Chapter

# Geomorphological Insight of Some Ice Free Areas of Eastern Antarctica

*Rasik Ravindra, Badanal Siddaiah Mahesh and Rahul Mohan*

## Abstract

The Schirmacher Oasis and Larsemann Hills are among the few significant ice free areas of East Antarctica that are conspicuous due to presence of more than a hundred melt water lakes each, preserving the signatures of climatic variation and deglaciation history since Last Glacial Maximum (19 to 24 ky BP) and beyond. There are evidences, recorded in the lake sediments of low lying Larsemann Hills, of marine transgression due to variation in sea level, isostatic upliftment and close vicinity of the Hills to the marine environment. The Schirmacher Oasis, on the other hand has preserved various landforms-both erosional and depositional-typical of a periglacial environment along with proglacial lakes (incorporating signals of ice-sheet dynamics) and epishelf lakes (signatures of marine influence) .

**Keywords:** geomorphological evolution, Schirmacher and Larsemann Hills, Paleoclimate

## 1. Introduction

The Antarctic continent, comprised of two distinct physiographic and tectonic domains i.e. the West Antarctica and the East Antarctica is divided into two unequal parts by a 3500 km long Transantarctic Mountain chain extending across the continent between the Ross and the Weddell Sea (**Figure 1**). The inhospitable climate, inaccessible terrain conditions with 98% of the terrain being covered by a thick apron of ice, the scanty outcrops are the best alternative (if not the only) to peep into the Continent's geological history. The rock outcrops are exposed in discontinuous mountain chains, along the coastal fringes of Antarctic Peninsula, West Antarctica, the Dronning Maud land, Enderby Land, Princess Elizabeth Land, Wilkes Land and Victoria Land in the east Antarctic Sector, apart from the Trans-Antarctic Mountains. (**Figure 1**). The interior of the Antarctic mainland is entirely ice covered and rise as ice plateau, attaining maximum height of around 3233 m above mean sea level (m.s.l.).

## 2. Ice free areas of East Antarctica

The East Antarctic coast is marked by a discontinuous mountain chain that can be traced intermittently all along the coast from $75^0$ 45′ E longitudes to $15^0$

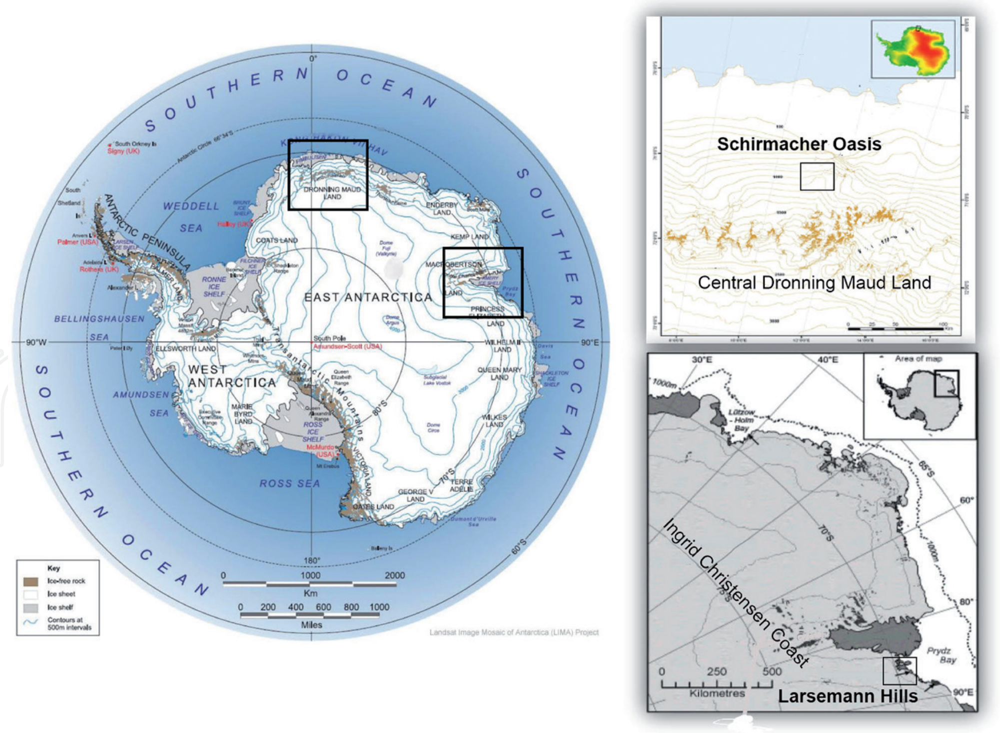


**Figure 1.**
*Map of Antarctica the Southern Ocean (Landsat image mosaic of Antarctica (http://lima.nasa.gov/pdf/A3_overview.pdf), with inset showing locations of Schirmacher and Larsemann Hills.*

