Chinese Journal of Polar Science, Vol. 9, No. 1, 9 - 18, June 1998

Characteristics of the mineral phase constituents of lacustrine deposits from the Fildes Peninsula of King George Island, Antarctica and their environmental implication

Peng Wenshi (彭文世), Zheng Honghan (郑洪汉) and Wang Guanxin (王冠鑫)
Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

Received October 6, 1997

Abstract Based on analytical data of mineral phase constituents at three sections from Tern Lake, West Lake and Kitezh Lake in the Fildes Peninsula of King George Island, Antarctica, the characteristics of mineral phase constituents, material source and their environmental implication have been discussed. Research results indicate that lacustrine deposits came primarily from widespread volcanic rocks at the peninsula. Under cold and dry condition in Antarctica, the weathering process of the parent rocks in some area is mainly physical weathering with a weak chemical one. The relation curves of abundance of kaolinite and calcite against deposition age change steeply at the boundary between lacustrine and glacial deposits, indicating that the corresponding environment changes are abrupt, which may be related to different transportation fashion of both different deposits and the protection of glacial deposits.

Key words Antarctica, lacustrine deposits, mineral phase constituents, environmental implication.

1 Introduction

Many lakes, unequal in size, are scattered in the Fildes Peninsula of King George Island, Antarctica. They lie in the front margin of glacial sheet and were formed in low depression due to the accumulation of deglaciation water while climate changed to warmer and the glacier was recessed in Holocene. Deposits in lakes are the weathering products of parent rocks and their minerals in source region which have undergone a transportation, sedimentation or even "deuterogenesis". The changes of mineral phase constituents are affected by type and age of parent rock, geological process and climatic environment, etc.. Therefore they are the reflection and record of these factors in a certain degree. A lot of study, for example, on volcanic rocks and their rock-forming mineral at the Fildes Peninsula (Li *et al*. 1992; Zheng *et al*. 1991; Liu and Zheng 1988), chemical weathering in soils (Liu 1991; Zhao and Li 1995; Zhao *et al*. 1990), the sediments in the Great Wall Bay (Wang 1993), the mineral of sediments in the sea area near Antarctica (Gao 1990; Ma *et al*. 1990) and sedimentary environment of Xihu Lake (Xie and Li 1990), have been carried out, respectively, but the study on the mineralogy of deposits in Antarctic lakes has not been reported till now. According to the systematic data of material constituents and compositions from three sections at Tern Lake, West Lake and Kitezh Lake, this paper will discuss their characteristics of mineral phase constituents, material source and environmental implication by comparative studies.

2 Geological sections and analytical samples

Analytical samples are collected by Yuan Baoyin and others during the 9th Chinese National Antarctic Research Expedition in 1993 from drill cores in sections of three lakes, Tern Lake, West Lake near by Great Wall Station and Kitezh Lake located to the northwest of Bellingshusen Station, Russia. The drilled depths are 394, 928 and 439 cm, respectively. Samples are cut with equal interval on layer and serially gathered. According to the structure of stratigraphic section, overlying lacustrine deposits and underlying glacial layer can be recognized in three deposit sections. For Tern Lake and West Lake there is an interglacial bed between two subglacial layers. The deposits were dated by Shen Chengde and Sun Yanmin by means of ^{14}C technique. A part of ages of deposits at the West Lake section has been calibrated on the basis of the slope of relation curve between age and depth (Liu *et al.* 1996).

3 Characteristics of mineral phase constituents of deposits and their formation environment

3.1 Characteristics of mineral phase constituents and material source

Table 1 gives the compositions and contents of mineral phase of the sedimentary sections at Tern Lake, West Lake and Kitezh Lake, which were determined by X-ray diffraction. Fig. 1 shows the X-ray diffraction patterns of several typical samples.

In the deposits at these lakes, whether lacustrine or glacial, their mineral phase constituents are quite similar to each other, but different in contents. The outstanding feature of mineral constituents is a great proportion of noncrystalline matter, about 50%, which can be fully proved from the high ground value of X-ray diffraction pattern. The wider Si-O stretching band at $\sim 1000\ cm^{-1}$ with poor resolving can also reflect clearly this feature (Fig. 2). In deposits the species of crystalline minerals are less. Plagioclase (labradorite An=60% - 70%) is main phase in primary minerals of source rocks with less quartz. The secondary minerals formed from the alteration and weathering are mainly the association of clay minerals such as montmorillorite, chlorite and kaolinite, etc.. K-bearing minerals are completely lacking in deposits. Obviously, all these can be assigned to be the mineralogical characteristics of meta-basic volcanic rock. The recent research results (Li *et al.* 1992; Zheng *et al.* 1991) show that Cenozoic basaltic, basalt-andesitic, andesitic and dacitic volcanic rocks extensively spread in the Fildes Peninsula and their principal rock-forming minerals are plagioclase (labradorite, bytownite), augite and quartz. Alteration in volcanic rocks have seriously taken place. Augite engenders generally chloritization. As a result, all porphyritic crystals become pseudomorph. Carbonization is quite common and zeolitization is often seen. All these indicate clearly that there are close genetic and inherited relationship between mineral phase constituents of lacustrine deposit and meta-basic volcanic rocks.

