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Advances in Antarctic geoscience studies: Indian contributions

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Indian contributions to Antarctic geosciences have been growing at a steady pace since last four decades or so, especially after the establishment of a national centre dedicated to polar studies (National Centre for Polar and Ocean Research, NCPOR). Several national organizations, laboratories and universities have contributed to the country's endeavors in Polar geosciences in varied fields such as structure and tectonics, metamorphism, geochronology, palaeo-climatology, sedimentology, seismo-tectonics, palaeomagnetism, and other related branches to generate a wealth of scientific data. The area of operations has been spread over parts of Central Dronning Maud land and the Larsemann Hills of Prydz Bay in East Antarctica, that expose poly-metamorphic deformed terrain with imprints of both the Grenville and Pan African orogeny. The geoscientific studies have focused on crustal evolution and geodynamics of the Antarctic continent and best fit model for India and Antarctic prior to the Gondwana amalgamation and split. Deep seismic profiles and related studies have revealed the subsurface nature of crust while other geophysical studies include geomagnetism and movement of Antarctic plate, ground penetrating radar surveys. The limnological studies, nature of surface sediments, sediments from melt water lakes, their provenance and microtextures etc, have been covered in another paper in this volume.

Introduction

Antarctica occupies the central stage in the studies on amalgamation and breaking up of continents during the multimillion year history of evolution of the Earth's crust. However, the impetus in the advancement of Polar sciences, including the geosciences, gained momentum only after the International Geophysical Year of 1957-58. In the early years, the Schirmacher and other areas of East

Antarctica (Enderby land etc.) received attention from the scientists of the-then USSR (Ravich and Kamenev, 1972; Ravich, 1982; Kamenev, 1982; Ravich and Soloviev, 1966, etc.) and the-then East Germany (Kampf and Stackebrandt, 1985; Kaiser and Wand, 1985; Bormann and Fritzsche, 1995). The Indian contributions to Antarctic geosciences commenced from the early 1980's after its first scientific expedition under the leadership of Dr S Z Qasim set foot on the icy continent on January 9, 1982. Over the years, the Indian Polar program has evolved with the successful completion of 38 expeditions to Antarctica to date (2018-19), establishment of three permanent research stations (Dakshin Gangotri located on the ice-shelf; Maitri, on ice free Schirmacher Oasis; and Bharati in the Larsemann Hills area; Figure 1) and extending the sphere of the country's scientific activities to the Arctic and the Southern Ocean. The annual expeditions to Antarctica have drawn scientists from several national organizations, laboratories and universities, enabling the the initiation of many multidisciplinary endeavors aimed at a better understanding of the continent. While the initial years were mostly periods of general reconnaissance around the Schirmacher Oasis, by the late 1980s sustained thematic and regional geological and geophysical studies had spread over the more interior mountain ranges of Wohlthat (Gruber, Petermann, Humboldt), Orvin and Muhlig-Hofmann Mountains, and further inland to Gjelsvkfjella Mountain, in parts of Central Dronning Maud land and to the Larsemann Hills area of Prydz Bay in East Antarctica (Figure 2). An area of ~20,000 km² has been covered by systematic geological mapping, thematic structural and metamorphic mapping by Indian geoscientists and detailed regional geological and geomorphologic maps have been published (Jayaram and Bejarniya, 1991; Geological Survey of India, 1998, 2006a,b).

Periodic reviews of the Indian contributions are available in Ravindra et al. (2008), Ravindra and Rahul Mohan (2011), Ravindra (2012), Nayak (2017), Pant et al. (2017a,b) etc.

Regional Geology

Central Dronning Maud Land

The sustained geological mapping that commenced in 1983 from the Schirmacher Oasis, -part of the mountain chain circling the coastal area of central Dronning Maud Land of East Antarctica- (cf. Sengupta, 1986a; Singh, 1986; Ravikant and Kundu, 1998; D'Souza and Chakraborty, 2000; Rao et al., 2000), stretched to Gruber (Kaul et