West longitudes, running nearly parallel to the coast line. There are some low lying, ice free areas in the coastal Antarctica such as the Schirmacher Oasis, Larsemann Hills, Vestfold Hills, Bunger Hills etc., that have been studied in detail for Late Pleistocene (~ 0.12 My) and Holocene glacial History [1–12]. These oases are distinguished from nunataks by the process of ablation. While most nunataks are located in the accumulation zone of glaciers and are kept free of ice by the strong winds, the oases are separated from the ice sheet by a distinct ablation zone. Schirmacher Oasis and Larsemann Hills, the two areas being discussed here, are such ice free regions that were covered by the ice sheet during the Last Glacial Maxima (LGM) or earlier, but are now exposed due to retreat of ice sheet.

Schirmacher Oasis (approximately 35 $km^2$ in area) is situated between longitudes $11^0$ 25′ E and $11^0$ 55′E and latitudes $70^0$ 44’S and $70^0$ 46’S, about 85 km inland of the Princess Astrid coast at the northern fringe of central Dronning Maud land. Larsemann Hills on the other hand, is spread over ~50 $Km^2$ [12] and comprise a group of ice free peninsulas (Broknes, Stornes and Brattnavet) Grovnes promontory and islands (McLeod, Fischer, Sandercock Island etc.) - located south of Prydz Bay at 69”24’S, 76′20’E on the Ingrid Christensen Coast of Princess Elizabeth Land that lie in between the Vestfold Hills and Amery Ice shelf. The two areas (Schirmacher Oasis and Larsemann Hills) are nearly 3000 km apart and experience different scale of environment, severity of climatic conditions and paleoclimate history.

The retreating ice sheet left bare rocks to be exposed to the strong Antarctic winds and other erosional processes. The areas demonstrate subdued topography with strong control of lithology and structure over the landscape. The low lying hills are devoid of horns, arêtes or conical peaks. The flat hills, dominate the landscape. The softer rock material has weathered out giving way to the glacial melt to form scores of lakes in the depressions thus created. The freeze–thaw cycles, frost action and the salt weathering are conspicuous and have resulted in formation of conspicuous landscape typical of periglacial and glacial environment [13].

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## 3. Schirmacher oasis

### 3.1 Physiography

Schirmacher Oasis and adjoining areas depict contrasting morphological units, viz. (a) the ice shelf to the north, (b) the structural hills, and (c) the continental or polar ice sheet to the south (**Figures 2**, **3** and **5**). The morphological features as seen in the ice and ice dominated regions around Schirmacher constitute an integral part of geomorphology of the region.

The ice shelf extends for about 80 km north of Schirmacher Oasis towards the Southern Ocean and displays a highly rugged and broken undulating upper surface dissected by a number of pressure ridges, crevasses and pods of melt water concentration in the western parts, as compared to a low gradient surface in the eastern sector. The Pressure ridges, formed due to the tidal activity in the sea below, and the obstacle offered by the landmass, are often seen at the contact of ice shelf and continent (**Figures 3** and **5**). A number of melt water channels concentrated close to the hills, in this part, can be noted. The continental ice sheet that encircles the Schirmacher Oasis overrides the bare rocks on its southern side. It has a regional