Table 1. Compositions and contents of mineral phases of lacustrine deposits at the lakes, Antarctica*

DS	DT	SN	Depth /cm	Age /a B. P.	Mineral contents/%								
					Mon	Gy	Kao	Cab	Chl	Q	La	Cal	Amor
GA3	Lac	3	39.2	0	2.6	1.5	5.6		6.1	7.9	20.4		54
		5	60.3	230	1.3	0.6	2.5		2.7	3.2	18.7		69
		13	136.8	3770	7.5		1.9			2.4	28.2		58
		15	151.4	4750	2.0	0.4		3.0	3.3	3.8	38.6		47
		18	165.1	5470	1.5		2.7	1.5	2.6	5.8	36.8		47
		28	207.7	7610		0.2				0.8	26.2		71
		32	223.3	8420	4.3	0.6	7.5		6.5	9.3	19.4		51
	Gl2	35	239.1	9170	3.8	0.5	7.9		5.4	14.0	16.9	5.8	44
		38	257.1	10040	2.1	0.7	10.1		9.5	13.1	23.5	2.0	37
	Fgl	40	268.1	10570	2.8	0.5		2.5		1.9	21.4		69
	Gl1	44	292.6	11000	3.0	0.9	11.8		8.7	7.4	20.3	4.9	42
		45	302.0		2.7	0.3	10.2		7.8	21.3	9.3	8.7	38
GA7	Lac	2	10.5		8.3	0.9	1.6	1.2	2.1	6.1	29.8		49
		7	36.1		6.6	1.3	2.5		2.7	4.1	26.1		55
		13	66.7	0	2.9	0.2	1.3		1.9	4.8	40.1		47
		15	75.4	156	3.9		1.5		3.2	3.4	42.0		44
		19	94.5	625	7.6			3.6	3.0	3.0	29.9		51
		25	125.2	1430	1.4			1.8		5.5	36.3		53
		27	138.0	1770	7.1	0.1		1.8	2.3	2.7	32.1		52
		29	147.1	2000	5.9	0.1	1.1	1.5	1.8	3.7	25.0		59
		31	159.8	2340	8.0	0.1	3.0	4.2		2.3	27.2		53
		35	185.4	3020	4.6		1.9	2.5	2.5	3.2	33.2		50
		39	211.6	3690	5.3		2.0	3.7	1.8	3.2	31.9		50
		42	230.6	4190	3.8		1.8	2.7	1.9	3.6	31.3		53
		46	255.6	4800	8.4	0.3	1.9	3.0	2.1	3.1	31.5		48
		50	274.1	5420	10.6		1.8	3.0	3.9	4.5	39.1		35
		54	292.2	6030	8.1		2.2	3.5	1.9	5.0	33.1		44
		58	310.3	6640	5.9		2.4	3.5	3.3	3.3	26.7		53
		63	332.4	7390	2.4			4.8		4.8	43.0		43
		66	348.1	7760	3.3		1.4	1.9	2.3	3.3	32.8		53
		70	359.0	8140	8.9		4.2	1.3	3.0	6.1	17.5		57
		74	375.6	8320	6.0		1.8	1.2	2.0	2.9	20.0		64
		79	398.0	8670	4.4		2.0	2.2	2.2	3.1	23.1		61
		83	416.1	8940	6.1		1.6	4.3	1.2	1.8	21.0		62
		84	420.4	8990	1.5		1.2	5.1	2.5	2.0	32.7		53
	Gl2	86	487.1	9600	10.7		1.9	0.9	5.2	5.6	17.6		56
	Fgl	89	503.5	10060	3.3		2.5	1.7	2.8	3.0	21.7		63
		93	524.7	10600	6.0	0.1	2.9	1.9	2.5	5.0	26.8		53
	Gl1	97	544.8		4.6		2.7	1.4	2.4	6.5	22.4		58
		110	688.0		7.9		4.4		2.6	12.4	37.1	3.5	30
		127	880.0		16.5		3.6			5.3	38.2	1.4	33
		128	885.0		11.8		4.5	1.1	2.5	8.7	26.4	1.0	43
GA9	Lac	4	24.7	580	29.3	0.8				1.2	28.7		38
		13	89.8	2070	31.5	1.1		1.5		1.0	23.9		39
		17	119.2	2740	29.0	0.7		1.4		1.1	24.8		41
		20	154.6	3570	26.1	1.5		1.0		1.2	28.1		40
		24	183.6	4210	31.3	1.4				0.9	22.4		42
		26	196.7	4530	13.3	0.6		1.2		2.5	29.4		51
		28	210.9	4850	19.3	0.4				1.7	34.5		42
		33	246.1	5660	13.4		1.9	1.7		2.4	28.2		51
		34	253.2	5820	10.6	0.5		1.4		2.0	30.5		53
	Gl	36	267.2	6140	24.3		1.2			1.8	24.7		46
		37	273.2		26.8					4.0	31.1		36
		44	310.0		21.0		1.0			3.4	26.2	5.4	41
		54	368		22.7		1.1			1.8	36.4	9.9	26

