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

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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, Antarctica¹,², 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 migmatises, 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
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 lakes. These lakes, receiving sediments from upland and surrounding areas, also serve as sites of sediment accumulation (Figure 3a).

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 3b). 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 3c).

**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.
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.

**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).
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 Jackson.14

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, CuKα radiation with a scanning speed of 2°2Ø 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).

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.
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\(^\text{15,16}\).

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 clays\(^\text{17}\) (Figure 5).

X-ray diffractograms

All the six diffractograms of each sample, i.e. saturated with Ca (Figure 6\(\text{a}\)), glycolated (Figure 6\(\text{b}\)), treated with K and heated at 25°C (Figure 6\(\text{c}\)), 100°C, 300°C and 550°C (Figure 6\(\text{d}\)) have been analysed for clay minerals identification. The criteria for identification are the peak values of the minerals\(^\text{14}\). 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 minerals\(^\text{11}\). Major, minor and trace elements analysis of +0.0625 to +0.125 mm sediments, in general, shows the dominance of SiO\(_2\), followed by Al\(_2\)O\(_3\) and MgO. CaO, Na\(_2\)O and K\(_2\)O 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 activities\(^\text{10}\).

The clay minerals, viz. illite, kaolinite, smectite and vermiculite have been identified in all the samples,
Table 1. Differential thermal analysis (DTA) and thermogravimetric analysis (TGA) values of the samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Onset (°C)</th>
<th>Peak (°C)</th>
<th>Peak height (μV)</th>
<th>Area (μV × s)</th>
<th>Weight gain (%)</th>
<th>Weight loss (%)</th>
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<td>Ice sheet</td>
<td>C1</td>
<td>582.55</td>
<td>585.51</td>
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<td></td>
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<tr>
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<td>45.289</td>
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<tr>
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<td>586.15</td>
<td>–0.772</td>
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<td>586.13</td>
<td>–0.410</td>
<td>14.546</td>
<td>0.509</td>
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<td>–0.670</td>
<td>28.741</td>
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<tr>
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<td>–0.605</td>
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<td>–0.538</td>
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</tr>
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<td>586.17</td>
<td>–0.476</td>
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<td>17.130</td>
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</tr>
<tr>
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<td>C16</td>
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<td>585.75</td>
<td>–0.387</td>
<td>21.171</td>
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Table 2. Clay minerals percentage in fine-grained fraction of the sample

<table>
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<tr>
<th>Minerals identified/ sample no.</th>
<th>Chlorite</th>
<th>Illite</th>
<th>Kaolinite</th>
<th>Smectite</th>
<th>Vermiculite</th>
<th>Quartz</th>
<th>K-Feldspar</th>
<th>Ca-Feldspar</th>
<th>Mixed layer</th>
<th>Amphibole</th>
<th>Total (%)</th>
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<td>7.20</td>
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<td>6.60</td>
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<td>11.50</td>
<td>12.70</td>
<td>–</td>
<td>9.60</td>
<td>100</td>
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<tr>
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<td>4.57</td>
<td>9.79</td>
<td>7.11</td>
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<td>10.83</td>
<td>13.96</td>
<td>13.88</td>
<td>–</td>
<td>13.88</td>
<td>100</td>
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<td>13.24</td>
<td>11.00</td>
<td>11.00</td>
<td>3.00</td>
<td>11.00</td>
<td>100</td>
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<td>6.43</td>
<td>12.68</td>
<td>6.34</td>
<td>5.97</td>
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<td>12.86</td>
<td>–</td>
<td>12.86</td>
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<td>6.80</td>
<td>9.40</td>
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<td>5.82</td>
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<td>11.11</td>
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<td>12.51</td>
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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.

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\cite{18,24,25}. It is common in marine environment; however, its \textit{in situ} origin has no evidence\cite{24,25}. In the recent set-up, illite is noticed to be a characteristic mineral of high latitudes\cite{25}, and a significant tool to interpret the weathering pattern of older sediments\cite{26}. The mineral is widespread along the Antarctic continental margin and East Antarctic Craton\cite{5,57}. The source of illite in East Antarctica is suggested to be the biotite-bearing metamorphosed rocks\cite{25}. Ehrmann et al.\cite{1} suggested that in glacial regime, any metamorphic rock of low- to high-grade, as
Kaoilinite 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\(^{10,28}\). Basically, the kaolinite composition, i.e. \(\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_8\) 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 groundwater\(^{29}\).

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 Antarctica\(^2\). However, low percentage of kaolinite has been reported in the Cenozoic sediments of McMurdo Sound, Antarctica\(^9\). Both source and origin of kaolinite were doubtedly interpreted by Ehrmann et al.\(^3\) and Hillenbrand and Ehrmann\(^1\). 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 Antarctica\(^30\).

Smectite is also identiﬁed in all the samples. The origin of smectite differs in different climates\(^31\). In the marine set-up, it can be authigenic or detrital in origin\(^2\). 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, palaeoclimatic 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 conditions, particularly in environments having slow movement of water\(^32\).

Chamley\(^2\) 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\(^1,2,34–37\). Ehrmann\(^1\) and Setti et al.\(^1,37\) carried out a detailed study of smectite at various depths from cores drilled at Viciolar 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 climate\(^2\), 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 process\(^39\). 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\(^5,6\), of which hydrothermalism is a more likely process than burial diagenesis\(^39\). 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 area\(^2\).

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 Peninsula\(^40\) and Prince Charles Mountain\(^41,42\). Vandervorret 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 interpretation of these minerals favours the formation of pyroxene, basalt and dolerite, whereas chlorite is derived from the primary micas.


**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