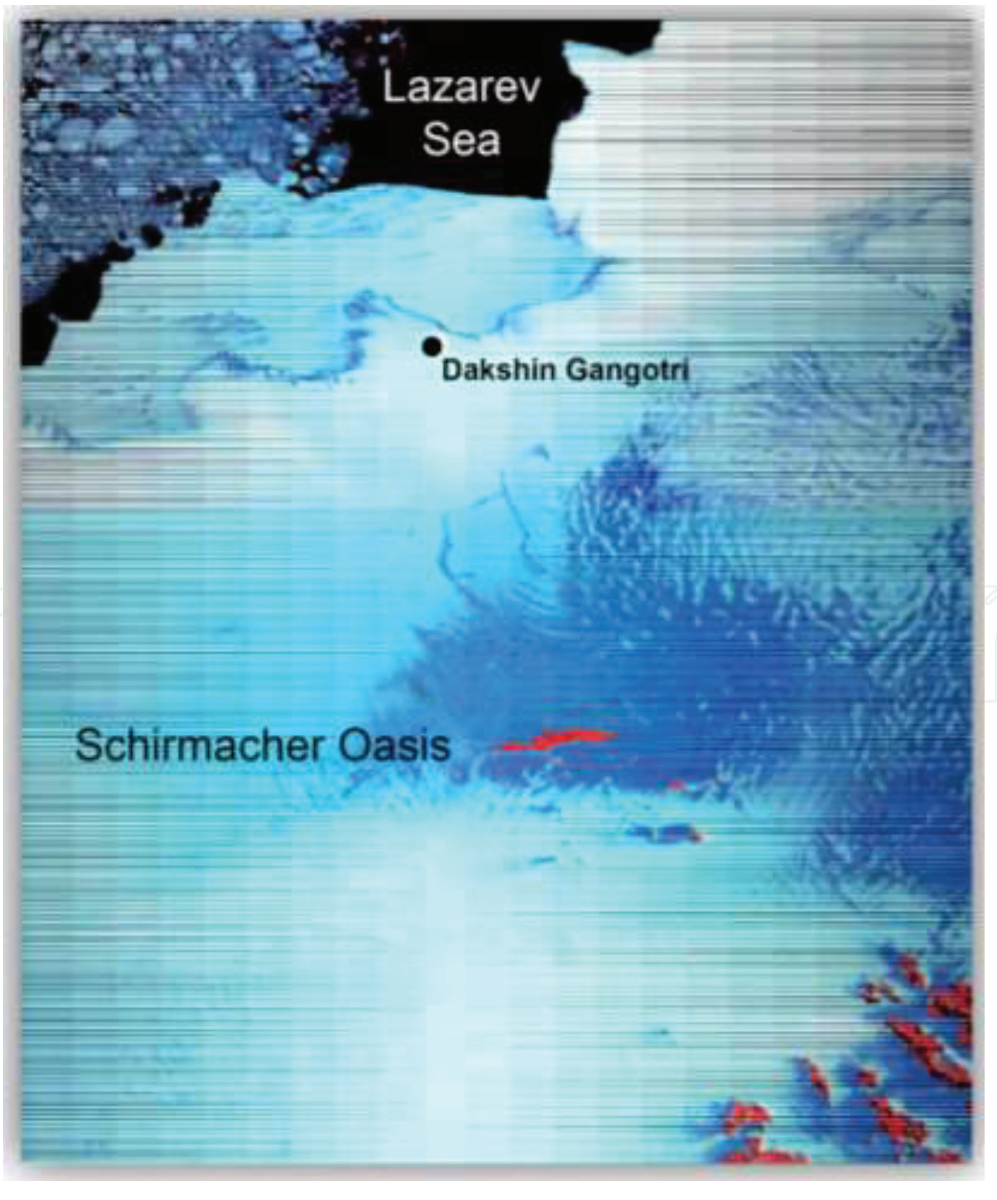


**Figure 2.**
*Map of Schirmacher oasis showing location of Maitri (Indian Research Station) with ice shelf and continental ice.*