*: GA3, GA7 and GA9 are taken from Tern Lake, West Lake and Kitezh Lake; Lac: lacustrine deposit; Gl: glacial deposits; Fgl: interglacial deposit; DS: deposit sections; DT: deposit type; SN: sample number; Mon: montmorilliorite; Gy: gypsum; Kao: kaolinite; Cab: cabsite; Chl: chlorite; Q: quartz; La: labradorite; Cal: calcite; Amor: amorphous. In the following tables the symbols are the same as in this table.

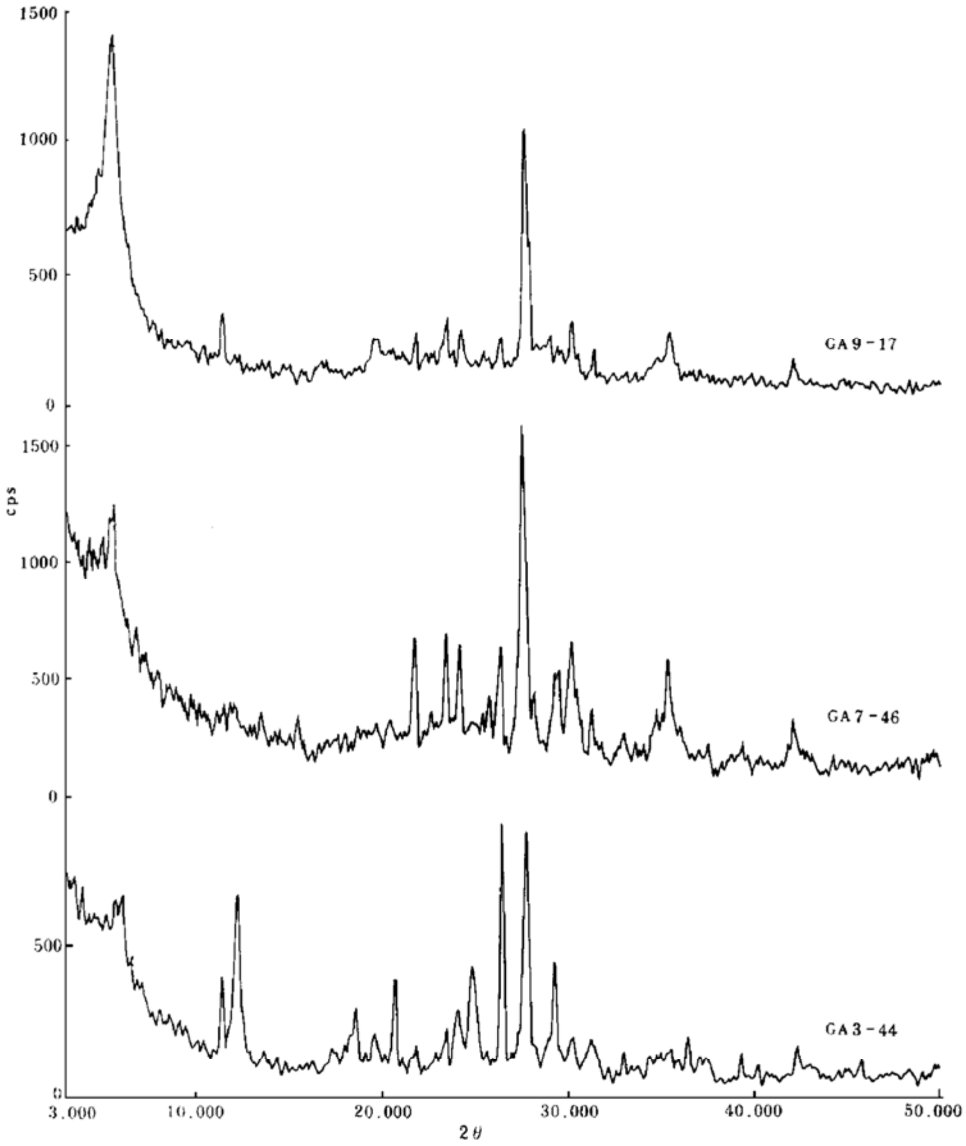

Fig. 1. Typical X-ray diffraction patterns of deposits at the lakes, Antarctica.

