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Research Paper

Recent Contributions to the Antarctic Geology - An Indian Perspective

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Indian geoscientists have been studying Antarctic geology for three and a half decades in Antarctica. The studies were mainly carried out in campaign mode for long but have now assumed greater focus as these have started investigating scientific questions of global interests. Starting from early report of anorogenic magmatism in the central Dronning Maud Land (cDML), identification and description of magmatic charnockites representing a chemically distinct magma to characterizing and confirming the continuation of East African Orogen in Antarctica. These studies represent some of the key contributions besides providing the baseline geological maps of the cDML area. The establishment of permanent station at the Larsemann Hills has allowed wider India-Antarctica geological correlation.The land-sea-ice interface in the cDML and use of marine sediments as archives of ice-sheet fluctuations as well as providing clues to the sub-ice geology is demonstrated from the Wilkes Land sector in east Antarctica. These ice-sheet proximal deposits allow reconstruction of time-constrained advance and retreat of the east Antarctic ice sheet.

The contributions include study of Quaternary deposits, especially the lake deposits which have significant bearing on understanding the ice sheet behavior during late Quaternary. Increasing participation in global scientific programs, multidisciplinary studies and active involvement in Scientific Committee on Antarctic Research (SCAR) specially in geoscience augurs well for future progress of Antarctic geoscience studies in India.

Keywords: Dronning Maud Land; Larsemann Hills; Schirmacher; Wilkes Land; Geology

Introduction

Indian contribution to the Antarctic Geology has largely been confined to the central Dronning Maud Land (cDML) sector of the east Antarctica for nearly three decades (1981-2011). This was on account of the location of the first two stations, Dakshin Gangotri, located on the ice-shelf and Maitri, the second station on ice free Schirmacher Oasis, from which only limited access was possible. The studies which began as localized geological descriptions have assumed significance lately for two reasons- first recognition of cDML terrain as possible extension of the East African Orogen (EAO) in Antarctica and the significance of sub-ice geology in the context of understanding and predicting East Antarctic Ice Sheet (EAIS) behaviour, the largest single mass of fresh frozen water on planet earth. The studies were extended to the Larsemann Hill sector in eastern Antarctica after 2006,following the identification of site for the Bharati Station in the Grovenes Promontory. Indian contributions to Antarctic geology are described in following description for the three domains, namely, the cDML, the Larsemann Hills and the Wilkes Land sector.

Central Dronning Maud Land Sector

Geological Studies

The Wohlthat Massif, a rugged mountainous terrain located ~100km south of the Schirmacher Oasis, exposes large magmatic bodies. Indian geologists in pioneering studies recognized largely anorogenic

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nature of this magmatism which ranged from ultrabasic to acidic in composition besides establishing presence of a distinct charnockitic magma in the region (Kaul *et al*., 1991, Joshi *et al*., 1991, Joshi and Pant, 1995, Ravindra and Pandit, 2000). Ravikant (1998) presented a thermal model for one of the largest Proterozoic anorthosite massif located at the Gruber Mountains in cDML which was followed by petrological and geochemical studies of this Neoproterozoic magmatic intrusive (Ravikant *et al*., 2011). The inter-relationship between various magmatic bodies is debatable and requires further investigation. Compilation of several decades of geological data produced geological maps of Schirmacher Oasis (Geol. Survey. of Ind., 1998), Orvinfjella (Geol. Survey of Ind, 2006a), Muhlig-Hofmannfjella, (Geol. Survey of Ind., 2010), Wohlthat Massif (Geol. Survey of Ind., 1991) and Geomorphological map of the Schirmacher oasis (Geol. Survey of Ind., 2006b).

The shear zones of the Schirmacher oasis were studied in detail (Sengupta 1993, Roy *et al*., 2015a). The dominant shear zones have a NE-SW trend with a variable southerly dip. The stretching and mineral lineation associated the shear zone is a low 30^o to sub horizontal from SE direction. The general movement sense is sinistral. The shear is a general shear with a pure to simple shear component in 45:55 ratio. The shear strain of $\gamma = 1.6$, calculated from deformed augen represents the cumulative strain suffered by these deformed rocks. The flow planes are parallel to regional foliation of rocks that define dominant fabric developed during the East African Orogeny. Based on the regional setting, nature and timing of this shear zones and its association with the retrogressive amphibolite-facies metamorphism (during the decompressive phase), these shear zones are inferredto be a part of the response of these rocks to the major exhumation phase (D'Souza *et al*., 2011). The mylonitic zones of the Schirmacher oasis are thought to have evolved during the late phase of D2/M2 to early D3/M3 tectonothermal event (Sengupta 1993, Bose and Sengupta 2003, D'Souza *et al*., 2011, Roy *et al*., 2015a).

