

Characterization of clay minerals in the sediments of Schirmacher Oasis, East Antarctica: their origin and climatological implications

Ashok K. Srivastava^{1,*}, Nelay Khare² and Pravin S. Ingle¹

¹Department of Geology, SGB Amravati University, Amravati 444 602, India

²Ministry of Earth Sciences, Lodhi Road, New Delhi 110 003, India

A total of 16 glacial sediments consisting of loose admixture of sand, silt and clay have been collected from different parts of the Schirmacher Oasis and adjoining areas, viz. main rocky land, inland lakes, ice sheet and coastal area. The clay from the sediments has been separated and studied for mineral identification using different thermal analysis (DTA), thermogravimetric analysis (TGA) and X-ray diffraction (XRD) analysis. The thermograms of all the samples are almost similar, showing minor gain or loss of weight. DTA curves show a small notch around 585°C, i.e. kaolinite. XRD analysis of the samples treated with Ca and K, glycolated, and heated at various temperatures shows well-developed peaks of chlorite, illite, kaolinite, smectite and vermiculite. An attempt has been made to decipher the origin of clay minerals along with their climatological implications.

Keywords: Clay minerals, climatological implications, glacial sediments, thermograms.

THE clay minerals of the Antarctic Peninsula are an aspect of special attention in polar studies because they have a direct bearing on the climatic change, weathering pattern and provenance of the sediments, e.g. Victoria Land Basin, Antarctica^{1,2}; Cenozoic Pagodroma Group³; Kainan Maru Seamount and northern Gunnerus Ridge⁴; Ocean Drilling Programme (ODP) sites in Bellingshausen Sea⁵, and Cape Roberts, McMurdo Sound, Antarctica⁶.

The Schirmacher Oasis, from which the sediments have been collected, is represented by high-grade metamorphic terrain where loose sediments of localized occurrence are accumulated mainly due to: (i) ice and wind activities on the main land, (ii) lake sedimentation, (iii) unplucking of the sediments due to ice melt in the south and (iv) coastal-shelf sedimentation in the north. So far, these sediments are less explored for their textural and mineralogical details, probably due to remote access and limited approachability, shorter time-span for field work, etc. The scientific expedition, arranged annually by the

Government of India made the data possible on the oasis. However, certain sedimentological attempts made in the past, have provided basic information about grain size and pattern of sedimentation⁷⁻⁹. Recently, Srivastava and Khare¹⁰ made a granulometric analysis of the sediments collected from various subglacial environments and interpreted that there is an intermixing of the sediments due to cumulative result of physical processes operating in the region. The same is also concluded by heavy mineral analysis, besides the short distance of transportation and immature nature of the sediments, and high-grade metamorphic rock as a source¹¹. These sediments are a significant tool to interpret the climate and weathering pattern through the study of clay mineral fractions. However, there is lack of any such attempt.

The present work encompasses the identification of various clay minerals through X-ray diffraction (XRD), differential thermal analysis (DTA) and thermogravimetric analysis (TGA). Emphasis has been given to their origin and climatological implications.

Geology and significant glacial units

The Schirmacher Oasis (lat. 70°44'30"–70°46'30"S and long. 11°22'40"–11°54'00"E) is an E–W trending strip of land, covering an area of about 35 sq. km. The maximum width of the oasis is about 2.7 km in the central part. Hills with low elevation (<200 m altitudes), depressions, lakes and glacial valleys characterize the area.

The basement is Precambrian crystalline terrain consisting of high-grade metamorphic suite of rocks represented by banded gneiss, alaskite, garnet–biotite gneiss, calc-gneiss, khondalite and associated migmatites, and streaky gneiss, which are intruded by concordant bodies of basalt, lamprophyres, pegmatite, dolerite and ophiolite (Figure 1)¹².

The significant glacial units of the area are: (i) main rocky land of Schirmacher, including lakes, (ii) ice sheet and (iii) coastal shelf area (Figure 2). The E–W elongated, main rocky land is abruptly overlain by thick piles

*For correspondence. (e-mail: Ashokamt2008@hotmail.com)

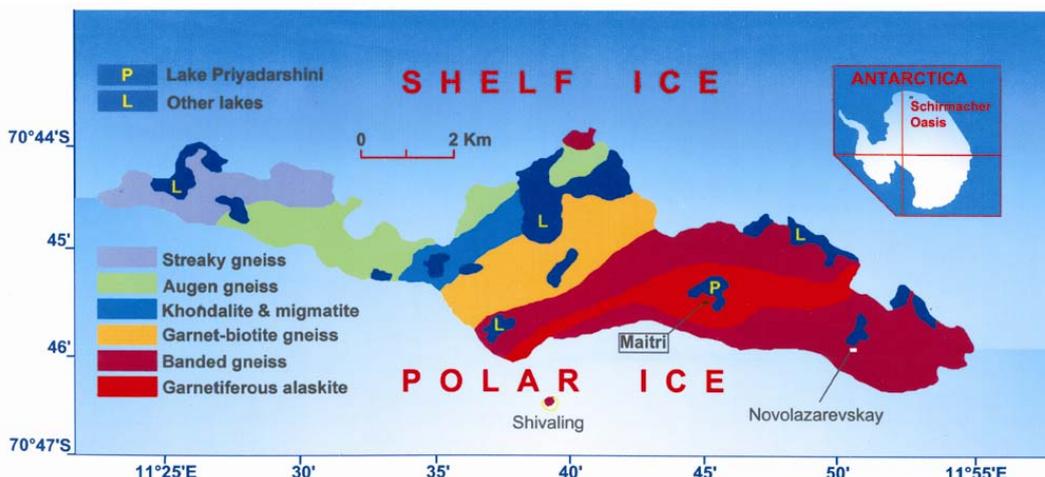


Figure 1. Geological map of the Schirmacher Oasis, East Antarctica (after Sengupta¹²).