Among clay mineral association, montmorillorite is dominant, followed by chlorite, and kaolinite is less. Generally, montmorillorite is not closely related to climate zone and results from the degeneration of volcanic glass. The conditions of degeneration of volcanic glass are in alkaline environment rich in Mg and poor in K, and arid region with less rainfall. It is obviously that Antarctic area is very favourable to the formation of montmorillorite. The curves between contents of both montmorillorite and noncrystalline and ages present basically a inverse correlation (Fig. 3), which powerfully supports this viewpoint. Chlorite is enriched commonly in high latitude area with weaker chemical weathering, but kaolinite is regarded as a product under serious chemical weathering and a clay mineral in low latitude area. Chlorite and montmorillorite are transformed into kaolinite under the condition of warm-moist climate. Not considering alteration genesis of kaolinite or presuming it to be a weathering product, such clay mineral association and its abundance (Table 1) in deposits from Antarctic lakes only indicate that chemical weathering is not strong but physical weathering is dominant.

It is apparently found from the comparison of average chemical composition be-

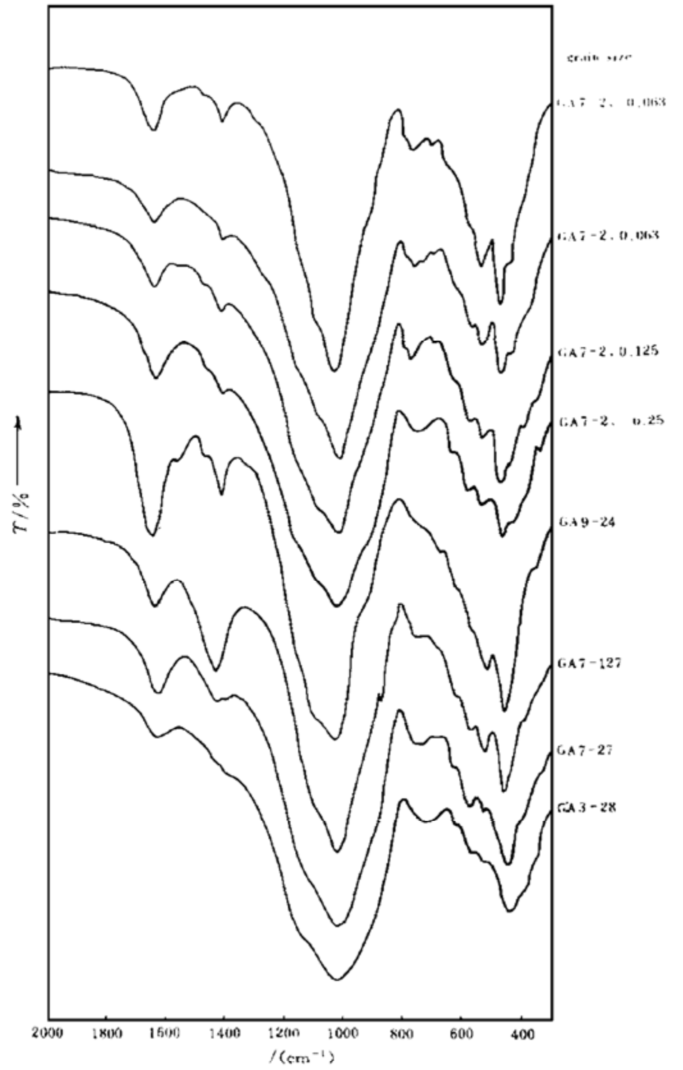

Fig. 2. Typical infrared spectra of deposits at the lakes, Antarctica.

tween deposits and volcanic rocks (Table 2) that the contents of Al_2O_3, FeO, MgO, CaO and Na_2O in deposits decrease slightly in a certain degree, which indicate that chemical weathering exists in some degree, but is relatively weak. Totally speaking, chemical compositions of deposits are quite similar to those of the volcanic rocks. The contents of SiO_2 in deposits calculated by means of average content of SiO_2(48.4%) in basic volcanic glass and the content of various silicate mineral in deposits are basically coincident with analytical values. Average analytical value over 30 samples is 50.59% (Table 2) and average calculated one 51.90%. It is evidently that the deposits keep essentially the characteristics of volcanic source rocks. As a result, there exists a close genetic and inherited relationship between chemical compositions of tie deposits and volcanic rocks.

