NNE within an area of about 3200 km^2 (Fig. 1(b)). The East Antarctica Ice Sheet (EAIS) flows in a northwestward direction from the inland continent through this region into the Lambert Rift, which is formed in Mesozoic and extends into the East Antarctic Shield for about 800 km [11].

Geographically, the Grove Mountains are situated between the largest ice-free area in the east Antarctica of the Prince Charles Mountains (PCM) and the ice-free areas exposed along the coastal line of the Prydz Bay of the Larsemann Hills and the Vestfold Hills, so it belongs to one of the very few inland ice-free areas in East Antarctica. During its evolutionary history, the Lambert Glacier produced a lot of Cenozoic glacial deposits which were discovered sporadically outcropped in those ice-free regions mentioned above [5–10] and drilled by ODP in the ice-shelf of the Prydz Bay [12–14], and reversely, these records now provide direct evidence in revealing its evolutionary histories [15]. In recent years, detailed investigations on Cenozoic sedimentary rocks that were responsible for the reconstruction of regional ice sheet movements in Prydz Bay and its inland basins have been carried out in this region, which greatly improved the understanding of the evolutions of the Lambert Glacier as well as the EAIS [6–8,16–19]. However, no formal scientific investigations in the Grove Mountains had ever been carried out until the first field trip made by the CHNARE team in the summer season of 1998–1999 because of its obscured geographic location, and it is still poorly known how the ice sheet has evolved in this region.

Cenozoic sedimentary erratics presented in the Grove Mountains were apparently produced by the activities of the Lambert Glacier that drains the EAIS through this region, and therefore, they contain invaluable information on the behavior of the Lambert Glacier as well as the EAIS [1,20]. Furthermore, because of their special position, these erratics also provide good correlations between different units of Cenozoic sedimentary rocks found in the Prince Charles Mountains, the Larsemann Hills and the Vestfold Hills.

3. Samples and methods

All the samples analyzed were collected from a debris belt named the "West-Dike Detritus Strip" which is lying over the blue ice to the west of Mt. Harding in the center of the Grove Mountains (Fig. 1(b) and 2(a)). This debris belt was assumed to be a floating ice-cored terminal moraine formed during an advancing event of the ice sheet after the Last Glacial Maximum [1]. It extends for more than 5 km, ranging in width from 50 to 300 m with a relative height of 40 m above the surface of blue ice (Fig. 2(a)). The iceboulders in the debris belt are mainly composed of clasts of bedrocks scratched from the basement and those dropped from surrounding nunataks, together with some sparsely distributed exotic sedimentary and ultramafic erratics, varying in sizes from several centimeters to several meters in diameters (Fig. 2(b)).

According to different degrees of lithofication and consolidation as well as differences in their textural characteristics, these erratics can be subdivided into four types of lithofacies [20]: the lithified massive diamictons (LMDs), which are poorly sorted consolidated diamictons; the lithified sandstones (LS), which are highly lithified massive sandstones; the semi- to weakly-lithified massive diamicts (SLMDs), which consist of non-sorted clasts of different sizes (ranging from boulders to pebbles) and the sand or mud matrix with a massive texture; and the semi-lithified laminites (SLL) which are semi-lithified stratified units consisting of millimeter scale couplets of sand/silt/mud layers interlayered by some gravel lenses. From their distributions and preservations, these sedimentary erratics were removed