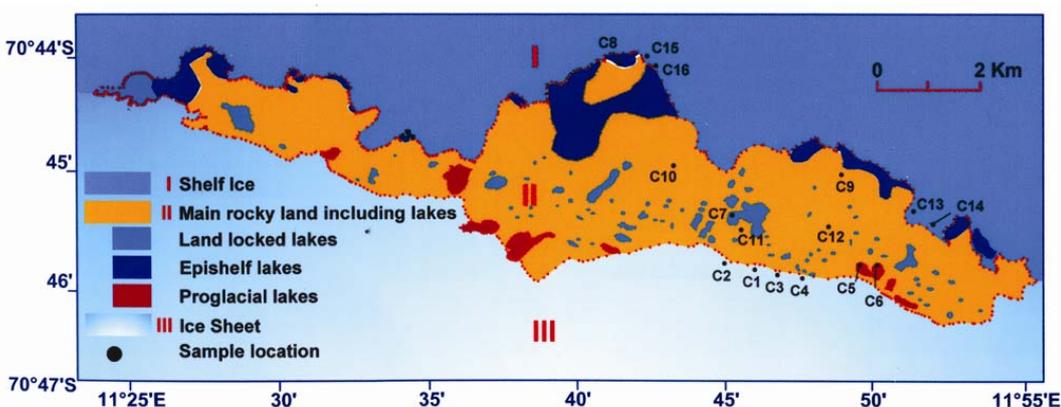


Figure 2. Significant glacial units of the Schirmacher Oasis (after Ravindra¹³) and locations of the sampling sites.

of ice sheets in the south, whereas the northern boundary slopes down under the shelf ice of the Antarctic Ocean. However, the narrow belt of exposed sloping area, at places, is intermittently sandy with clasts of variable size. This area receives sediments from the channels formed due to melting of ice sheet, wind-derived sediments and also through the weathering and erosion process of the crystalline terrain. All these processes working either separately or jointly accumulate the sediments in the form of small debris or patches of loose admixture of sand, silt and clay on the surface, or in small depressions and channels. The land is also marked by numerous lakes of diverse origin, i.e. epishelf lakes, land-locked lakes and proglacial lakes¹³. These lakes, receiving sediments from upland and surrounding areas, also serve as sites of sediment accumulation (Figure 3 a).

The ice sheet, a regional feature, covers most of the area in the south. Its northern boundary, limited to the Schirmacher Oasis, is a scarp face showing various horizontal layers of ice, which are easily differentiable by their transparency, various shades of brown colour and

differential melting. The ice sheet is impregnated with abundant silt to sand-sized sediments which normally get accumulated in melt-water channels and depressions formed on the surface of the ice sheet or on the scarp face. An easy approach to collect these sediments is from the small debris formed on the ground, adjacent to the scarp face, where the sediments are brought down with melt water of the ice sheet and get accumulated on the ground (Figure 3 b). The third unit is the E–W trending narrow belt with patches of loosely packed sediments on the northerly sloping northern boundary of the mainland limited by a cover of shelf ice in the north. Though a well-defined coast is lacking in this area, these sediment patches seem to be deposited by the same, and hence the area is referred as coastal shelf. Besides, this region also receives sediments through melt-water channels of the mainland and ice sheet. These channels are normally governed by the slope of the area, therefore, finally discharges to the coastal shelf area because of general steepness of the mainland towards the same. This region is also covered by a thick pile of shelf ice in the north.

However, certain marginal areas showing sediment exposure provide scope for sample collection (Figure 3 c).

Sampling sites

A total of 16 samples have been collected from the entire area representing equally the ice sheets (C1–C4), lakes (C5–C8), main rocky land (C9–C12) and coastal shelf area (C13–C16). Location-wise details of the samples are provided below (the number in brackets shows the original index number of the sample; Figure 2).

Ice sheet

C1 (A-2): Base of ice sheet scarp face, south of Maitri.

C2 (A-5): Base of ice sheet, SW of Maitri.

C3 (A-33) and C4 (A-34): Ice sheet lying at the base near scarp margin at two different locations, roughly 500 m apart, south of Maitri.

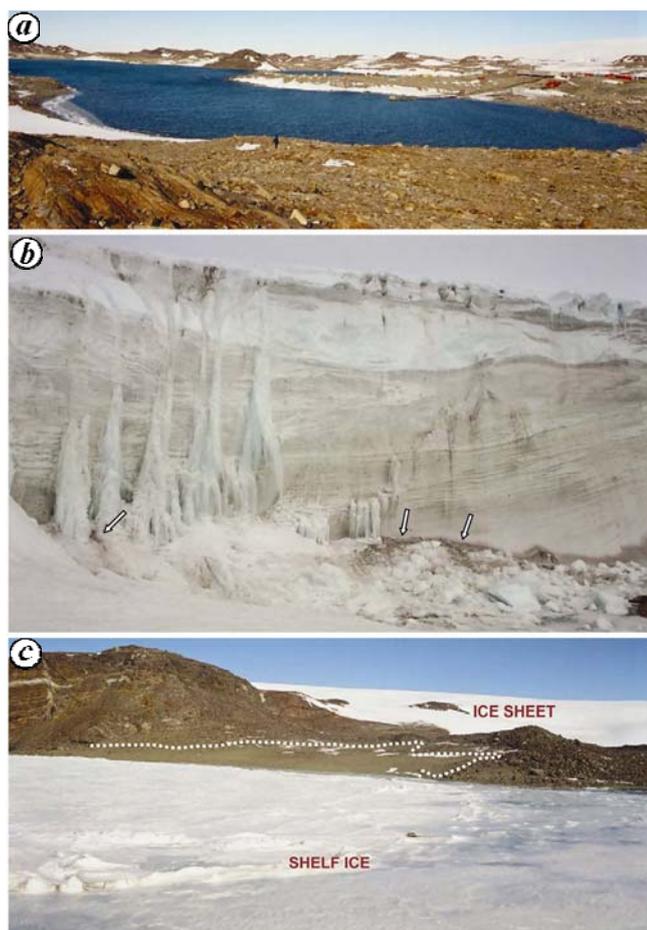


Figure 3. a, Rocky mainland and Priyadarshini Lake; b, Scarp face of ice sheet south of Maitri (arrows mark the sediment accumulation sites); c, Shelf exposed north of Maitri. The marked area is a patch of loose sediments.

Schirmacher main rocky land and lakes

Sampling in these units has been made taking two criteria into consideration: (i) lakes, where the supply of sediments is mostly by the melt-water channels from upland and adjoining areas, and (ii) main rocky land, exhibiting significant activity of wind apart from melt-water channels for sediment accumulation. The sampling sites of lakes (C5–C8) and main rocky land (C9–C12) are as follows:

C5 (A-7): Margin of a lake located about 2 km east of Maitri, on the route to the Russian station, viz. Novalazarevskay.

C6 (A-13): Margin of another lake situated adjacent to the previous (C5).

C7 (A-19): Margin of Priyadarshini Lake.

C8 (A-28): Margin of an epishelf lake located extreme north at about 5 km distance.