An area of about 4 sq. km. was mapped on 1: 10,000 scale in the Baalsrudfjelletnunatak, southeast of the Schirmacher Range, during 31st Indian Antarctic expedition (2011-12). The lithological assemblage exposed in this nunatak consists of an interbanded sequence of quartzo-feldspathic gneiss, pyroxene granulite, metapelite with intrusives like lamprophyre and quartz veins. The country rock is represented by the quartzo-feldspathic gneisses with or without orthopyroxene and garnet. The melanocratic quartzo-feldspathic gneiss is rich in amphibole and biotite. The mineral assemblage of plagioclase + quartz + biotite + garnet + orthopyroxene + amphibole indicates granulite facies peak metamorphic conditions. Geochemical attributes of these orthogneissesindicate a syncollisional setting. The metapelite is represented by the mineral assemblage quartz + biotite + plagioclase + garnet + sillimanite. The peak metamorphism for metapelite is estimated at 635°C at 6-7Kbar assumed pressure (Roy *et al*., 2015b). Pyroxene granulite is one of the major rock types interbanded with the quartzo-feldspathic gneiss. It is composed of plagioclase + orthopyroxene + clinopyroxene + biotite + Ca-amphibole ± ilmenite. Two-pyroxene geothermometer indicates peak temperature of 730°C at intermediate pressure. The dominant pervasive fabric trends ENE-WSW. The map pattern of the nunatak is structurally controlled. The area underwent three phases of folding deformation (F_1, F_2 and F_3).The dome and basin structure is a result of the interference pattern of F_1 and F_2 folds. The ENE-WSW trending F_2 folds are the most dominant whereas the F_3 is of mild intensity. The lamprophyres are calc-alkaline in nature and are syn- to post-F_2 deformation. The oldest date obtained during the present studies from monazite within the metapelite of ~640Ma indicates that the area is a part of EAO marking the suture between east and west Gondwanaland and provides continuity of extension of EAO between Schirmacher and Wohlthat (Roy *et al*., in press). On the basis of lithotypes, petrography, structure and deformation fabrics, the Baalsrudfjelletnunatak shares geological continuity with the Schirmacher Oasis.

The complex metamorphic evolution of the cDML terrain has been a subject matter of intense studies by the Indian geosciences community. Central Dronning Maud Land, East Antarctica is a high grade polymetamorphosed and polydeformed terrain (Ravikant 2008, 2009; Ravikant *et al*., 2011). In several papers the Neoproterozoicage of metamorphism in the Schirmacher Oasis was demonstrated including the nature of the oceanic crust which allowed the authors to conclude that the proposed extension of EAO is likely to be within the Schirmacher Oasis (Ravikant *et al*., 2004, 2005, 2007; Ravikant 2005, 2006, 2008). It is significant as EAO in this terrain signifies the suture zone between the east and the west Gondwana blocks and is marked by the granulite grade rocks of ~650Ma age. In a detailed petrological study with geochronological constraints it was shown that the extension of EAO can be established further ~100km inland in the Humboldt Mountains in cDML (Pant *et al*., 2013a). Grain growth parameters and mineral zoning suggested an ~8km thick sequence regionally metamorphosed to granulite grade conditions (Pant and Verma, 1994). Calc-silicate rocks have been found to be intimately associated mainly with the metasedimentary units in the area. These rocks occur as zones exposing prominent marble bands and associated calc silicate rocks. The marble bands present in cDML have shown peak assemblages of forsterite-spinel-calcite-dolomite-plagioclase-biotite suggesting metamorphism at 750°-780°C under high XCO_2 (0.9) condition(D'Souza *et al*., 2012). The occurrence of granulites and enderbitic-charnockites, having anhydrous mineral assemblages may be related to this event. The calc-silicate rock shows scapolite-wollastonite-diopside-plagioclase assemblage with development of coronal garnet (D'Souza *et al*., 2012). The reaction textures present in the rock has helped constrain the P-T fluid history of calc silicate rock in particular and the metamorphism in cDML in general. The peak metamorphic temperature obtained through these textures is around 900°C under high pressure (~ 9kbar) conditions. The calc-silicate rocks and the marble have shown effect of amphibolite-facies retrogression under the influence of high H_2O content and reduced X_{CO2}value. Replacement of forsterite by clinohumite suggests at 650°C temperature and $X_{CO2} \sim 0.3$. The presence of clinohumite and diopside on other hand suggests further fall in X_{CO2}values and increased activity. This study shows the values obtained for calc silicate rocks to be higher than the estimates available from metapelite. However there are reported occurrences of UHT assemblages in cDML area (Grew 1983). The P-T fluid histories indicated for cDMLcalc-silicate rocks are strikingly similar to the calc silicate marbles reported from Ambasamudram area in of Kerela Khondalite Belt (KKB) and in Highland complex of Sri Lanka. These areas have been shown to be part of East African Orogen (EAO) associated with formation of Gondwana.