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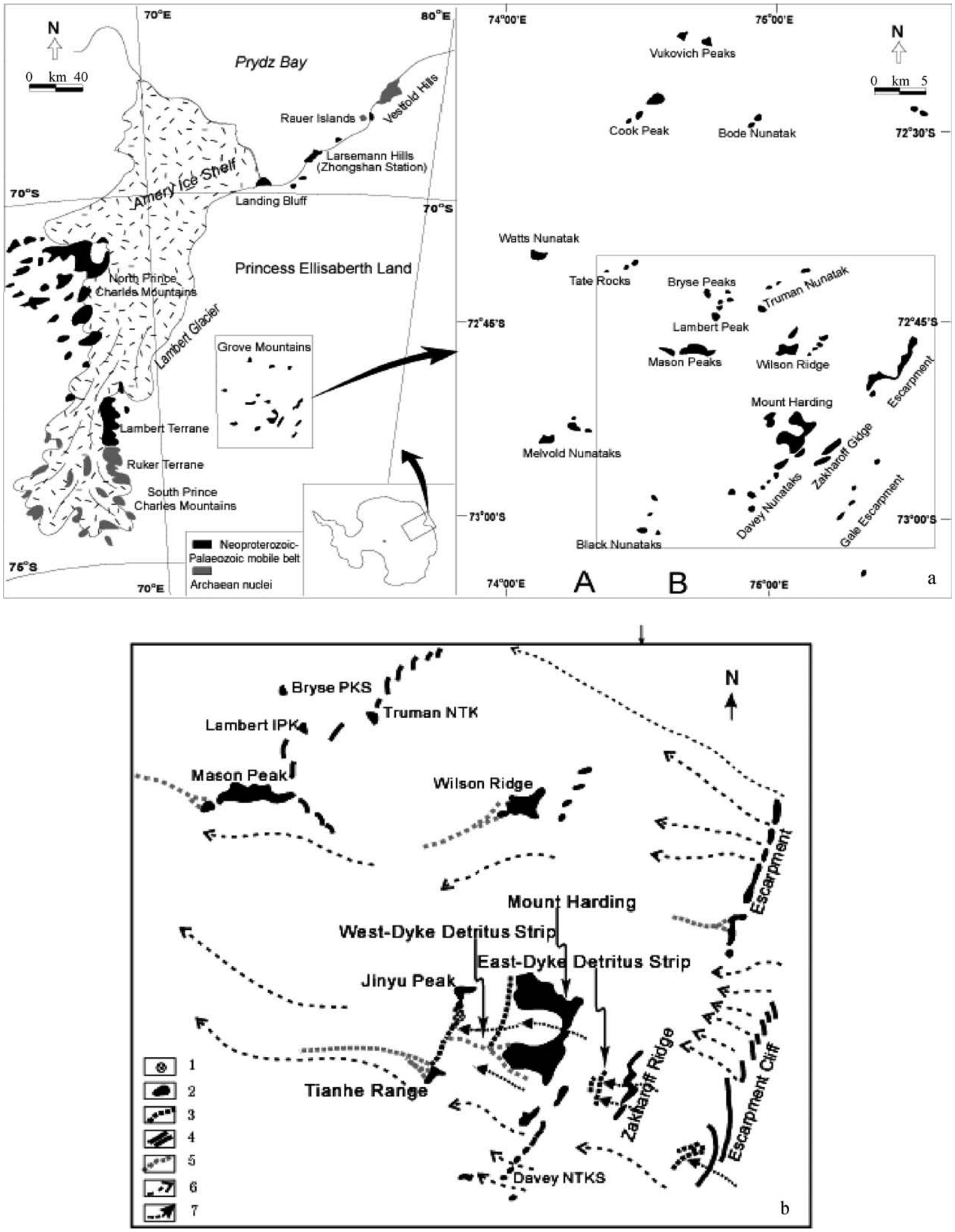

Fig. 1. Location (a) and geographic map (b) of the Grove Mountains in East Antarctica.

from their original strata and transported here by the ice sheet in a very short distance, which indicates that their primitive outcrops might exist in the upstream area of the glacier beneath the ice [1].

All together 12 samples (Table 1) from different lithologies were selected to conduct sporo-pollen analyses. Among them, four samples (S1501, S1507, S1509 and S1514) were collected during the 1998–1999 CHNARE

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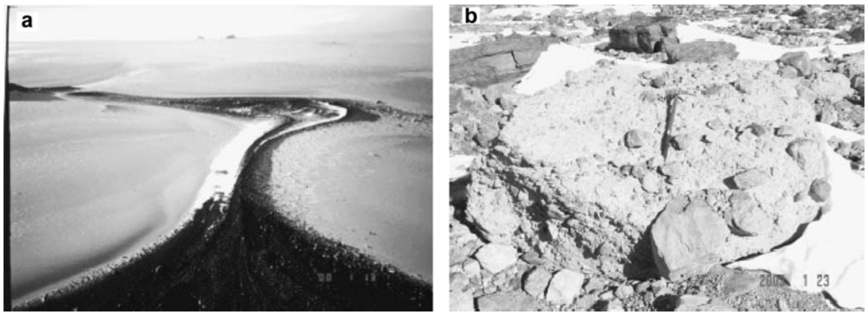