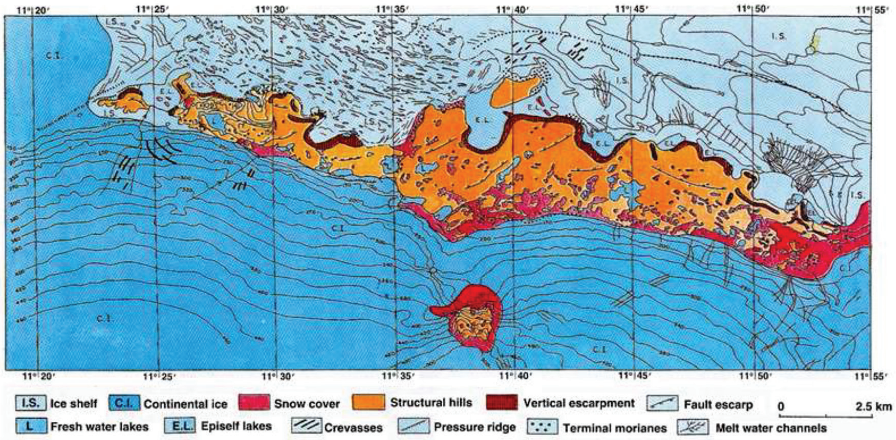


**Figure 3.**
*Geomorphological map of Schirmacher oasis.*

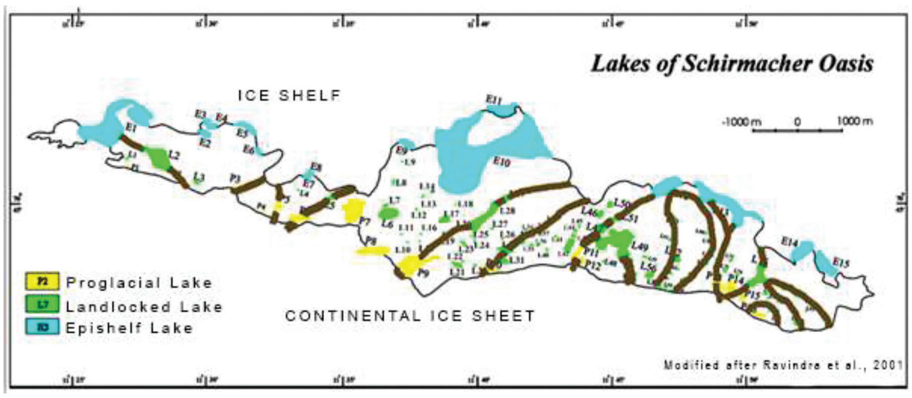


**Figure 4.**
*Distribution of fresh water lakes in Schirmacher oasis and paths of glacier movement.*

northerly gradient but locally the flow has swerved because of the nunataks and the land mass of Schirmacher which offered a resistance to its normal flow. The western component of gradient is conspicuous. A broken trail of end moraines is seen at the contact of continental ice-sheet and rocks of Schirmacher at some places in eastern margin.

The rocks of Schirmacher Oasis are aligned in ENE-WSW direction and represent middle Proterozoic sequence of quartzo-feldspathic gneiss, augen gneiss, quartzite and sillimanite garnet gneiss etc. bearing close similarity to the khondalite rocks of eastern and southern India. The rocks exposed in the form of low lying hills extend roughly for about 17 km in length and 3 km in width (at its widest in the central parts), covering an area of ~35 sq. km. The ice-free area exhibits rolling subdued topography with concordant hill tops. At both its eastern and western extremities, the hills are comparatively low lying, smoothened and capped by a thin veneer of glacier boulders. The ice-free area exhibits rolling subdued topography with concordant hill top. At both its eastern and western extremities, the hills are comparatively low lying, smoothened and capped by a thin veneer of glacier boulders The elevation varies from sea level (at the margin of westernmost lake, which has broken the apparent continuity of rocks). The central part, on the other hand, exposes hills that are comparatively higher in elevation with isolated peaks of the order of 212 m and 228 m. On an average, the height varies between 120 and 130 m above m.s.l. The southern end of the Schirmacher range is slightly elevated in comparison to the steep northerly margin. The northern margin is conspicuous by its vertical escarpment almost all along its length (**Figure 3**). The escarpment at places is more than 140 m as in the central part (70° 43′ 30″S,11°42′E). The jagged hills south of Schirmacher Oasis forms a part of the Wohlthat Mountains which rise to elevation 3500 m above m.s.l. leading to Polar Plateau, further south wards (**Figure 2**).

The landscape of Schirmacher Oasis is dotted by more than a hundred lakes of varying dimensions (**Figure 4**). The retreating ice cap vacated the land mass and exposed the rocks of Schirmacher Oasis, scooping out the material from weaker zones in the terrain. There were also blockages created at the mouth of glaciers due to dumping of debris carried by some glaciers. Due to these phenomenon, a number of inland lakes came into existence. Aerial survey over Schirmacher Oasis reveals a definite pattern of concentration of these lakes. Considering the morphological disposition of such lakes and their genesis, these lakes have been grouped in three different classes viz., Proglacial Lakes, Periglacial Lakes (also land locked/inland lakes) and Epishelf Lakes [14]. Proglacial and periglacial lakes dominate in number over the Epishelf lakes and together account for about 87% of the total lakes. The Proglacial Lakes, formed as a result of scouring of the rocks lying at the foot of snout tongues of glaciers, are located at the margin of continental ice sheet and run all along the southern end of Schirmacher Oasis. A NNE–SSW trending lineament cutting across all the three physiographic units viz. continental ice sheet, shelf ice and hard rock, located in the eastern part, defines a prominent fault running for nearly 8.5 km. It is seen as a well-defined crevasse zone in the former two units while in the later unit, it manifests itself in the form of shearing, tight folding, and escarpment demonstrating the structural control over geomorphology.

In the central region, the orientation and location of some inland lakes define a palaeo-channel. The path of the extinct glacier is evident from the U-shaped valley containing sporadic shallow lakes. These lakes have been carved out from structural and lithological weak zones like shears, lineaments, faults etc. (**Figure 3**). The palaeo-paths of the glaciers reconstructed using the evidences of glacial striations, moraine deposits etc., indicate a bimodal direction of the glaciers i.e., NE to ENE in the western and central parts while NNW in the eastern parts (**Figure 4**). This observation is supported by the results obtained by GPS campaign [15] that shows varying magnitude of the horizontal velocities in the range of 1.89–10.88 $ma^{-1}$. There are a number of epishelf lakes that are located at the northern margin of Schirmacher Oasis which have been described as 'sea bays' (**Figure 6**) as these are connected to sea from beneath and thus respond to tidal waves as is evidenced by pressure ridges. The loci of these epishelf lakes also coincide with the sites where glacial flows must be debauching the ablation material including moraines and melt water as is evidenced by the concavity of the hills and vertical escarpment at these locations.