Table 2. Comparison between average chemical compositions of lacustrine deposits and volcanic rocks at the Fildes Peninsula(%)*

Type	Volcanic rocks	Basement rocks	Weighted average	Lacustrine deposite
SN	35	4	39	30
SiO_2	49.88	51.57	50.05	50.59
TiO_2	0.81	0.89	0.82	1.28
Al_2O_3	18.80	18.37	18.76	16.64
Fe_2O_3	4.18	5.03	4.27	4.68
FeO	5.27	5.85	5.33	3.66
MnO	0.19	0.20	0.19	0.14
MgO	4.37	4.47	4.38	3.77
CaO	9.51	9.69	9.53	6.49
Na_2O	3.26	3.24	3.26	2.44
K_2O	0.32	0.39	0.33	0.80
P_2O_5	0.13	0.16	0.13	0.26
H_2O^+	1.59	1.45	1.58	5.44
H_2O^-	0.59	0.61	0.59	2.18
LOI	0.75		0.75	8.99**
Total	99.65	101.92	99.88	99.74

* Data source: volcanic rocks from Liu and Zheng (1988), basement rocks from Liu (1991). Lacustrine deposits: this paper. ** Including the contents of H_2O^+ and H_2O^-.

In deposits the minerals related to deuterogenic process may be calcite and gypsum. Biogenetic carbonate or calcareous muckle consists principally of some calcareous microfossil. It is commonly believed that the most primary factor controlling the last feature of biomuckle is productive ability of biotic matter, but the effect of temperature on productive ability of biotic matter is most important. Obviously, a great deal of multiple of biotic matter is hampered under serious cold condition in Antarctica so that the appearance of biogenetic carbonate is impossible in large scale. It has been discovered in this study that the content of calcite in glacial drift layer is much

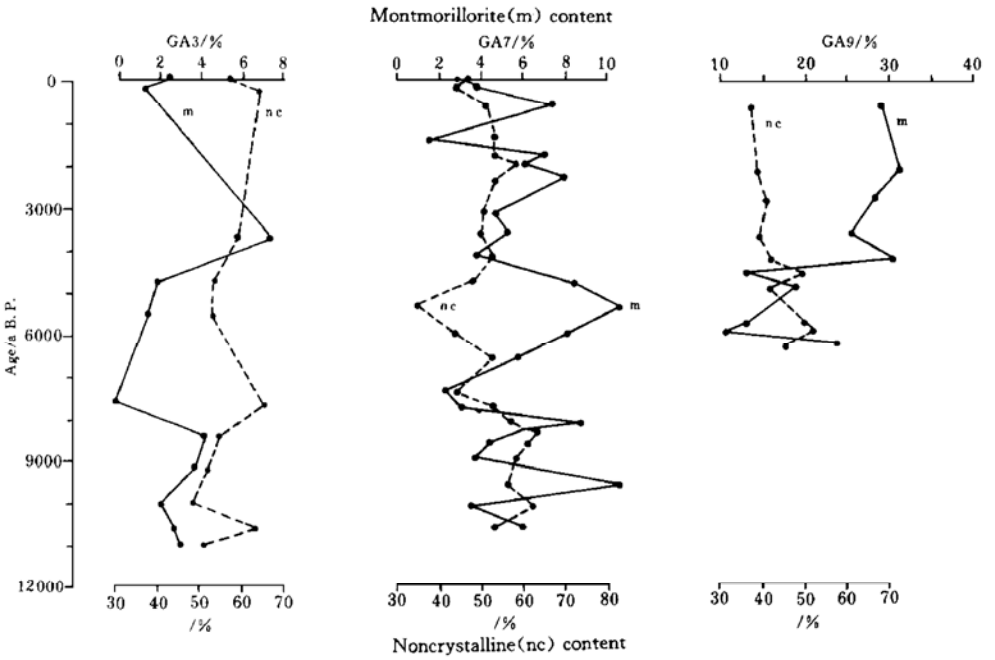

Fig. 3. Relation curves showing the contents of montmorillorite and noncrystaline matter and the ages.

higher than that in lacustrine deposit layer, which is related to general carbonization of parent rocks and the protection of glacial till for calcite during transportation. All these prove fully that calcite is mainly terrestrial source. Gypsum may be the product of deuterogenic process. It develops commonly in warmer, arid and high vaporizing region but its content is less in deposits, which indicates that deuterogenic process is very weak in deposits in Antarctic lakes. Weathering product of parent rocks is chief material source of lacustrine deposit, which can be powerfully proved from close genetic and inherited relationship between mineral phase constituents and chemical compositions of lacustrine deposits and parent rocks.

3.2 Relation curves between contents of minerals and ages

The changes of contents of some minerals are related to the deposit type in the same section. Relation curves between contents of kaolinite and ages (Fig. 4) clearly show the high and low value regions, the ages of their boundary for Tern Lake, West Lake and Kitezh Lake are 9000, 8200 and 5700 a B. P., respectively. These ages are approximately coincident with respective measured boundary ages between glacial drift layer and lacustrine deposit layer (Table 1). As to Tern Lake section, there is a most clear low value point between two glacial drift layers, corresponding age being 10600 a B. P.. This age is just coincident with measured age of interglacial drift layer. The same feature is also showed on the relation curves between integral intensity (direct proportion to the content of calcite) of infrared band at 1420 cm^{-1} (CO_3^{2-} asymmetry stretching) and ages (Fig. 5) but corresponding boundary ages move to 9100, 9600 and 6500 a B. P., respectively. However the boundary age of interglacial drift layer for Tern Lake is 10600 a B. P., too. Apparently, the comparison between two relation curves show that curve changes present basically the same trend with increasing the depth (or age). The sets of relation curves have common feature, i. e. curve changes between lacustrine deposit layer and glacial drift layer, or between glacial drift layer and interglacial drift layer are steep, which indicates that corresponding environmental changes are abrupt.