Fig. 2. Outlook of the west-Dike Detritus Strip (a) and the glaciogenic sedimentary debris (b).

summer season field investigation, three samples (S1604, S1605 and S1606) were collected at the second field survey in 1999–2000 and five samples (Nj02, Nj04, Nj05, Nj07 and Nj08) were collected at the third field survey in 2001–2002. All the samples were analyzed in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. Furthermore, diatom and other microfossil analyses were also conducted subsequently in the Korea Ocean and Research and Development Institute (KORDI).

Routine sporo-pollen analyzing procedures dealing with Quaternary sediments [22,23] were used as references to process all the samples in the laboratories mentioned above, including the following steps: (1) Sample preparation. Each sample was crushed into small pieces and sieved through a mesh screen (0.5 mm) to get rid of the coarse particles (the pebbles and coarse sands), and after this about 100–150 g of the residual dry powder was weighed out to be analyzed; (2) removal of the calcium cements by adding proper amount of 10% HCl; (3) removal of the humic acid and organic matter by adding KOH (10%) and heating; (4) removal of mineral materials by density separation using a density solution made from KI and CrI (specific gravity = 2.2) through centrifugation; (5) removal of silicates by adding HF (40%) and boiling; (6) slides preparation. Slides were prepared by mounting the residues extracted from the samples in a dilute glycerine jelly. The pollen grains were identified and counted on 4–6 slides for each sample. However, for those samples that contain very sparse pollens, almost all the pollens in the extracted residues have been checked for identification.

For diatom analyses, we followed the methods proposed by Fleming and Barron [24]. After observing more than 40 slides made from these samples, no diatoms were found.

4. Results

The abundance of pollen and spores contained in the erratics varies greatly from sparse to rare, with a maximum concentration less than 10 grains per 10 g of dry sediments, which occurs in sample S1604. After having observed all slides made from these 12 samples, a total of 191 grains of pollen and spore have been obtained. By further identification, they belong to a total of 27 pollen taxa and seven spore taxa (Table 2), which are characterized by species of genus *Pinus*, *Picea*, *Podocarpinuss*, *Osmunda*, *Nothofagus*, Chenopodiaceae, *Artemisia* and *Quercus*. Some of these

Table 1
Characteristics of the samples for sporo-pollen analysis.

Sample	Lithology	Main characteristics
S1501	Lithified Pebbly sandstones	Grey massive lithified rocks, with about 10% pebble-sized particles ranging in sizes from 0.2 to 2 cm with angular geometric shapes, 75% sand-sized particles, and about 15% mud and calcite cements
S1507	Muddy sandstones	Dark grey semi-lithified sandstones, mainly composed of sand-sized grain particles, with about 25% mud cements
S1509	Loose fine sediments	Dark grey loosely aggregated fine sediments (mainly mud-sized grains), coated on some pebbles of metamorphic rocks
S1514	Sediment matrix	Dark grey loosely aggregated sediments filled as matrix between some pebbles of metamorphic rocks
S1604	Muddy sandstones	Yellowish grey, semi-lithified sandstones, mainly composed of sand-sized grains and about 25% of muddy cements
S1605	Muddy sandstones	Dark grey, semi-lithified sandstones, mainly composed of sand-sized grains and about 25% of muddy cements
S1606	Pebbly sandstones	Dark grey, semi-lithified pebbly sandstones, mainly composed of sand-size particles, with about 5% pebbles varying in their diameters from 2 cm to 2 mm and about 10% of mud cements. This sample experienced very little wind weathering since it has fresh and subangular geometric outlines
Nj02	Lithified Pebbly sandstones	Highly lithified hard sedimentary rocks, well cemented by calcite. It consists of non-sorted gravel clasts of different sizes and sandy mud matrix, showing a massive sedimentary texture
Nj04	Laminates	Grey yellow semi-lithified stratified unit, consisting of millimeter scale couplets of sand/silt/mud layers interlayered by some gravel unit lenses, with some synsedimentary folding inside
Nj05	Laminates	Semi-lithified stratified unit, consisting of millimeter scale couplets of sand/silt/mud layers interlayered by some gravel unit lenses, with some synsedimentary folding inside
Nj07	Pebbly sandstones	Dark grey half-cemented, mainly composed of sand-size particles, with about 15% of mud cements
Nj08	Pebbly sandstones	Dark grey half-cemented, mainly composed of sand-size particles, with about 20% of mud cements