Geological evolution of the Schirmacher Oasis can be related to three temporally distinct tectonothermal events. Magnetic susceptibility studies indicate three phase deformation of these rocks (Pandit *et al*., 2008) which can be summarised as below:

- Structural evolution includes at least two folding events followed by intense shearing during the D_3 deformation phase.
- Observed magnetic susceptibilities are in the range of paramagnetic to mixed-type (paramagnetic + ferromagnetic) values with biotite and hornblende as the main carriers of magnetization.
- The magnetic fabric anisotropies define two groups characterized by prolate (linear) and oblate (planar) geometries, respectively. Anisotropies are higher for the oblate fabrics (P' 1.1 to 1.15) compared to the prolate ones (P'< 1.05). Oblate fabrics can be related to D_1 and D_2 fabrics while the prolate, lower-anisotropic geometries (SW-dipping magnetic lineations) are a result of D_3 shear overprint.

Quaternary Geology/Paleoclimate Studies

The Antarctic ice sheet is dynamic and continuously moving towards north under the influence of gravity. The portion of ice sheet, which floats over the sea, is called ice shelf. The loci of points where Land-Ice-Sea (L-I-S) meet, is called grounding line or hinge line and it has been demarcated for the area close to Schirmacher oasis through GPR profiling (Dharwadkar *et al*., 2012; Swain and Goswami, 2014). The grounding line is not fixed but keeps shifting in response to changes in environment. The location of grounding line is important in order to evaluate the dynamic processes occurring at the distal edge of ice sheet. Ground-penetrating radar (GPR) is a non-invasive, time and cost effective, environmentally safe technique for high-resolution geophysical mapping that is effectively used in the Polar Regions for subsurface mapping. During GPR data collection an-electromagnetic pulse (10-1000 MHz) is transmitted into the ground along a survey line. This pulse is reflected back to the surface from subsurface interfaces where dielectric properties of different mediums change and are recorded.

GPR profiles in a continuous stretch extending from the tip of Baalsrudfjelletnunatak, where the rocks are exposed, to the edge of ice-shelf and covering a distance of about 78 km were taken during 28th to 31st expeditions undertaken between 2008 and 2011. Data generated through these profiles has been used to demarcate the boundaries between land-ice-sea (Dharwadkar *et al*., 2012). This study has provided significant inputs to the mass balance of Antarctic ice and in estimating the vulnerability of the ice shelf to calving and affecting the land cargo routes between Maitri Station and the docking area of the ship carrying the supplies for Indian and Russian Stations. The continuous GPR profile from continent edge to the present day sea shore (~78 km) bring out the gradual changes in thickness of the ice sheet. The total volume of ice in this stretch is estimated to be about 7240 km^3 and assuming a uniform density of 0.85 for the ice, it amounts to about 6154 km^3 of water. The L-I-S interface occurs at 70°51’S: 12°14’E at a depth of 340 m below the surface along a north-south stretch east of the Schirmacher Range (Dharwarkar *et al*., 2012). During the present study a 30m high convex structure was detected north of the grounding line, but the presence of any subsurface mound could not be detected.