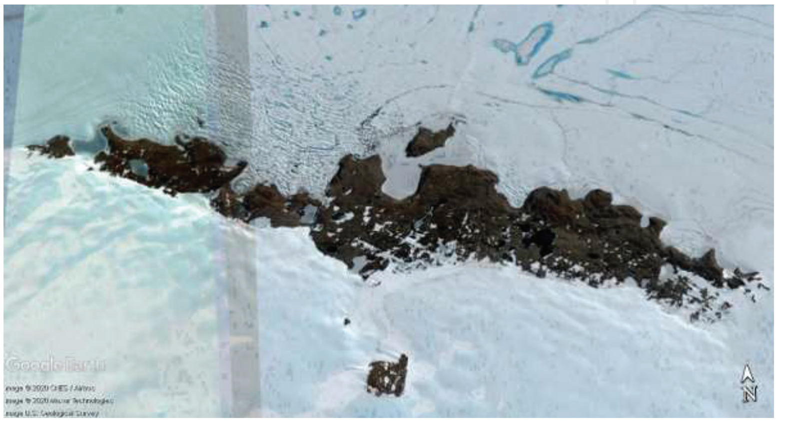


**Figure 5.**
*Aerial photographic mosaic of Schirmacher displaying three physiographic units (A, B and C), Pressure Ridges and disposition of lakes defining lineaments.*

**Figure 6.**
*An Epishelf lake (E13) at northern margin of Schirmacher oasis. Note the vertical escarpment at the margin of lake. Continental ice sheet is located overriding part of hill (photo courtesy: Prof. Yusuke Suganuma, NIPR, Japan, SONIC: India-Japan coring expedition).*

### 3.2 Deglaciation history

The Antarctic ice sheet extended across the continental shelf edge, before and during the LGM. The interior surface-elevation of ice sheet did not change significantly, but there was thickening of the ice around the edge of Antarctica. The LGM ice volume accounted for ~120 m of sea level lowering. Abrupt sea level rise occurred at 19,000 calendar years ago [16] following the beginning of Termination/deglaciation and at 14,200 (Melt water Pulse 1A, MWP1A). Detailed records of $\delta^{18}O$ reveal that the last isotopic maximum (LIM, near 18,000 cal years BP) is younger than the LGM as defined by sea level low stand (~ 21 cal ka BP). This suggests early warming of the deep sea, and implies that the deep ocean circulation must have played a key role in the termination of the LGM. During the last glacial cycle (between 19 and 71 cal ka BP), a sizeable portion of high latitude continental shelf was occupied by ice sheets. Ice sheets on the shelf were inherently unstable, being controlled by sea level. Therefore shelf glaciations played a critical role in the dynamics of deglaciation.

The isostatic rebound, a consequential to retreat of ice sheet, has resulted in uplifting of the landmass. Though the exact component of uplift cannot be quantified due to lack of beach features, the morphological evidences such as: a) existence of comparatively higher relief of the structural hills on the northern periphery of the landmass than the central corridor, b) the steep escarpment at the northern margin, and c) the indication of a fault running all along the northern margin give credence to the statement.

The different processes of deposition and erosion under the prevailing periglacial environment have left their imprints on the morphology of Schirmacher Oasis. There was an extensive phase of erosion in operation, during and after the retreat of glacier as evidenced from the erosional features such as a) rolling topography, b) absence of sharp peaks, c) glacial striations and polishing of the rock surfaces and d) the existence of en-echelon pattern of the Roche Moutonees over a large area in the oasis. Features such as block fields, cavernous pits, etc. were formed due to extreme variation in the diurnal temperatures and strong wind erosion. The superimposition of the wind features on the glacial imprints, as seen under electron microscope imply the long period of exposure of the terrain to the weathering processes after the retreat of the ice mass. The depositional features are marked by extensive moraines, terraces, erratic boulders on hill tops and lacustrine deposits. The detailed description of landforms is given by [13].