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grains were decayed and considered to be recycled from older sedimentary rocks.

Although the abundances and species of the pollen and spores found in the glacial erratics in the Grove Mountains is not enough to reconstruct their original plant communities, they do provide some information about a terrestrial palaeo-flora that had ever existed in the Grove Mountains at a certain period of time. From the occurrence of pollen and spores in the samples we studied, the abundance of the gymnospermous pollens (such as Pinaceae, *Podocarpus* and Araucariaceae) and the angiosperm pollen (such as Chenopodiaceae and *Atemisia*) is relatively high, while that of the fern spores is very low. Among the major types of sporo-pollens, *Pinus* is a predominant element, and *Picea*, *Podocarpus*, Chenopodiaceae, *Osmunda*, *Quercus* and *Artemisia* are the subordinates. Besides, there are also a few pollen grains from the species of shrubs (*Nothofagus*), which reflect that the palaeo-flora is a complex one. It might be a mixed conifer (such as Pinaceae, *Picea*, *Podocarpus* and Araucariaceae) and the broad-leaf (*Quercus*) forest, while herbs lived in dry conditions. There are also some ferns that lived under the forest. Such a palaeo-flora demonstrates that the climatic conditions at the deposit time should be considerably warmer and more humid than today.

Besides these common characteristics, however, the sporo-pollens that occurred in the lithified samples (S1501 and Nj02) differ from those in the unlithified samples in that the former does not contain any herbacous pollen, while the latter contains some pollen grains of Chenopodiaceae, *Artemisia*, Asteraceae or Gramineae. As a result, the sporo-palynological assemblages that occurred in these samples might belong to different ages. According to the differences of the sedimentary erratics in their cementation types, consolidation and geochemical compositions, these erratics might be derived from different sedimentary units formed at different stages after the initiation of the ice sheet in this region [1], which corresponds to the results obtained from the current pollen and spore analyses.

Table 2
Occurrence of sporo-pollen from the glacial erratics in the Grove Mts.

Spore and pollen types	S1501	S1507	S1509	S1514	S1604	S1605	S1606	Nj02	Nj04	Nj05	Nj07	Nj08	Total
Cryptogam spores													28
Toroisporis (*Lygodiaceae*)	4		1										5
Granulatisporites (Pteridaceae?)	1		1										2
Osmunda (Osmundaceae)	5	1	4		1								11
Polypodiaceae	1				1								2
Magnastriatites (Parkeriaceae)					1								4
Deltoidospora					3								1
Trilete spore					3		1						3
Gymnospermous pollen													**99**
Araucariaceae	3	1	2										6
Podocarpus (Podocarpaceae)	9		3	1	6						1		1
Dacrydium (Podocarpaceae)					1					2	1	1	20
Taxodiaceae					1								5
Pinus (Pinaceae)					24	3	7	2			1	3	40
Keteleeria (Pinaceae)					1								1
Picea (Pinaceae)					22					1		2	25
Tsuga (Pinaceae)												1	1
Angiospermous pollen													64
Chenopodiaceae			2	2	5	2	2			1	2		16
Artemisia (Asteraceae)		2	2		2				1				7
Asteraceae					1	1							2
Gramineae												2	2
Fraxinoipollenites (Oleaceae)	2												2
Oleoidearumpollenites (Oleaceae)			1										1
Oleaceae							1						1
Operculumpollis	1												1
Nothofagidites (*Nothofagus*)	2	1	1	1									5
Rhus	2				1								3
Quercus (Fagaceae)	1	1			3	1	3				3		12
Juglans (Juglandaceae)					1								1
Pterocarya (Juglandaceae)							1						1
Liquidambar (Hamamelidaceae)					2								2
Ulmus (Ulmaceae)					1	1	1						3
Ulmoidepites (Ulmaceae)					1								1
Tilia						1							1
Proteacidites (Proteaceae)	1									1			2
Tricolpopollenites	1												1
Total grains	33	6	17	4	81	9	16	2	1	5	8	9	191