The sediments in the epi-shelf lakes of the Schirmacher Oasis represent a composite of source rock compositions, weathering, sediment transportation processes and depositional processes along with influence of the marine environment and have been used to decipher Quaternary climate evolution. SEM imaging of quartz grains selected at random, reveals a very high degree of mechanical abrasion characterized by features originating from glaciofluvial transport processes (Asthana *et al*., 2009, 2013; Shrivastava *et al*., 2012).

The palaeoclimate and deglaciation history of Schirmacher has been built by evidence from radiocarbon dates from the lake core sediments and a few glacial till samples. The data from earlier available record of geochronology of the sampleshave also been analyzed. The sediment cores collected from the L-49 (Priyadarshini Lake) have been dated.

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 (Achyuthan *et al*., 2008).Reconstruction of the palaeoclimate history from the pollen spores present in the lichens and sediment samples of Priyadarshini Lake (L-49) by Bera (2006) and Bera *et al*., (2012). They showed 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 9-2.4 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 with 1 ka B.P. These alternating phases of climate were inferred on the basis of dominance of grasses, Cosmarium (fresh water algae) and Acritarch.

The lake history from 13 ka B.P. to the present has also been attempted by Phartiyal *et al*. (2014) by using the magnetic and geochemical properties of vertical sediment profiles along an east-west transect in theSchirmacher Oasis and with the help of AMS ^{14}C dates. These authors believe that from 13 to 12.5 ka B.P., the whole area was dominated by glaciers with plenty of glacial lakes which have been landlocked today. However, due to the onset of early Holocene warming conditions (~11.5 ka B.P.), the glaciers retreated leading to the formation of five large pro-glacial lakes which are located on the low lying valleys of the Schirmacher Oasis. Colder conditions prevailed in the Schirmacher Oasis between 13-12.5 ka B.P.; ~12-11.5 ka B.P. and 9.5-5 ka B.P. The radiocarbon dates obtained recently (Govil *et al*., 2012) from sediment cores (L-6) describe a time span of 10650, 9590, 3660, 2340 and 640 years BP for depths varying from 162 cm to about 8 cm.

The sedimentation rates for these depths as calculated indicate steep gradient of 18cm/K year to low gradient of 3 cm/K year for the basal sections and the segment just above, respectively. This indicates warmer climate between 9590 and 1065 years BP, followed by a cooler period for greater part of the period till about 4000 years BP. The dating of the glacial deposit debris also indicate gradual retreating trend of the ice sheet between 8942 years and 5471 years BP in four stages, the middle two periods being at 7,720 and 6,843 Years BP. Srivastava *et al*. (2013) undertook a study on samples collected from different glacial environments and found out a mineralogical control over the observed geochemical pattern and anomalies of these sediments that comprised essentially quartz, feldspar and heavy minerals and a small fraction of clay minerals. Asthana *et al*. (2009) also have given an account on paleoclimate of Schirmacher Oasis based microscopic structure on quartz grains while Warrier *et al*. (2014) have used environmental magnetism as proxy to work out glacial-interglacial variation in the Schirmacher Oasis. Thamban *et al*. (2012) have reconstructed palaeoclimate variation in Coastal Dronning Maud Land using ice core proxy records.

Geomorphological Studies

The low lying rocky mass of Schirmacher Oasis, disposed in the form of small hills, has been given rise to by the retreat of the ice cap and consequential uplifting of the landmass. The workers have cited examples such as, existence of comparatively higher relief of the structural hills on the northern periphery of the landmass than the central corridor, the steep escarpment at the northern margin and the indications of a fault running all along the northern margin in support of their arguments. The architectural pattern of the Schirmacher Oasis has evolved under the different depositional and erosional processes in a periglacial environment (Ravindra, 2001).

The excessive erosional phase is evidenced by absence of sharp peaks, shattering of rocks producing block fields, rolling topography, cavernous pits, glacial striations, polishing and en-echelon pattern of Roche Moutonees over a large area in the Oasis (Ravindra, 2013). Extensive development of patterned ground in the low gradient to near horizontal slopes has been mapped to indicate the fluctuations of the upper active layer of permafrost. Recent studies have shown possibilities of retreat of glaciers from Schirmacher much before the Holocene (Achyuthan, 2008). Geomorphological evolution of the Schirmacher oasis including that of the glacial lakes was discussed by Phartiyal *et al*. (2011).