C9 (A-11): About 2 km NE of Maitri.

C10 (A-14): About 2 km NW of Maitri.

C11 (A-17): A small sand pocket accumulation near Maitri.

C12 (A-39): About 2 km east of Maitri.

Coastal shelf area

C13 (A-8): Shelf approachable at about 3.5 km east of Maitri.

C14 (A-23): East of Maitri, at a distance of about 4 km.

C15 (A-27) and C16 (A-36): Two different locations lying about 5 km north of Maitri.

Methodology

The samples consisting of a loose admixture of sand–silt–clay were collected from a depth of about 15–20 cm by digging the ground surface. These sediments were air-dried in the laboratory and a fine fraction < 0.0625 mm of silt and clay was collected through the sieving process. The fine clay from these mixed sediments was separated according to the procedure of Jackson¹⁴.

The fine clay fractions thus obtained were subjected to mineral identification by XRD analysis of oriented mounts saturated with either Ca or K (ref. 12). K-treated samples were analysed at 25°C, 100°C, 300°C and 550°C, using Phillips Analytical X'Pert, Ni-filtered, CuK α radiation with a scanning speed of 2° θ min⁻¹.

The remaining fraction of the fine clay, initially separated for XRD analysis was subjected to thermal analysis. This was carried out in an air atmosphere, up to the temperature of 1000°C, with a scan rate of 10°C/min for TGA and DTA on a computerized TA instrument (model PerkinElmer Diamond TGDTA).

Analytical results

Thermograms

DTA curves of all the samples have more or less similar trends showing uniformity of clay mineral content in the admixture (Figure 4). They show a small notch of endothermic peak around 585°C, the usual position of kaolinite (Figure 4, Table 1). This is due to the removal of structural water from the aluminium atoms^{15,16}.

The TGA curves also have an almost uniform pattern and show minor loss or gain in weight which is due to the loss of bound water in the clays¹⁷ (Figure 5).

X-ray diffractograms

All the six diffractograms of each sample, i.e. saturated with Ca (Figure 6a), glycolated (Figure 6b), treated with K and heated at 25°C (Figure 6c), 100°C, 300°C and 550°C (Figure 6d) have been analysed for clay minerals identification. The criteria for identification are the peak values of the minerals¹⁴. The X-ray patterns indicate a

strong and well-defined peak of illite in all the samples, apart from smectite, vermiculite and kaolinite. Chlorite is identifiable in only four samples, one each from the mainland and lake, and two from the shelf area. The peaks of primary minerals like quartz, feldspar, mica and amphibole are also represented. Table 2 shows the percentage of various clay minerals.

Discussion

The clays of different nature ranging from hydrous aluminum silicate to potassium, magnesium, iron, sodium and calcium-rich varieties show a varied range which may be due to significant changes in the physio-chemical condition operating within the system. Apart from the minor fraction of the clay minerals, the glacial sediments are rich in quartz and feldspar, and, minor but diversified nature of heavy minerals, i.e. zircon, tourmaline, rutile, garnet, hornblende, zoisite, lawsonite, chlorite, spinel, topaz and opaque minerals¹¹. Major, minor and trace elements analysis of +0.0625 to +0.125 mm sediments, in general, shows the dominance of SiO₂, followed by Al₂O₃ and MgO. CaO, Na₂O and K₂O have a narrow range. As such, it is difficult to differentiate the sediments of various glacial units, i.e. ice sheet, rocky land, lakes and coastal shelf area on the basis of mineralogy, including heavy minerals and geochemistry. The same has also been inferred from granulometric analysis, as there is a lot of intermixing of the sediments due to glacial and wind activities¹⁰.

The clay minerals, viz. illite, kaolinite, smectite and vermiculite have been identified in all the samples,

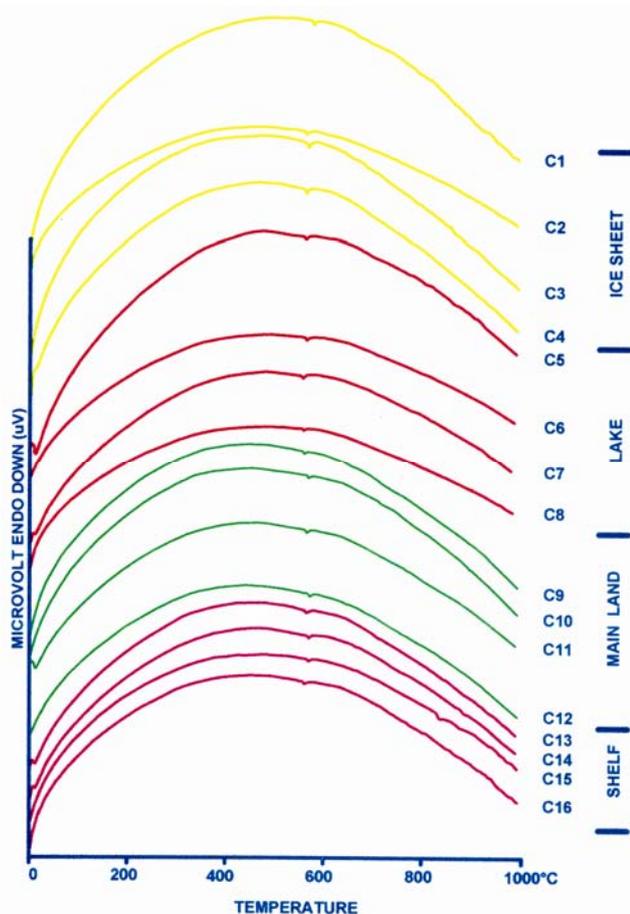


Figure 4. Differential thermal analysis curves of the samples showing a small notch at about 585°C.

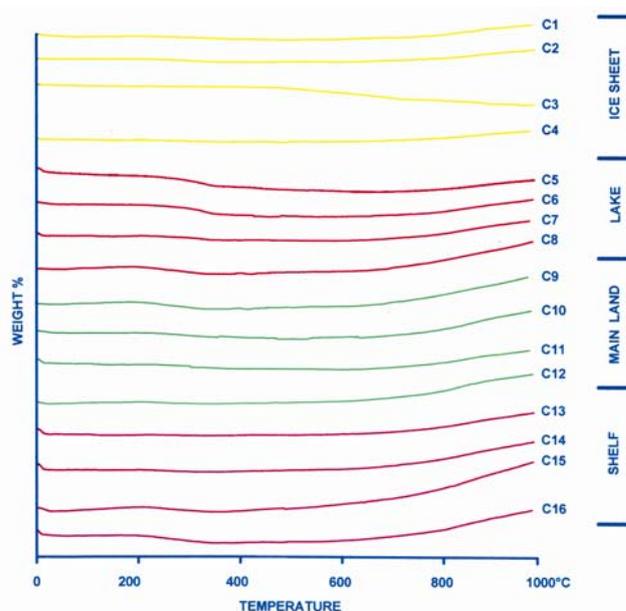


Figure 5. Thermogravimetric analysis curves of the samples showing almost similar pattern.