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5. Discussion

5.1. Source analysis

According to the textural characteristics and mineral components of the sedimentary erratics, their primitive rocks are derived from a suite of *in situ* glaciogenic deposits, and mainly from a set of bottom tillites [1]. So the source areas of the rocks that bear these pollen and spores are assumed to be local, or in up-glacier areas from the flow lines to the Grove Mountains.

Most of the sporo-pollen which occurred in the samples we studied are well preserved. They are different from these long-way-transported or recycled pollens as reported in the surface samples in Rose Sea [25] and Prydz Bay [26]. Therefore, palynological assemblages that occurred in the sedimentary erratics in the Grove Mountains are considered *in situ* deposits.

Nevertheless, some of the sporo-pollens that occurred in the assemblage might be recycled from some older sedimentary sequences by erosion and transportation of ancient glaciers since they have broken configurations with dark colors. However, the sources of these recycled pollen grains should also be located in the up-glacier areas, i.e. in the inland of the east Antarctica beyond the Grove Mountains. Therefore, they also belong to a terrestrial plant community of inland Antarctica.

5.2. Correlations

Published data on sporo-palynological assemblages found in strata younger than Miocene in the Antarctic continent, especially in its inland areas, are rare. So far, there have been only reports on palynological assemblages found in the Sirius Group in the Transantartic Mountains [27–30]. However, components inside these palynological assemblages are fairly monotonous. For example, the palynological assemblage in the Sirius Group reported by Hill and Truswell [28] is almost totally composed of *Nothofagidites* (*Nothofagus)*, which is considered a representative component in a coastal flora that lived in frigid zones in Antarctica, such as the cases in the sequences of drill cores of CIROS-1 and CRP-2/2A from the MecMurdo Sound [31] and CRP from the southern Victoria Land [32,33], where *in situ* palynomorphs are dominated by *Nothofagidites* pollen through much of the successions. Obviously, palynological assemblages in samples we studied are quite different from those of the Sirius Group. This difference might have resulted from the different geographic situations of the two sites of the Grove Mountains and the Transantarctic Mountains since the latter is closer to the offshore lines, i.e., the palynological assemblage inside the Sirius Group represents a near shore flora, while the latter reflects more rigorously the characteristics of an inland terrestrial flora in the Antarctic continent. A much more diverse vegetation has been recently reported from the Meyer Desert Formation by Ashworth and Cantrill [34]. This stratigraphic unit consists of a set of nonmarine glaciogenic deposits that form the upper part of the Sirius Group in the Meyer Desert and the Dominion Range region of the Transantarctic Mountains [2,35,36], and a biostratigraphic age of less than 3.8 Myr has been assigned to this formation based on reworked marine diatom data [2,37]. By comparison, palynological assemblage found in the erratics of the Grove Mountains contains more similar plant species in the vegetation of the Meyer Desert Formation.

Plant microfossils are recovered from the stratigraphic sequences penetrated during the Ocean Drilling Program (ODP) at Sites 1165, 1166 and 1167 of Leg 188 and at Sites 739 and 742 of Leg 119 in the Prydz Bay. However, most of these pollen grains and spores are supposed to be recycled from old strata ranging in ages from Permian and Early Jurrassic to late Eocene, Oligocene and early Miocene [38,39]. Recently, large quantities of marine diatom fossils have been found in the Later Neogene strata of the Pagodroma Group [9,18] and the Sorsdal Formation [5,17] that outcropped in the vicinity areas of the Grove Mountains, the Charles Mountains and Vestfold Hills. However, no sporo-pollen has been found in these strata. On the contrary, sedimentary erratics in the Grove Mountains contain no marine microfossils. As a preliminary result, we thought that microfossil assemblages in the sedimentary erratics of the Grove Mountains were also completely different from those in the Pagodroma Group and the Sorsdal Formation. Such a result not only reflects the differences between their sedimentary environments, i.e. the original strata from which the sedimentary erratics of the Grove Mountains formed should be deposited in a terrestrial sedimentary environment, while the latter should be in a marine one, but also shows that there are no transportation of marine diatoms from the near-shore areas of the Prince Charles Mountains and Vestfold Hills into the inland area of the Grove Mountains.