The existing planar surfaces of the Schirmacher Oasis offer a unique landscape that indicates a pre-Holocene weathering profile. In the absence of the reliable dating, it is not possible to comment with firm conviction if the surface has been a result of Mesozoic weathering profile subsequent to fragmentation and breaking of Gondwanaland supercontinent or a Pleistocene event. However, reported ages of 53.7 ± 8.2 and 51.2 ± 9.4 ka from two sediment cores [17] obtained from the lakes of Schirmacher Oasis could be correlated with the beginning of the oxygen isotopic stage 3 (MIS 3). The surficial glacial till deposit have been dated by him at 30 to 40 cal ka BP [17]. Such an old age does give credence to the hypothesis that Schirmacher was ice free during LGM and before. This is also supported by the studies [18] from other Eastern Antarctic Oases, such as Bunger and Larsemann Hills, believed to be vacated by ice much before LGM.

Two long sediment cores collected from the L-49 have been dated at different depths. The oldest dates obtained from the basal and near basal sections at 168 to 174 cm from the top have been dated at 30,640 years and 32,655 years BP. Cold conditions prevailed in the Schirmacher Oasis from 30,640–21,685 years B.P. having a low sedimentation rate of 0.005 mm/year. Warmer conditions existed between 32,655–30,640 years B.P. with a higher sedimentation rate of 0.015 mm/year. The $^{14}C$ dates of another core suggested a wet climate between 29,920–28,890 years B.P. with a sedimentation rate of 0.09 mm/year [19]. Study of clay minerals from core samples has led [20] propose that there was a gradual shift in the weathering regime and climate from strongly glacial to fluvio- glacial specially around 42 ka..

Reconstruction of the paleoclimate history from the pollen spores present in the sediment samples of Lake (L-49) by [21] shows that the region witnessed cold and dry climate during 10–9 ka B.P. followed by a long phase of warm and moist climate from 9 to 2.4 ka B.P. Subsequently from 2.4–1 ka B.P. onwards, dry and cold conditions set in the Schirmacher Oasis. However, the climate ultimately turned warm and moist beginning at 1 ka B.P. The sedimentation rate of the fluvio-glacial deposits, especially in the lakes give an indication of the varying paleoclimate. It is evident from the studies that between 8000 and 3500 years BP the climate was warm as compared to the period before and after it so as to yield fast inflow of the sediments in the lakes during this period. The interpretation is in conformity with the palyonological data [22] that infers a warm, humid and warm & humid climate between this time span, on the basis of pollen studies. These alternating phases of climate were made on the basis of dominance of grasses, cosmarium (fresh water algae) etc.

The lake history from 13 ka B.P. to the present has also been attempted by using the magnetic and geochemical properties of seven vertical sediment profiles along an east–west transect in Schirmacher Oasis [23]. Further, based on the results of AMS $^{14}C$ dates [24], reports that greater parts of Schirmacher was dominated by glaciers from 13 to 12.5 ka B.P and colder conditions prevailed in the Schirmacher Oasis between 13 and 12.5 ka B.P.; ~12–11.5 ka B.P. and 9.5–5 ka B.P. However, due to the onset of warming conditions (~11.5 ka B.P.), the glaciers retreated leading to the formation of five large pro-glacial lakes which are now located on the low lying valleys of the Schirmacher Oasis. Based on the environmental magnetic properties of sediments deposited in Sandy Lake, glacial–interglacial climatic variation was reconstructed for the past 42.5 cal. ka B.P. [23]. Extremely cold periods in the Schirmacher Oasis were recorded during 40.8, 36, 34.51, 29 and, 28.02–21.45 cal. Ka B.P. Relatively warm periods were documented during 38.4–39.2 cal. ka B.P., 33.7–29.8 cal. ka B.P. and 28.5 cal.ka B.P. The Holocene period was characterized by alternating phases of relatively warm (12.55–9.9 cal. ka B.P.and 4.21–~2 cal. ka B.P) and cold (9.21–4.21 cal. Ka B.P. and from ~2 cal. ka B.P. onwards) events. These results are in conformity with results of other studies, as documented above. Further, the geochemical proxies (TC%, TN%, C/N ratios, $\delta^{13}C$ and $\delta\ ^{15}N$) along with the physical proxies (grain size: sand-silt-clay) for three different periglacial lakes viz., Long Lake, Zub Lake and Sandy Lake [1–3] spanning the glacial–interglacial variations (spanning up to 43 cal ka BP). These studies presents the evolution of lake through reconstruction of productivity patterns, source of organic matter and the hydrological processes through grain size variation complimenting the environmental magnetism records from the same lakes [5, 6]. The deglaciation history from the above observation suggest most likely that parts of Schirmacher Oasis were ice-free even during the LGM. This can be supported records of consistency in the continuity of the sedimentary sequences. However, parts of Schirmacher Oasis became ice free during the last deglaciation i.e., Termination 1. Hence, to better understand the deglaciation history of Schirmacher Oasis, the sedimentary records needs to be supplemented by further studies using novel techniques such as cosmogenic dating of rock outcrops and erratic all across Schirmacher Oasis.