Table 1. Differential thermal analysis (DTA) and thermogravimetric analysis (TGA) values of the samples

Sample		DTA				TGA	
		Onset (°C)	Peak (°C)	Peak height (μV)	Area (μV × s)	Weight gain (%)	Weight loss (%)
Ice sheet	C1	582.55	585.51	-0.616	23.710	0.459	-
	C2	582.49	585.75	-0.674	29.314	0.718	-
	C3	581.50	585.46	-0.902	45.289	0.460	0.225
	C4	582.70	586.15	-0.772	33.186	0.450	-
Lake	C5	583.24	586.13	-0.410	14.546	0.509	0.744
	C6	582.70	585.94	-0.670	28.741	0.515	0.149
	C7	582.84	586.22	-0.605	23.574	0.462	0.114
	C8	583.57	586.02	-0.269	6.780	1.032	0.172
Mainland	C9	583.24	585.67	-0.324	10.549	0.711	0.067
	C10	583.25	585.99	-0.374	12.666	0.574	-
	C11	582.68	585.93	-0.538	21.092	0.457	0.158
	C12	583.00	586.09	-0.506	17.019	0.629	-
Coastal shelf	C13	582.68	586.17	-0.476	16.849	0.525	0.124
	C14	582.79	586.14	-0.435	16.427	0.648	0.172
	C15	582.47	585.59	-0.380	17.130	0.988	-
	C16	583.26	585.75	-0.387	21.171	0.813	0.201

Table 2. Clay minerals percentage in fine-grained fraction of the sample

Minerals identified/ sample no.		Clay minerals					Quartz	K- Feldspar	Ca- Feldspar	Mixed layer	Amphibole	Total (%)
		Chlorite	Illite	Kaolinite	Smectite	Vermiculite						
Ice sheet	C1	-	28.70	7.20	14.5	6.60	9.30	11.50	12.70	-	9.60	100
	C2	-	33.95	4.57	9.79	7.11	5.87	10.83	13.96	-	13.88	100
	C3	-	28.00	6.14	13.31	8.00	6.14	13.23	11.00	3.00	11.00	100
	C4	-	27.66	6.43	12.68	6.34	5.97	11.94	12.86	-	16.08	100
	Average	-	29.57	6.08	12.57	7.01	6.82	11.87	12.63	0.75	12.64	-
Lake	C5	-	42.47	6.80	9.40	3.30	5.82	8.32	7.07	-	17.76	100
	C6	-	62.52	3.67	7.60	12.38	1.96	11.76	-	-	-	100
	C7	-	34.62	10.88	13.00	9.07	5.29	10.58	-	-	16.32	100
	C8	3.40	13.06	11.92	9.08	11.92	4.54	11.92	-	20.44	13.63	100
	Average	-	38.16	8.31	9.77	9.16	4.40	10.64	-	5.11	15.90	-
Main land	C9	6.13	23.46	9.82	3.54	8.86	12.27	15.95	7.63	-	12.27	100
	C10	-	15.54	7.25	28.49	6.21	3.88	-	-	-	16.57	100
	C11	-	22.32	4.96	10.42	13.39	3.72	32.74	-	-	12.40	100
	C12	-	43.79	5.76	12.10	2.01	17.28	10.37	-	-	8.64	100
	Average	-	26.27	6.94	13.63	7.61	9.28	19.68	-	-	12.47	-
Coastal shelf	C13	-	16.20	11.21	17.70	18.44	2.99	13.96	-	-	19.44	100
	C14	-	15.61	10.95	17.52	11.50	16.43	11.50	-	-	16.43	100
	C15	7.00	18.00	12.00	13.00	11.00	6.00	22.00	-	-	11.00	100
	C16	4.51	44.00	11.86	7.34	2.25	16.34	4.51	-	-	9.00	100
	Average	-	20.41	10.59	13.65	20.65	9.41	12.18	-	-	13.02	-
Total average	-	30.25	7.98	12.06	11.11	7.48	12.36	4.20	1.46	12.51	-	

whereas chlorite is present only in two samples. A comparative study of the quantitative values of clay minerals shows that illite is the dominant mineral in all the glacial units followed by smectite, vermiculite and kaolinite (Figure 7, Table 2). As such, it is difficult to establish any trend or interrelationship of clay minerals in various units; however, their mean values show that illite and

smectite are the two most dominant of all the units, as well as for the entire area, whereas kaolinite and vermiculite have almost uniform trends with low value of less than 10% (Figure 8).

Chlorites have an occasional representation with a maximum in four samples of the entire area. In general, chlorite is considered to be a common mineral of detrital