5.3. Ages

Palynological assemblages found in glacial erratics in the Grove Mountains provide new materials to determine the formation age of their primitive rocks. From the composition of the palynological assemblages we studied, they are similar to a southern hemisphere Neogene flora since most species in these assemblages lived in a Neogene Weddellian biogeocenose, and the major pollen types, such as the Penaceae, *Podocarpus*, *Araucariaceae*, Chenopodiaceae and *Artemisia* are common components of a Neogene flora in the Gandwana continent.

Occurrence of the pollens of herbacious angiosperm and their abundances in a sporo-palynological assemblage are most important indicators to distinguish and subdivide a Neogene stratum [40]. For example, the Chenopodiaceae, the Polygonaceae, the Gramineae and the Cyperaceae all experienced a similar development from initiation to booming during the Neogene [41–43]. The first occurrence

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of the *Atemisia* is supposed to be from the late Neogene around the world, and its abundance increases after that [44]. More concretely, the first occurrence of herbage angiosperms is generally supposed to be from the early Miocene, but with only a few species; during the late stage of the middle Miocene, the herbage angiosperms began to increase not only in their species but also in their abundance; and however, the herbage angiosperms have not reached their boom stage until Pliocene, especially at the end of Pliocene. At that period of time, superior assemblages of the herbage angiosperms always occurred in some special environments, such as the assemblage of Chenopodiaceae, *Atemisia* and Polygonaceae, whose wide occurrence is supposed to start at Pliocene [44]. Although the abundance of the pollens of the herbage angiosperm species is not so high in the palynological assemblages we studied, some *Atemisiaepollenites*, Chenopodiaceae and Gramineae did occur in the semi- to weakly-lithified samples we analyzed (S1507, S1509, S1514, S1604, S1605, S1606, Nj04, Nj05, Nj07 and Nj08), therefore, it can be inferred that the formation age of the sporo-palynological assemblage in these samples should be Neogene.

Although most species of the herbacious angiosperms that developed in Pliocene have lasted into Pleistocene, palynological assemblages in Pleistocene always have a higher abundance of Chenopodiaceae, *Artemisia* and Gramineae than those in Pliocene, which is not the case for the palynological assemblage in the samples we studied. Furthermore, from their pressured shapes and dark-colors, pollen grains in the erratics should not be formed in Pleistocene, i.e., they are most likely to be formed in Pliocene. As for the sporo-palynological assemblage in lithified erratics, such as in samples 1501 and Nj02, it does not contain any pollen of the herbage angiosperms, indicating it must be older than the herbage angiosperms bearing assemblage, i.e., it might be formed in Miocene or Oligocene.