## 4. Larsemann Hills/Prydz Bay Area

The Larsemann Hills represents one of the largest coastal ice free area of Antarctica, located in the Prydz Bay Region on the Ingrid Christensen Coast. The area is comparatively free of ice shelf with hills protruding in the sea as two prominent peninsulas- Broknes and Stornes Peninsula. In between these two, smaller landmasses namely Grovnes and Brattnevet promontory and several smaller islands (McLeod, Fisher, and Bens etc.) dot this region (**Figure 7**). The area exposes Proterozoic felsic/gneissic basement, overlain by a pelitic and psammitic paragniesses rocks, dominated by medium to coarse grained garnet bearing gneisses as compared to Archean gneisses with s crossing cutting mafic dykes found in Vestfold Hills.

### 4.1 Physiography

The Ingrid Christensen Coast is marked by a zig-zag coast line with sporadic occurrence of low lying hills. Theses hills are over ridden by continental ice sheet

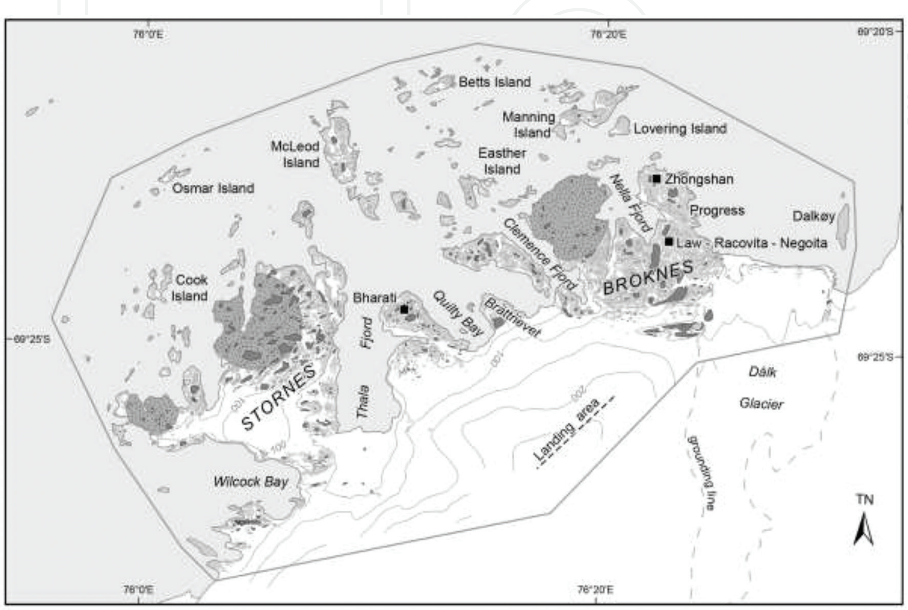


**Figure 7.**
*Map of Larsemann Hills showing major ice free hills. (https://www.antarctica.gov.au/).*

towards south exhibiting steep gradient. The Polar Record Glacier, the Polar Times Glacier and the Polarforschung Glacier flow west of Larsemann Hills in the Publication Ice shelf as a part of the Lambert Glacier system. The Publication Ice shelf itself marks a very steep margin east of Polar Record Glacier till it ends abruptly south east of Bolingen Islands. Fjords, such Thala, Quilty and Clemence have cut deep into the ice reaching the ice sheet while Nella fjord has made its way through a valley in the Broknes Peninsula.

The Larsemann Hills exhibit horst and graben structures, signifying a tectonic control in their disposition. The Stornes Peninsula, Grovnes Promontory, Fischer Island and Broknes Peninsula from west to east, are conspicuous as horsts with their straight N-S to NNE–SSW trending margins with Thala fjord, Quilty Bay, Clemence Fjord and Nella Fjord respectively flowing in the complimentary grabens (**Figure 7**). The hills are totally devoid of peaks and show low hummocky and rounded tops with isolated erratic boulders on top (**Figure 8**). The general elevation varies between 50 and 70 m above m.s.l. with some parts approaching ~100 m above m s l. The hills are dissected by vertical valleys demonstrating past fluvio-glacial action. The hill tops show weathered surfaces with pits while the windward sides show cavernous pits at places. Moraines are rare. The landscape is dotted with more than 150 water bodies which have been mapped and numbered systematically by [25]. While most of the lakes are shallow up to 3 m depth, and may be classified as ephemeral ponds, there are some deep lakes such as Lake Progress (34 m) in Broknes Peninsula, Lake Oskar in Stornes Peninsula (18 m) and lake LH 7 (14 m) in Grovnes (Bharati) Promontory. Some lakes are saline in nature due to close vicinity of the ocean and the wind born salt spray and/or excessive evaporation and support a thick biomass mat in upper levels. .