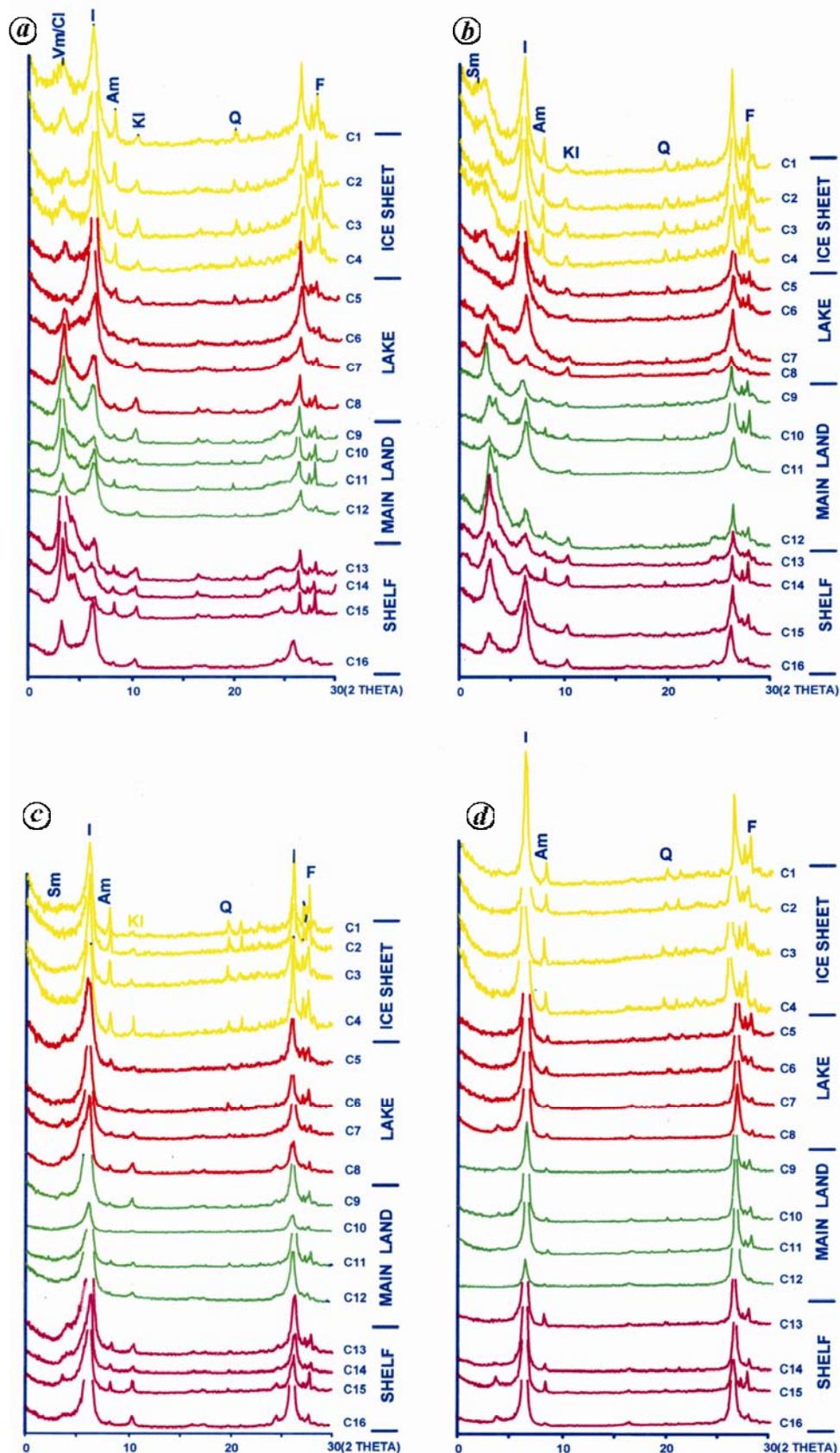


Figure 6. X-ray diffraction spectra of the samples showing clay peaks (a) Ca-saturated; (b) Ca Eg; (c), (d) K-saturated samples at 25°C and 550°C temperature respectively.

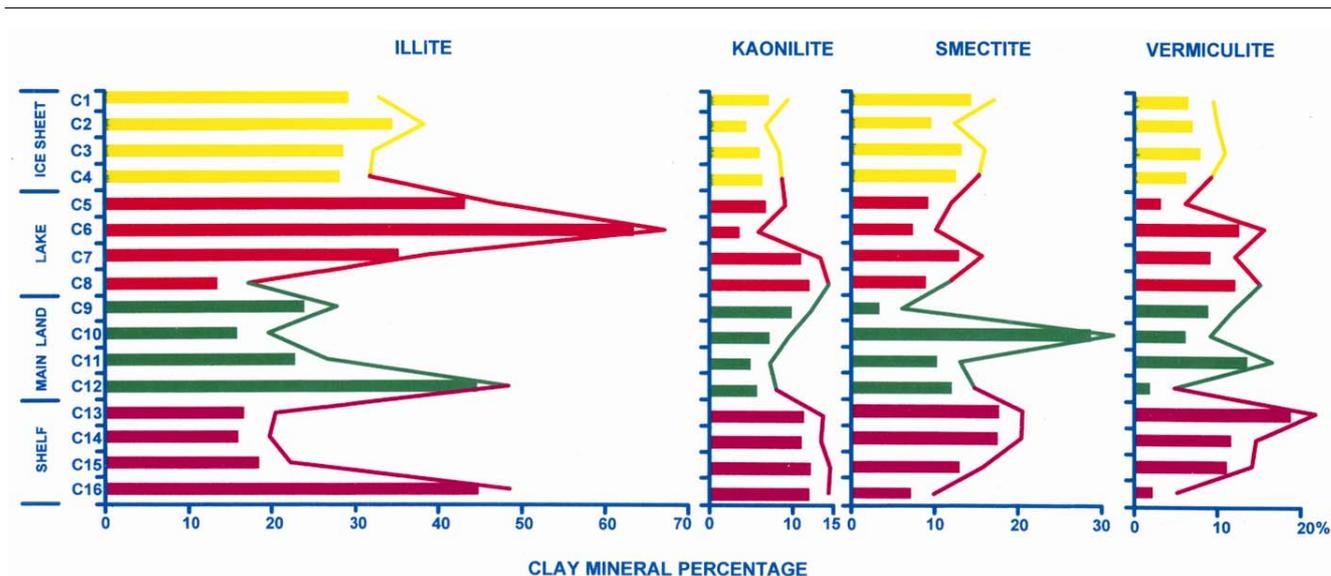


Figure 7. Percentage of various clay minerals in the clay fraction of individual samples (horizontal bar). The line denotes the irregular trend of clay minerals in various units.

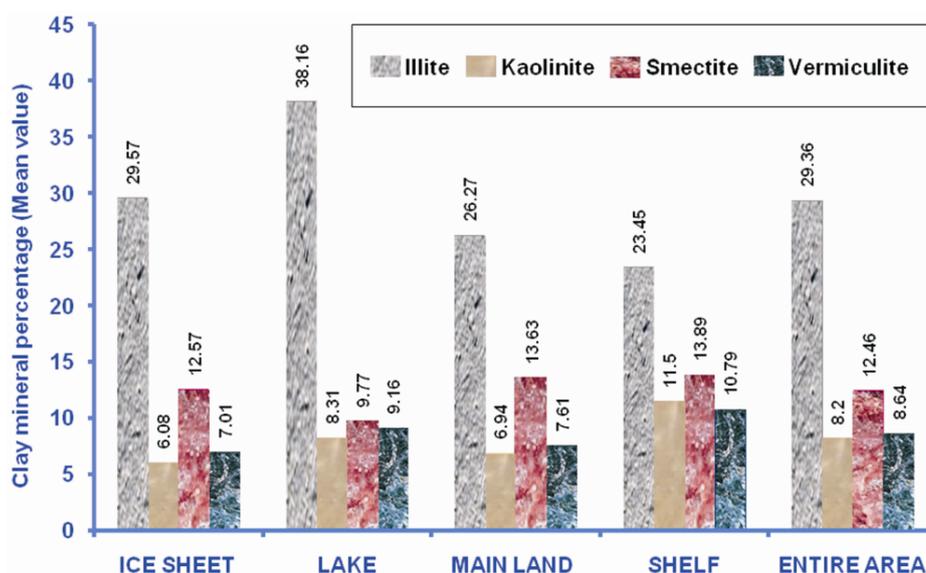


Figure 8. Comparison of mean values of various clay minerals of different units with the entire area.