Kaolinite and calcite are liable to be eluviated and lost during weathering, transportation and deposition so that they are often regarded as an important objective

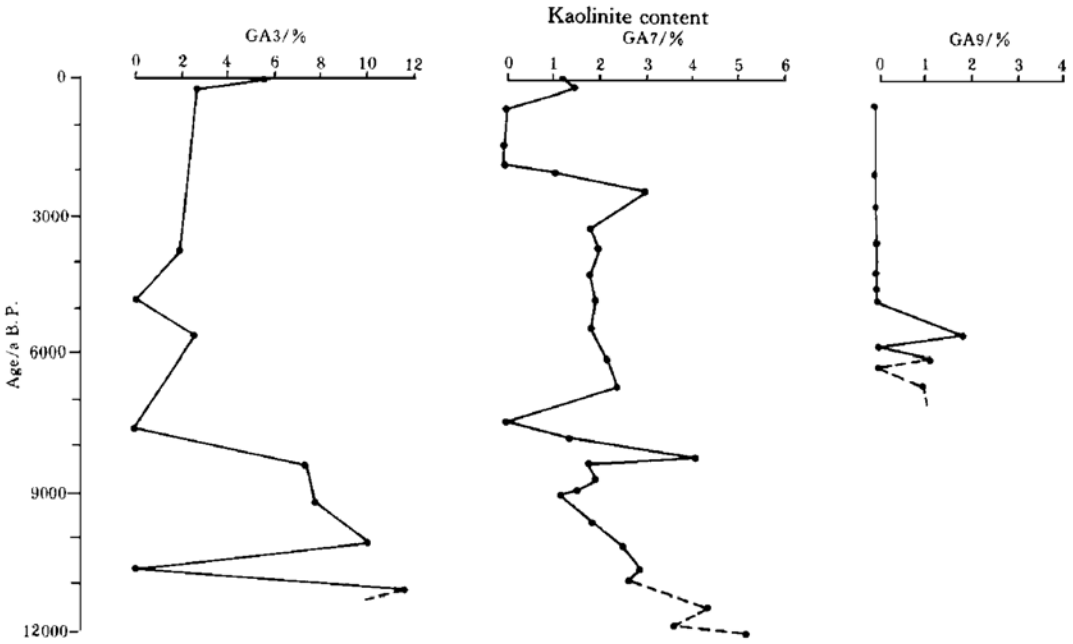

Fig. 4. Relation curves between contents of kaolinite and ages.