The morphological studies on quartz grains, using SEM have shown multiple events of glacial crushing; grinding, conchoidal fractures, deep groves etc produced by attrition under high mechanical energy scenario. Removal of matter by wind action and chemical precipitation has also been recorded (Asthana *et al*., 2009; Shrivastava *et al*., 2012).

The surface textures and the morphological features indicate differential transportation under glacial regime as the angularities of the edges are still preserved and rounding/sub rounding typical of fluvial action as nearly absent.

Larsemann Sector

An area of 3 km^2 was mapped around Bhartistationin Grovness area of the Larsemann Hills, East Antarctica on 1: 2500 scale in order to establish correlation of crustal evolutionary history of this area with that of the Eastern Ghats, India. Based on the petrographic, mineral chemistry and petrochemical studies combined with field observations, four major rock types, representing three major suites of rocks, could be delineated, namely-pyroxene granulite and garnetiferous granite-granodiorite gneiss representing the metamorphosed igneous suite; sillimanite gneiss and metapelite (a. sillimanite + spinel + cordierite + magnetite ± garnet bearing and b. spinel + sillimanite/ kyanite (?) + magnetite ± cordierite ± garnet) representing the metamorphosed sedimentary suite and small patches of granitoids and migmatite representing the post tectonic intrusive igneous suit (Nath *et al*., 2011). The older relict amphibolite, garnetiferous mafic enclaves and diorite occur as rafts and enclaves within the garnetiferous granite-granodiorite gneiss country rock. Two prominent and persistent coplaner foliation planes, S1 and S2 were recorded in the study area trending ENE-WSW with a southerly dip varying from sub-horizontal to 45^o. The Larsemann Hills is affected by three progressive deformation events D1, D2 and D3 and a later NNE-SSW trending S2 layer parallel possible thrust component (D4?). Three generations of folds, namely the early relict, rootless, thickened hinged tight isoclinal recumbent F1folds; tight isoclinal to open upright to recumbent F2 mesofolds developed on S1 gneissosity/ schistosity and a D3 generated broad open warp F3 folds, were identified (Nath *et al.*, 2011). Two persistent joint planes J1 and J2 at high angle (~60°) were also noticed at many places across the litho-units, proving its late origin. These rocks had been put to a progressive metamorphic evolution from amphibolite-upper amphibolite to granulite grade, endorsed by conventional geothermobarometry. The prograde metamorphic dehydration melting reactions are defined by the inclusion assemblage of sillimanite in garnet and cordierite, amphibole in pyroxenes. This also indicates that the prograde P-T condition was well within the second sillimanite stability zone at the peak of metamorphism. The peak metamorphic P-T condition calculated by conventional geothermobarometry is 843°C at ~6 kb for the pyroxene granulites and 805°C at ~6 kb for the metapelites (Nath *et al*., 2011). The retrograde path is defined by the isothermal decompression due to exhumation (uplift) after reaching the peak (granulite grade) followed by isobaric cooling to lower amphibolite grade metamorphic conditions (Nath *et al*., 2011). An attempt has been made to correlate the crustal evolutionary history, with the available data generated from the study area during the previous expeditions, with that of the available literatures of the Eastern Ghats. It was observed that in the Anantagiri-Araku areas of the Eastern Ghats, thermobarometry indicates exsolution of pigeonite at ~950°C, of (100) clinopyroxene in orthopyroxene and vice versa at 750-820°C and formation of garnet at around 700-725°C, 7 kb, all in response to cooling of the rock. This shows a nearly isobaric cooling path subsequent to peak metamorphic conditions. Subsequently, the rock suffered nearly isothermal decompression to 5 kb. Hydration and K-metasomatism of the assemblage occurred at lower temperatures (~500°C) in the final phases. The study area is typically a Pan-African terrain where the peak metamorphic event, in 602±10Ma, and subsequent retrograde events occurred at lower temperature of ~523°C in 490±14Ma are quite evident from the P-T calculation and chemical dating of monazite. Similar Pan-African ages are also reported from various pockets of the Eastern Ghats.