origin and a product of intense weathering in tropical conditions¹⁸. However, it is frequently reported from the cold climate of the polar regions, i.e. Victorial Land Basin², Pagodroma Group³, ODP sites off Cape Roberts, McMudro Sound^{6,19}, Dronning Maud Land²⁰ of Antarctica and Greenland ice sheet²¹. Jeong and Yeon²² reported kaolinite from King George Island, West Antarctica and considered it as a weathering product of unaltered bed rock. Hillenbrand and Ehrmann^{4,23} interpreted that chlorite of the southern polar area is predominantly supplied by the physical weathering of basement metamorphic and igneous rocks and, probably the altered calc-alkaline volcanics were the major source.

Illite is a dominant mineral in all the samples with an average percentage of 30.25. In general, illite is considered as a detrital clay and derivative of acidic crystalline rock^{18,24,25}. It is common in marine environment; however, its *in situ* origin has no evidence^{24,25}. In the recent set-up, illite is noticed to be a characteristic mineral of high latitudes²⁵, and a significant tool to interpret the weathering pattern of older sediments²⁶. The mineral is widespread along the Antarctic continental margin and East Antarctic Craton^{4,19}. The source of illite in East Antarctica is suggested to be the biotite-bearing metamorphosed rocks²⁷. Ehrmann *et al.*³ suggested that in glacial regime, any metamorphic rock of low- to high-grade, as

felsic to basic plutons and dykes can produce illite. Accordingly, the occurrence of illite in the present area is conventionally justifiable as the terrain of Schirmacher is also characterized by high-grade metamorphic suite of rocks which served as the source rocks for the formation of the minerals under reference.

Kaolinite is also present in all the samples but its average percentage is the lowest, i.e. 7.89. It is a common mineral of the continent and largely reported as a weathering product under tropical condition^{18,28}. Basically, the kaolinite composition, i.e. $\text{Al}_2\text{SiO}_5(\text{OH})^+$ can be formed by any aluminium silicate by weathering, provided the K^+ , Na^+ , Ca^{++} , Mg^{++} and Fe^{++} should easily leach from the parent rock. Feldspar, particularly rich in K^+ and Na^+ , an abundant constituent of granites and gneisses, apparently yields kaolinite after weathering and leaching away of K^+ and Na^+ , mainly under the influence of groundwater²⁹.

Kaolinite has a widespread occurrence in the Antarctic region. It is a prominent mineral of the Cenozoic Battye Glacier Formation, North Prince Charles Mountain, East Antarctica³. However, low percentage of kaolinite has been reported in the Cenozoic sediments of McMurdo Sound, Antarctica⁶. Both source and origin of kaolinite were doubtfully interpreted by Ehrmann *et al.*³ and Hillenbrand and Ehrmann⁴. Since kaolinite cannot be formed under polar conditions, Ehrmann *et al.*³ suggested that in Battye Glacier Formation, it either may have been produced in an interval of warmer and wetter conditions resulting in the chemical weathering of orthogneiss, mafic granulites and quartzite, or, it is of detrital origin, derived from a distant source, probably situated beneath the ice. In the study area, feldspar is one of the major constituents of the gneissose plateau forming the basement. However, the prevailing cold climate is not favourable for the formation of kaolinite. Therefore, it is possible that temperature variations within the limits of the prevailing cold climate and humidity might have played a significant role in the formation of kaolinite through chemical weathering. The mineral as a product of chemical weathering is well reported from the drill-core sediments of the Palaeocene–Eocene boundary at Maud Rise, Weddell Sea region, East Antarctica³⁰.

Smectite is also identified in all the samples. The origin of smectite differs in different climates³¹. In the marine set-up, it can be authigenic or detrital in origin³². The authigenic variety is mainly produced by volcanism, hydrothermal activity and diagenetic processes, of which, the submarine alteration of volcanic glass and fragments is the most significant. The detrital variety comes mainly from the nearby areas; hence, it is comparatively more useful to decipher about the sediment source, palaeoclimate and weathering. The detrital smectite usually belongs to aluminous montmorillonite–beidellite series, whereas authigenic varieties are nontronites or saponites^{32,33}. In continental sediments, smectite is normally produced in humid and relatively warm climatic condi-

tions, particularly in environments having slow movement of water³².

Chamley³² suggested that smectite formation in recent Antarctic environment is only a subordinate process, reported from a few soils and tills. However, there are several reports about the occurrence of smectite in Cenozoic and Quaternary sediments, including drill cores which are interpreted for palaeoclimatic reconstruction^{1,2,34–37}. Ehrmann¹ and Setti *et al.*^{1,37} carried out a detailed study of smectite at various depths from cores drilled at Victorial Land Basin, Antarctica. The mineral showed a change in the abundance structure and crystallinity which they interpreted as due to its genetic aspects, i.e. authigenic and detrital origins of the mineral due to change in host-rock mineralogy, diagenetic process, climatic condition and hydrothermal activity. The factor responsible for the detrital origin of smectite was suggested to be from the soil of the adjacent continent during humid climate³², which is less evident in present set-up of the Schirmacher Oasis. Authigenic smectite mostly comes from transformation of volcanic rock fragments, pyroxenes and iron oxides in the sediments as well as formal detrital smectite, growth in the pore cavity similar to halite and coating on the surface of detrital grains^{3,6}. Similarly, smectite as a thick radial overgrowth on the quartz grains is also an authigenic process³⁸. Setti *et al.*³⁹ suggested that smectite may precipitate from fluids mixed with marine water. However, low temperature, hydrothermalism and burial diagenesis play a significant role in the formation of authigenic smectite^{3,6}, of which hydrothermalism is a more likely process than burial diagenesis³⁹. The transformation of pyroxenes, iron oxides and volcanic fragments seems to be more logical for the present samples as the Schirmacher Oasis is well represented by pyroxene as a major constituent of pyroxene pegmatite, lamprophyres, pyroxene–granulite, khondalite, etc. though the terrain is dominantly felsic in nature. Volcanic rocks in the form of intrusions of basalt and dolerite are frequently reported from the area¹².