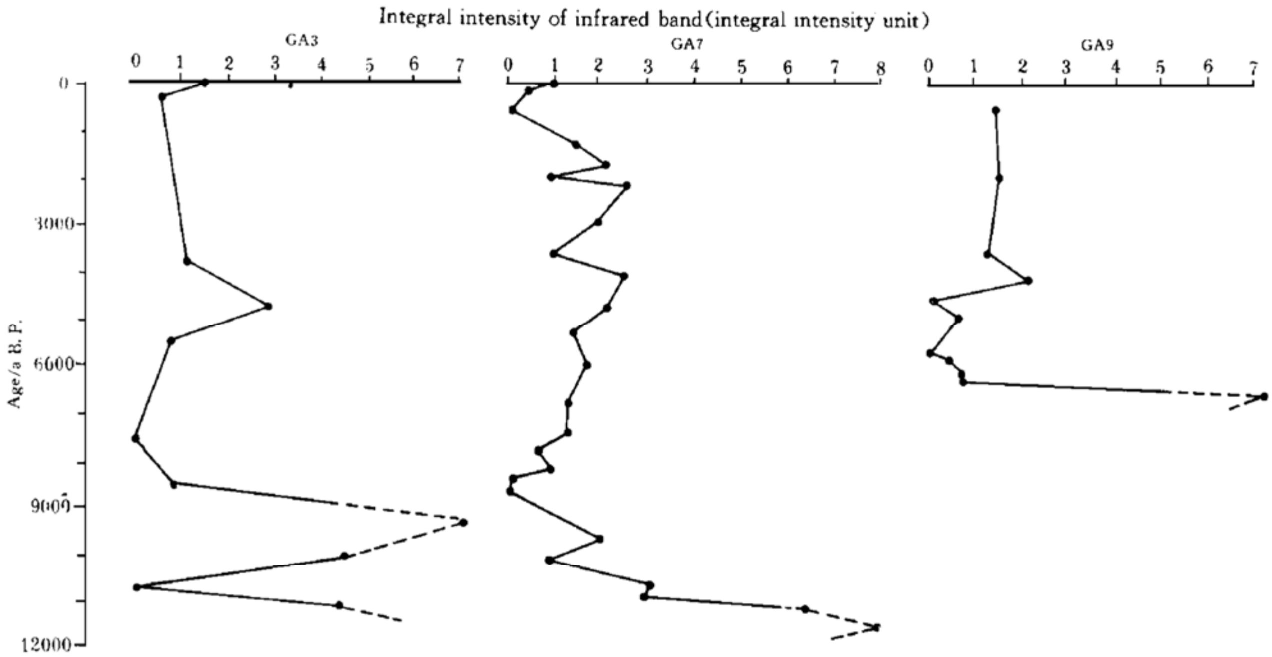

Fig. 5. Relation curves showing the integrated intensity of infrared bands at ~1420 cm^{-1} for calcite and ages.

mark of climatic and environmental change. However, in glacial period in Antractica, fundamental process for transporting the terrestrial source materials to ocean and lake is glacial dissipation , Antarctic glacier seems to play the role of protection rather than to be a geological process of erosion. Thus, mineral contents of glacial drift layer obtained from the analyses of total rock reflect mainly much or little of these minerals in source area, but for lacustrine deposit layer these express the eluviated and preserved degree during the transportation and deposition. Abrupt changes of mineral contents between glacial drift layer and lacustrine deposit layer may be related to the different transportation fashions of two deposit phases and the protection of glacial drift for the easily eluviated minerals.

3. 3 Mineral phase in deposits with different grade

Table 3 show average mineral content of 30 samples of deposits in different depth (GA7-) and 45 samples in meta-clay grade (GA7'-) (the solid products after suspending the samples with grade <0. 065 mm for 30 min and contrifugation). It is clearly found that there are noticeable changes between mineral phase costituents of these two grade samples. Their mineral species are the same and the difference is the apparent increase of total quantity of clay minerals and the decrease of feldspar and quartz in meta-clay grade samples.

As parent rocks of source area suffer fragment weathering, grain size trends to decrease and surface area increases largely. All these are favourable to chemical weathering process. Thus mineral phase constituents should be separated and enriched in some degree during weathering and transportation. Some minerals, which are easy of weathering, are eluviated and at the same time new mineral phase will appear. It is evidently found from Table 3 that mineral phases of deposits elementarily underwent physical change with weak chemical change during weathering , transportation and sedimentation. All these are correspondent to cold and dry climate in the long period in Antarctic area.

Table 3. Comparison of mineral phases of deposits in different grade at the West Lake section

DT	SN	Average contents of mineral phases/%									
		Mon	Gy	Kao	Cab	Chl	Q	La	Cal	NC	Total
GA7	30	6. 4	0. 1	2. 0	2. 1	2. 2	4. 4	29. 8	0. 2	50. 8	98. 0
GA7'-	45	17. 1	0. 1	4. 3	2. 0	1. 9	1. 5	14. 8	0. 2	56. 3	98. 2

3. 4 Comparison of mineral phases between various sections

The comparison of mineral phases (Table 1) and average contents of some minerals (Table 4) in three deposit section, Tern Lake, West Lake and Kitezh Lake, obviously show that their mineral phase constituents are similar to each other in some degree but there also is apparent difference. The contents of kaolinite, chlorite, quartz and noncrystalline matter tread to decrease from GA3 to GA9. Generally speaking, GA3 is more similar to GA7, and principal differences of GA9 from both GA3 and GA7 lie in its noticeable high content of montmorillorite, lack of chlorite, and clearly low contents of quartz, kaolinite and moncrystalline matter. As reflected in mineral phase, average chemical composition of deposits (Table 5) shows this similarity and difference between GA9 and GA3 and GA7. All these may be related to material source of GA9. Judging by geographical position, Tern Lake and West Lake are near to Great Wall Station, but Kitezh Lake is located in the northwest side of Belingshausen Station. On the other hand, under condition of cold and dry climate in Antarctica, chemical weathering is quite weak and deposits can better keep the features of rocks in source area. Xie (1988) pointed out in discussing chemical weathering in frozen ground region that the characteristics of clay mineral in this region are elementarily dependent on the type of parent rocks but less on the weathering degree. Thus, it can be considered that the rock characteristics of material source in Antarctica are principally controlling factor of the constitutes and abundance of deposit.