Besides pollens from the herbacious angiosperm, the occurrence of the *Nothofagidites* in samples S1501, S1507, S1509 and S1514 also provides some special evidence for the nature and age of the sporo-palynological assemblage in the Grove erratics since *Nothofagus* is a typical component of the Weddellian biogeocenose. It is regarded as the major species in plant communities so far reported in the Cenozoic strata outcropped in the Antarctic continent. Traditionally, most researchers considered that the first occurrence of the *Nothofagus* was in Cretaceous, after that, this species bloomed during the Oligocene [41] and disappeared in Paleogene [45]. However, the occurrences of its pollen and mega-fossils in Pliocene strata of the Sirius Group (references) have greatly changed this traditional opinion. For a long time, the Sirius Group has been considered the most famous as well as the most controversial Cenozoic strata in the Antarctic continent. Lithologically, this group is composed of a series of glaciogenic and nonglaciogenic units of compact sedimentary rocks [35]. According to the abundant marine diatoms which occurred in it, some researchers thought that the Sirius Group was deposited in Pliocene [37,46]. In the middle of the 1980s, Prentice et al. [47] and Harwood [25,46] (in Askin & Markgraf [33], Webb et al. [48]) had almost simultaneously found the pollen and mega-fossils of the *Nothofagus* in the Sirius Group outcropped in the Beardmore Glacier region of the Transantarctic Mountains. Subsequently, Carlquist [49] botanically studied the xylem fossils found in this group and determined it as the species of *Nothofagus*. After that, Webb [50], Webb and Harwood [29,30] and Hill and Truswell [28] reported continuously the occurrences of the fossils and pollen of the *Nothofagus* in the Sirius Group at different sites along the Transantarctic Mountains. Furthermore, the pollen of the *Nothofagus* was also found in the Pliocene strata distributed in some other places of the Antarctica. For example, Heusser [51] discovered *Nothofagidites* well preserved in the Cenozoic sedimentary sequences drilled by the Deep Sea Drilling Program in Rose Sea, and Fleming and Barron [14] found a large quantity of *Nothofagidites* as the major component of the palynological assemblages which occurred in the succession of the DSDP-274 to the northern-east of Cape Adare. According to the diatoms and radiolararian preserved in the strata of the DSDP-274 borehole, the palynological assemblages that contain abundant *Nothofagidites* were formed in Pliocene (about −3 Ma). Therefore, the fossils of *Nothofagus* might be distributed widely in the strata of Pliocene to earlier Pleistocene in the Antarctic, i.e., it should last at least into the Pliocene. Furthermore, *Nothofagus* might be the major species in a Pliocene plant community of the Antarctic continent.

The glaciogenic sedimentary rocks of the ice boulders in the Grove Mountains are quite similar to the Sirius Group in their lithological and sedimentological characteristics, and both of them contain *Nothofagites*. Therefore, the finding of *Nothofagidites* in sedimentary ice boulders in the Grove Mountains provides new evidence for a wide distribution of the *Nothofagus* in the Pliocene strata in Antarctica, and it can be inferred that the source strata from which the sedimentary ice boulders originated might be simultaneously deposited with the Sirius Group.

6. Conclusions

Spores and pollen grains from the glacial erratics found in moraines of the Grove Mountains, east Antarctica provide useful information in revealing the Cenozoic glacial and climatic evolutions of the region since they are supposed to be derived from a suite of glaciogene strata hidden beneath the Antarctic Ice Sheet in the Lambert glacier drainage system that are unknown from current outcrops and drill-holes. Most of the pollen grains and spores originated from the local sources except for some older exotic components that might be recycled from the basement sedimentary rocks by the ice sheet, so they are *in situ* sporo-palynological assemblages. Furthermore, because of the inland geographic location of the Grove Mountains, these palynological assemblages should represent a continental

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flora that survived at a certain period of time in this region. Compared with Neogene microfossil assemblages reported in places within the Antarctic continent or its surrounding areas, palynological assemblage found in the erratics of the Grove Mountains contains more similar plant species in the vegetation of the Meyer Desert Formation, but they are quite different from other plant communities. Based on the findings of some diagnostic pollen grains, such as *Artemisia,* Chenopodiaceae and *Nothofagus*, they may belong to late Tertiary (most probably Pliocene).

According to the available climatic data observed at the present time [21], the average daily temperature in the Grove Mountains is −18.5 °C in January of the summer, ranging from −13.1 to −22.6 °C, far below zero. Therefore, it is impossible to form sedimentary rocks and the palynological assemblages in such a condition, i.e., quite different environmental conditions, especially, a much warmer-than-today's climate must exist for the formation of the fossils in these local erratics in the Grove Mountains.

As a preliminary conclusion, we think that the existence of the Cenozoic palynological assemblages in the glaciogenenic rocks presents new evidence for a much warmer-than-today's climatic event and a large scale of glacial retreat in the Grove Mountains, east Antarctica, and thus supporting a dynamic East Antarctic Ice Sheet (EAIS). Furthermore, the absence of diatoms in the samples analyzed may indicate that there are no Cenozoic marine strata in the interior of east Antarctica beyond the Grove Mountains.

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