Vermiculite also makes a frequent occurrence with almost the same average value as that of smectite, i.e. 11.11. Reports of its occurrence from the surface sediments and drill cores are comparatively less from the Antarctic Peninsula and Antarctic Ocean; however, it has been widely reported from the soil, i.e. Lassiter Coast, south of Antarctic Peninsula⁴⁰ and Prince Charles Mountain^{41,42}. Vanderaveroet *et al.*⁴³ analysed the Pleistocene sediments of northwestern Atlantic Ocean and identified the presence of illite–vermiculite mixed layer. They interpreted that these micas are derived from chemical weathering of micaceous phyllosilicates due to erosion of high-latitude continental areas. Kristoffersen *et al.*²⁰ reported its occurrence from shallow drill core, up to 15 m below the sea bed from the continental shelf, Weddell Sea, Antarctica, and considered its origin from the primary mica due to hydration.

Conclusion

Clay minerals, viz. chlorite, illite, kaolinite, smectite and vermiculite have been identified in the loose sediments of ice sheets, mainland, including lakes, and shelf area, with the help of thermograms and XRD analysis. Illite is noticed to be a dominant clay mineral followed by smectite and vermiculite, whereas chlorite is found occasionally. Most of the clay minerals are formed due to weathering and alterations of highly metamorphosed terrain of Schirmacher in the cold climate, e.g. chlorite from the physical weathering of metamorphic and igneous rocks, similar to illite in the same manner however, felsic pluton contributed more for the later. Kaolinite is a product of chemical weathering of feldspar in which temperature variations have also played a significant role. Smectite is interpreted to be of authigenic origin formed due to transformation of pyroxene, basalt and dolerite, whereas vermiculite is derived from the primary micas.

The climatic interpretation of these minerals favours the existing cold climate of the region. Though the prevailing climate of the region is cold, variation in temperature is quite evident, as well as that of humidity in summer and winter periods. These factors also play a role in chemical weathering as revealed by the formation of kaolinite through feldspar. The origin and climatic interpretations of the presently reported clay minerals in the area are also well supported by published data on the clay of various other parts of East Antarctica, e.g. McMurdo Sound, Victoria Land Basin, Prince Charles Mountain, etc.

1. Ehrmann, W., Smectite content and crystallinity in sediments from CRP-3, Victoria Land Basin, Antarctic. *Terra Antarct.*, 2001, **8**(4), 533–542.
2. Setti, M., Marinoni, L. and López-Galindo, A., Crystal chemistry of smectite in sediments of CRP-3 drill core (Victoria Land basin, Antarctica): preliminary results. *Terra Antarct.*, 2001, **8**(4), 543–550.
3. Ehrmann, W., Bloemendal, J., Hambrey, J. M., McKelvey, B. and Whitehead, J., Variations in the composition of the clay fraction of the Cenozoic Pagodroma Group, East Antarctica: implications for determining provenance. *Sediment. Geol.*, 2003, **161**, 131–152.
4. Hillenbrand, C. D. and Ehrmann, W., Palaeoenvironmental implications of Tertiary sediments from Kainan Maru Seamount and northern Gunnerous Ridge. *Antarct. Sci.*, 2003, **15**(4), 522–536.
5. Hillenbrand, C. D. and Ehrmann, W., Late Neogene to Quaternary environmental changes in the Antarctic Peninsula region: evidence from drift sediments. *Global Planet. Change*, 2005, **45**, 165–191.
6. Ehrmann, W., Setti, M. and Marinoni, L., Clay minerals in Cenozoic sediments off Cape Robert (McMurdo Sound, Antarctica) reveal palaeoclimatic history. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 2005, **229**, 187–211.
7. Lal, M., Sedimentology of the glacial sands and lake terraces sediments from Schirmacher Oasis and sea bed sediment of Princess Astrid Coast, Queen Maud Land, Antarctica. In Third Indian Scientific Expedition to Antarctica, Technical Publ., 1986, vol. 3, pp. 219–223.
8. Khun, G., Melles, M., Ehrmann, W. U., Hambrey, M. J. and Schmiel, G., Character of clasts in glaciomarine sediments as an indicator of transport and deposition processes, Weddell and Lazarev Seas, Antarctica. *J. Sediment. Petrol.*, 1993, **63**(3), 477–487.
9. Asthana, R. and Chaturvedi, A., The grain size behavior and morphology of supraglacial sediments, south of Schirmacher Oasis, East Antarctica. *J. Geol. Soc. India*, 1998, **52**, 557–568.
10. Srivastava, A. K. and Khare, N., Granulometric analysis of glacial sediments, Schirmacher Oasis, East Antarctica. *J. Geol. Soc. India*, 2009, **73**, 609–620.
11. Srivastava, A. K., Khare, N. and Ingle, P. S., Textural characteristics, distribution pattern and provenance of heavy minerals in glacial sediments of Schirmacher Oasis, East Antarctica. *J. Geol. Soc. India*, 2009, **75**, 393–402.
12. Sengupta, S., Geology of Schirmacher range (Dakshin Gangotri), East Antarctica. In Third Indian Scientific Expedition to Antarctica, Technical Publ., 1986, vol. 3, pp. 187–217.
13. Ravindra, R., Geomorphology of Schirmacher Oasis, East Antarctica. In Proceedings of the Symposium on Snow, Ice and Glacier. Geological Survey of India, Special Publication 53, 2001, pp. 379–390.
14. Jackson, M. L., *Soil Chemical Analysis – Advance Course*, Department of Soil Science, Wisconsin University, Madison, USA, 1979, 2nd edn, p. 895.
15. O’Gorman, J. V. and Walker, P. L., Thermal behaviour of mineral fractions separated from selected American coals. *Fuel*, 1973, **52**, 71–79.
16. Kotoky, P., Bezbaruah, D., Baruah, J., Borah, G. C. and Sharma, J. N., Characterization of clay minerals in the Brahmaputra river sediments, Assam, India. *Curr. Sci.*, 2006, **91**(9), 1247–1250.
17. Lipsey, G., *Atlas of Thermoanalytical Curves*, Akademiai Kiado, Budapest, 1973, pp. 84–85.
18. Biscaye, P. E., Mineralogy and sedimentation of recent deep-sea clay in Atlantic Ocean and adjacent seas and oceans. *Geol. Soc. Am. Bull.*, 1965, **76**, 803–832.
19. Tingey, R. J., *The Geology of Antarctica*, Oxford Monographs on Geology and Geophysics, Clarendon Press, Oxford, 1991, vol. 17, p. 650.
20. Kristoffersen, Y., Strand, K., Vorren, T., Harwood, D. and Webb, P., Pilot shallow drilling on the continental shelf, Dronning Maud Land, Antarctica. *J. Antarct. Sci.*, 2000, **4**, 463–470.
21. Drab, E., Gaudichet, A., Jaffrezo, J. L. and Colin, J. L., Mineral particles content in recent snow at summit (Greenland). *Atmos. Environ.*, 2002, **36**, 5365–5376.
22. Jeong, G. Y. and Yeon, H. I., The origin of clay minerals in soils of King George Island, South Shetland Islands, West Antarctica, and its implication for the clay mineral composition of marine sediments. *J. Sediment. Petrol.*, 2001, **71**, 833–847.
23. Hillenbrand, C. D. and Ehrmann, W., Distribution of clay minerals in drift sediments on the continental rise west of Antarctic peninsula, ODP leg 178, sites 1095 and 1096. In Proc. ODP, Sci. Results (eds Barker, P. F. *et al.*), 2001, vol. 178, pp. 1–29.
24. Griffin, J. J., Windom, H. and Goldberg, E. D., The distribution of clay minerals in the World Ocean. *Deep-Sea Res.*, 1968, **15**, 433–459.
25. Windom, H. L., Lithogenous material in marine sediments. In *Chemical Oceanography* (eds Riley, J. P. and Chester, R.), Academic Press, New York, 1976, vol. 5, pp. 103–135.
26. Holmes, M. A., Clay mineral composition of glacial erratics, McMurdo Sound. *Antarct. Res. Ser.*, 2000, **76**, 63–72.
27. Diekmann, B. and Kuhn, G., Provenance and dispersal of glacial-marine surface sediments in the Weddell Sea and adjoining areas, Antarctica: ice-rafting versus current transport. *Mar. Geol.*, 1999, **158**, 209–231.
28. Singer, A., The palaeoclimatic interpretation of clay minerals in sediments: a review. *Earth Sci. Rev.*, 1984, **21**, 251–293.