Magnetic susceptibility studies in the Bharati Promontory of the Grovness Peninsula indicated that all the lithological units contain ubiquitous magnetite, however, with wide variation in the volume proportions that has resulted in a range of magnetic susceptibility values (10^{-4} to 10^{-2} SI units). Magnetic foliations show a correspondence with the general trend of lithounits (050° NE) and define a resulting geometry of mainly D_1 and D_2 foliations (Pandit and de Wall, 2014 and Pandit, 2016). The magnetic lineations show a preferred orientation with moderate easterly plunge (mean vector 093/36). The observations have implications for the magnetic field survey because such fabrics would impart a strong horizontal component of induced magnetization.

Geomorphological Studies

Geomorphological studies around the Bharati station on Grovenes promontory, in particular and the Larsemann Hills in general, commenced simultaneous with construction of the station during 2010-2012. The comparison of the physiographic elements, sedimentary processes, hydrochemistry and the lacustrine environments in two different polar peri-glacial milieu of the Schirmacher and areas of the Larsemann Hills such as Fisher IslandandBroknes Peninsula were attempted by Asthana *et al.* (2013). Ionic characters of lake water of the Bharati promontory have also been studied (Shrivastava *et al*., 2012). Lakes of the Larsemann Hills have been studied in some detail. While Govil *et al*. (2012) established influence of grain size distribution on biological productivity in fresh-water ecosystems, Majumdar *et al*. (2013) inferred existence of cold-conditions during the Holocene period in freshwater lakes in the Vestfold Hills.

Princess Elizabeth Land (PEL) and Contiguous Areas

The first campaign of an international collaborative project, ICECAP-2 (International Collaborative Exploration of Central East Antarctica through Airborne geophysical Profiling), funded partially by a United Kingdom Global Innovation Award was undertaken in 2015-16 season. This season operations were hosted by Polar Research Institute of China (PRIC) and conducted from the Zhongshan Station with participation from USA, UK, China and India using airborne geophysical surveys for 44,000 line-km of ice sounding radar, laser altimetry, gravity and magnetic data collection. Following are some of the preliminary findings of this campaign (Sun *et al*., 2016).

- PEL hosts an assortment of previously unidentified subglacial lakes and complex geomorphology
- Confirms the presence and extent of a 1,100 km-long system of canyons connecting the Lambert Rift to the Leopold and Astrid Coast
- A subglacial lake situated within the southern section of the canyon system, likely one of the largest known lakes in Antarctica

Corroborative geological field investigations are in progress.

Wilkes Land Sector

Examination of heavy mineral fraction of the marine sediments of Integrated Ocean Drilling Program (IODP) Expedition 318 off the coast of the Wilkes Land in east Antarctica (drillsite U1359) brought out the sourcing of sediments from the Precambrian hinterland constituting the east Antarctic shield as well as from the Palaeozoic Trans Antarctic Mountains and Ross Orogen (Pant *et al*., 2013b). The shield area is indicated to be a polymetamorphic terrain with a low-grade orogeny indicated by ~800Ma monazite within a biotite schist (Pant *et al*., 2016). This is the first report of signatures of a Neoproterozoic orogeny in this area and has significant bearing on the Australo-Antarctica reconstruction.

Clay mineral record was employed to reconstruct the fluctuations of the East Antarctic Ice Sheet (EAIS) during Mio-Pliocene and increased concentration of smectite suggested retreat of EAIS during 6.8-6.2, 5.8-5.5, ~4.5 and ~2.5Ma possibly coincident with the formation of Antarctic Bottom Water in Ross sea area (Verma *et al*., 2014). The period between 7-9 Ma at this depocenter marks the maximum concentration of Ice Rafted Debris (IRD) which include basaltic rock fragments sourced from the Ferrar Large Igneous Province towards east. This is also in conformity with the ice-retreat phases inferred using clay minerals at 7.4-7.3 and ~8.5 Ma (Verma *et al*., 2014).

Summary

The contributions of Indian geoscientists ranged from pioneering work in geological mapping and terrain definition in east Antarctica but were mainly concentrated in central Dronning Maud Land area and lacked collaboration with similar studies by other southern polar groups. In recent times, the field of activity has increased especially with the additional logistic support available in form of second permanent station at Bharati. The emphasis has shifted to collaborative studies as well as it is now well-diversified to address the current focus on paleoclimate, ice sheet evolution and integration of geophysics with geology. Further, the utilization of marine sedimentary archives to infer sub-ice geology is being utilized to bridge the crucial data gap in understanding ice sheet-bedrock interaction.

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