Earlier records [26, 27] have given an account of the post glacial regional climate variability along the East Antarctic coastal margin. A detailed description of the region (ANARE reports) and of the microbial communities inhabiting the lakes of Larsemann Hills are provided elsewhere [28–30]. The minimum age of deglaciation of the islands has been inferred to be late Pleistocene/early Holocene. However, reconstruction of relative seal level (RSL) records [31] have stressed that the presence of marine sediments with radiocarbon ages ranging from 40 to 30 ka BP to the east of Filla Island suggest that deglaciation of some areas could have commenced much earlier. Diatom abundance and fossil pigment records [32, 33] also opine that Larsemann Hill were not fully covered by ice during the LGM and gradually deglaciated between c. 13.5 and 4 ka BP. Relatively wet conditions prevailed between c. 11.5 and 9.5 ka BP in a lake on one of the northern islands in the Larsemann Hills [26]. Basal samples from a sediment core at ~158 cms in Larsemann Hills revealed presence of a marine sediments [34] while two more records based on diatom

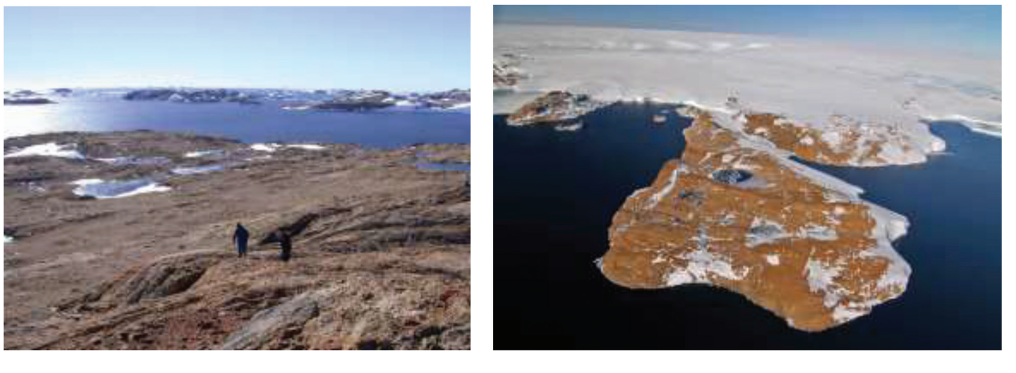

**Figure 8.**
*Larsemann Hills. Low hills with hummocky tops near Grovnes promontory. Note the open sea in austral summer and the continental ice sheet marking coast line.*

records and geochemical proxies suggest presence of marine sediments during mid-Holocene [3, 35] and while diatoms endemic to sub-Antarctic island corresponding to MIS 5e stage were recorded from Broknes Peninsula (Last Interglacial) [33, 36]. The reduced elevation and planation surfaces must have been carved before the LGM facilitating the marine transgression. Based on the variation of diatom population present in sediments suggest that the influence of seawater got weakened after ~5000 yrs. BP [37] and relative warmer climatic condition was prevalent [37, 38]. Core studies from a lake in Grovnes Promontory by [39] have shown high productivity between ~8.3 to ~6 cal ka BP and that the ice free conditions prevailed around 4 cal ka BP.

## 5. Conclusions

The geomorphology of Schirmacher Oasis and Larsemann Hills, the two prominent ice free areas present distinct erosional and depositional landforms characteristic of a polar periglacial environment. Both the areas house hundreds of melt water lakes that have preserved the signatures of glacial–interglacial climate variations in the sediments deposited. Paleaoclimate history for the past ~42 cal. ka B.P [5] has revealed wide spread glaciation in LGM with Holocene being characterized by alternating warm and cold phases. Presence of marine sediments were documented from two coastal lakes viz., Pup Lagoon [35] and Heart Lake [3, 35] suggesting isostatic upliftment in the region. The sedimentological data viz.: sediment sorting, composition and the SEM studies on quartz grains from the two areas have shown similar results except the extent and strength of glacial processes. While there was a strong effect of glacial processes on quartz grains from Larsemann Hills, the imprints of glaciofluvial activity were more prominent on quartz grains from Schirmacher Oasis [40].

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## Author details

Rasik Ravindra[1*], Badanal Siddaiah Mahesh[2] and Rahul Mohan[2]

1 National Centre for Polar and Ocean Research, Goa, India

2 National Centre for Polar and Ocean Research (NCPOR), Ministry of Earth Sciences, Headland Sada, Goa, India

*Address all correspondence to: rasikravindra@gmail.com

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