RESEARCH ARTICLES

29. Keller, W. D., Environmental aspects of clay minerals. *J. Sediment. Petrol.*, 1970, **40**, 788–813.
30. Robert, C. and Kennett, J. P., Antarctic humid episode of Palaeocene–Eocene boundary: clay mineral evidence. *Geology*, 1994, **22**(3), 211–214.
31. Güven, N., Smectites. In *Hydrous Phyllosilicates, Reviews in Mineralogy* (ed. Bailey, S. W.), Mineralogical Society of America, 1988, vol. 19, pp. 497–552.
32. Chamley, H., *Clay Sedimentology*, Springer, 1989, p. 623.
33. Hiller, S., Erosion, sedimentation and sedimentary origin of clays. In *Origin and Mineralogy of Clays* (ed. Welde, B.), Springer, 1995, pp. 162–219.
34. Campbell, I. B. and Claridge, G. G. C., *Antarctica: Soil, Weathering Processes and Environment*, Elsevier, Amsterdam, 1987, p. 368.
35. Robert, C. and Maillot, H., Palaeoenvironments in the Weddel Sea area and Antarctic climates, as deduced from clay mineral associations and geochemical data ODP Leg 11. In *Proc. ODP, Sci. Results* (eds Barker, P. F. *et al.*), 1990, vol. 113, pp. 51–70.
36. Ehrmann, W. and Mackensen, A., Sedimentological evidence from the formation of an East Antarctic ice-sheet in eocene/oligocene time. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 1992, **93**, 85–112.
37. Setti, M., Marinoni, L., López-Galindo, A. and Delgado Huertas, A., Compositional and morphological features of the smectite of sediments of CRP-2/2A, Victoria Land basin, Antarctica. *Terra Antarct.*, 2000, **7**(4), 581–587.
38. Wise Jr, S. W., Smellie, J., Aghib, F., Jarrard, R. and Krissek, L., Authigenic smectite clay coats in CRP-3 drillcore, Victoria Land Basin, Antarctica, as a possible indicator of fluids flow: a progress report. *Terra Antarct.*, 2001, **8**(3), 281–298.
39. Setti, M., Marinoni, L. and López-Galindo, A., Mineralogical and geochemical characteristics (major, minor, trace elements and REE) of detrital and authigenic clay minerals in a Cenozoic sequence from Ross Sea, Antarctica. *Clay Miner.*, 2004, **39**, 405–422.
40. Boyer, S. J., Chemical weathering of the rocks on the Lassiter Coast, Antarctic peninsula, Antarctica. *N. Z. J. Geol. Geophys.*, 1975, **18**(4), 623–628.
41. Bardin, V. I., Bubnova, M. I. and Gerasimova, V. M., Clay minerals in unconsolidated deposits of the Prince Charles Mountains. *Inf. Bull. Sov. Antarct. Exped.*, 1979, **71**, 120–128.
42. Bardin, V. I., Composition of East Antarctic moraines and some problems of Cenozoic history. In *Antarctic Geoscience* (ed. Craddock, C.), University of Wisconsin Press, Madison, USA, 1982, pp. 1069–1076.
43. Vanderaveroot, P., Bout-Roumazeilles, V., Fagel, N., Chamley, H. and Deconinck, J. F., Significance of random illite–vermiculite mixed layers in Pleistocene sediments of the northwestern Atlantic Ocean. *Clay Miner.*, 2000, **35**, 679–691.

ACKNOWLEDGEMENTS. We thank Dr D. K. Pal, National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), Nagpur for valuable suggestions. Financial assistance in the form of a major research project (No. 24/287/06EMR-II), funded by CSIR, New Delhi is acknowledged. XRD analysis was carried out at NBSS & LUP and DTA/TGA at SAIF, IIT Mumbai. Samples were collected by one of the authors (A.K.S.) as a Member, Summer Team, 21st Indian Antarctica Expedition organized by NCAOR, Goa. The cooperation extended by R. P. Lal, and other team members to carry out this work is acknowledged.

Received 25 August 2009; revised accepted 11 November 2010