Table 4. Average mineral contents of various deposit section

Deposit sections	Average contents of mineral phases/%				
	Mon	Kao	Chl	Q	NC
GA3	2.8	5.0	4.4	7.6	52.3
GA7	6.4	2.0	2.2	4.4	50.8
GA9	23.0	0.4	0	1.9	42.0

Table 5. Average chemical compositions of various deposit section

DS	SN	Average contents of chemical compositions/%														
		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O^+	H_2O^-	P_2O_5	LOI	Total
GA3	6	51.91	1.26	16.23	3.46	4.66	0.13	3.73	6.56	2.41	0.98	5.21	1.52	0.31	8.84	100.49
GA7	16	52.27	1.37	16.7	4.46	3.92	0.15	3.84	6.72	2.69	0.82	4.18	1.66	0.27	6.61	99.81
GA9	8	46.98	1.10	16.93	6.05	2.39	0.13	3.69	6.00	1.94	0.53	8.14	3.59	0.19	13.99	99.92

4 Conclusions

Based on the discussion of some features of mineral constituents and chemical compositions of deposits from three lakes in the Fildes Peninsula of King George Island, Antarctica, the following conclusions can be obtained:

(1) In Tern Lake, West Lake and Kitezh Lake, whether glacial deposits or lacustrine deposits, there are a close genetic and inherited relation between mineral phase constituents and chemical compositions of deposits and middle-basic volcanic rocks wide-spread in the area.

(2) Clay minerl association with montmorillrite as a main mineral phase in lacustrine deposit, the similarity and a slight difference of chemical compositions between deposits and volcanic rocks, and the similarity of mineral phase constituents between total rock of deposits and meta-clay grade, indicate that the weathering process in

source area is mainly physical weathering with a weak chemical weathering.

(3) Relation curves between abundance of kaolinite and calcite and age clearly show the high and low value regions and their boundary ages are basically consistent with corresponding measured ages. Boundary lines of interglacial driff layer are also coincident with measured boundary ages. Steep changes of curves between glacial deposits and lacustrine deposits, glacial deposits and interglacial bed prove that corresponding environmental changes are abrupt. These characteristics of curve changes may be related to the difference of transportation fashion of both deposits and the protection of glacial deposits for the easily eluviated minerals.

(4) Obvious differences of mineral phase constituents and chemical compositions of deposits between the Kitezh Lake and Tern Lake or West Lake are due to that the climate is cold and dry, chemical weathering is quite weak and rock characteristics of material source are the principal controlling factor of mineral phase constituents and abundance of deposits in the Antarctic area.

Acknowledgments This project was supported by the State Antarctic Committee of China. The authors thank Prof. Yuan Baoyin, Ye Chuanxian and others for their help in sampling and chemical analysis, respectively in this study.

References

Gao ST (1990): Clay minerals in the Northwestern sea area of the Antarctic Peninsula. Antarctic Research (Chinese Edition), 2(1): 35 - 41.

Li ZN *et al*. (1992): Volcanic rocks of the Fildes Peninsula, King George Island, West Antarctica. Beijing: Science Press, 43 - 71(in Chinese).

Liu DS *et al*. (1996): Environment record of lacustrine deposites from Fildes Peninsula of King George Island, Antarctica. Compilation of achievement of state key project under the Antarctic science and technology program.

Liu GN (1991): The chemical weathering in soils at Fildes Peninsula of King George Island, Antarctica. Antarctic Research (Chinese Edition) , 3(1): 22 - 29.

Liu XH, Zheng XS (1988): Geology of volcanic rocks on the Fildes Peninsula, King George Island, Antarctica. Antarctic Research (Chinese Edition), 1(1): 25 - 35.

Ma KJ, Wang XL, Li ZZ *et al*. (1990): A study on clastic minerals of surface sediments in the sea area northwest of the Antarctic Peninsula. Antarctic Research (Chinese Edition), 2(3): 27 - 38.

Wang XL (1993): The geochemical characteristics and divisions of the sediments from the Great Wall Bay, Antarctica. Antarctic Research (Chinese Edition) , 5(1): 24 - 30.

Xie YY (1988) : Chemical weathering in permafrost regions of Antarctica — Great Wall Station, Casey Station and Davis Station areas. Antarctic Research (Chinese Edition) , 1(2): 8 - 14.

Xie YY, Li JY (1990): A preliminary study on sedimentary environment of Xihu Lake in the Great Wall Station area, Antarctica. Antarctic Research, 2(1): 43 - 52(in English).

Zhao JL, Liu PT, Li TJ (1990): Correlation between chemical compositions of both primitive soil and parent rocks in King George Island region . Antarctic Research (Chinese Edition), 2(1): 53 - 65.

Zhao Y, Li TJ (1995): Analysis of the chemical weathering characteristics of soil-minerals on Fildes Peninsula of King George Island, Antarctica. Antarctic Research (Chinese Edition), 7(2): 18 - 24.

Zheng XS, E Molan, Liu XH *et al*. (1991): The volcanic geology, petrological characteristics and the formation and evolution of the tertiary volcanic rocks from the Great Wall Station area, King George Island, West Antarctica. Antarctic Research (Chinese Edition), 3(2): 10 - 109.