Figure 1. Map of Antarctica showing the locations of the three Indian research bases, (1) Dakshin Gangotri (now abandoned); (2) Maitri, and (3) Bharati. Map extracted from http://lima.nasa.gov/pdf/A3_overview.pdf, Public Domain, <https://commons.wikimedia.org/w/index.php?curid=9570048>

al., 1987), Petermann Ranges (Joshi et al., 1991; Joshi and Pant, 1995), Humboldt (Ravindra et al., 1991), Payer-Weyprecht and Skeids Mountains, (Bejarniya et al., 1995; D'Souza et al., 1995), Orvin-Conrad (Bejarniya et al., 1998), Muhlig-Hofmanfjella (D'Souza et al., 2006), and further to Stabben-Jutulssessen nunataks in Gjelsvkfjell Mountains (Dharwadkar et al., 2017), covering a vast region of Central Dronning Maud land of East Antarctica between 2°E and 15°E longitudes and extending up to the last southern exposures close to the Polar Plateau (Figure 2). Subsequent to the opening of yet another sector in Prydz Bay, the region encompassing Larsemann Hills and adjoining promontories was also covered by detailed structural and

metamorphic mapping (Beg and Asthana, 2012; Nath et al., 2016; Roy, et al., 2017).

The Schirmacher Oasis- a coastal oasis on the Princess Astrid coast of Central Dronning Maud land (CDML) - represents a poly-metamorphic and extensively deformed terrain exposing garnet-biotite gneiss, augen gneiss; inter-banded mafic granulite, khondalite, calc-silicate and charnockite (Sengupta, 1986a,b; Singh, 1986). Mafic granulite with hypersthene-plagioclase and/or two- pyroxene-plagioclase, garnet-sillimanite gneiss and khondalite have also been mapped as dominant litho-units. Kaul et al. (1987) identified three mineral assemblages in the gneisses of the area, viz.

Figure 2. Map of the Central Dronning Maud land (CDML), East Antarctica, showing the Schirmacher Oasis and the inland mountains (© GSI, 2006)

- i. Garnet-orthopyroxene-clinopyroxene-perthite-plagioclase-quartz $\pm$ apatite
- ii. Garnet-biotite-hornblende-perthite-plagioclase-quartz $\pm$ apatite $\pm$ zircon $\pm$ ilmenite; and
- iii. Quartz-plagioclase-garnet-perthite-orthopyroxene-apatite $\pm$ ilmenite

The tectonothermal, structural and metamorphic history of these high grade rocks has been worked out by many workers (e.g. Sengupta, 1986a, b, 1993; Kaul et al., 1991; Bose and Hazra, 2000; Bose and Sengupta, 2003). The first event of metamorphism (M_1), as per Ravikant and Kundu (1998) took place at 750-800°C temperatures under 8kbar pressure followed by M_2 isothermal decompression at 750°C. This was associated with syn- D_2 Charnockite dyke intrusions. An isobaric cooling of rocks at 5-6 kbar pressure (M_3) followed. The M_4 metamorphism, responsible for a retrogressive phase has also been widely recognized. They have described the reaction textures and have drawn retrograde pressure-temperature-deformation paths from the granulite rocks.

The structural history as deciphered by Sengupta (1986b) shows an early deformation D_1 present only as tectonic layering. The rocks subsequently underwent four generations of superposed folding. The F_{2a} (isoclinals, rootless intrafolial folds with high amplitude/ wave length ratios) and F_{2b} (isoclinal, very tight, occasionally highly asymmetric) folds were followed by F_3 folding that represents a set of upright folds with plunge towards SSW. The F_4 phase of folding is shown by asymmetrical folds with steep axial planes and very low plunge towards east or west. The last generation of folds (F_5) represents a weak localized deformation. Bose and Hazra (2000) have proposed that granulites exposed in the eastern parts have been thrust over the amphibolitic rocks along a thrust zone that occurs at the contact of augen gneiss and inter-layered calc-khondalite unit. The lamprophyre dykes that intrude the gneisses of Schirmacher have been described as alkaline and calc-alkaline types based on their geochemical characteristics (D'Souza et al., 1994; D'Souza and Chakraborty, 2000; Prasad et al., 2000).

The area lying between Schirmacher Oasis and the Wohlthat massif exposes a number of nunataks namely Tallaksenvarden, Stenersenknatten, Baalsrudfjellet, Hauglandtoppen, Sonstebynuten, Starheimtind, Pevikhornet etc. and others such as Austree and Midtre lying north of the Petermann ranges. These nunataks have been investigated by Kaul et al. (1991), Roy et al. (2017) and others, who have described the geology and petrography of the gneisses, basic granulites and quartz-syenite rocks exposed therein.

The nature and petrography of the Anorthosite Massif exposed in the Gruber Mountains as intrusives into Late Mesoproterozoic orthogneisses and other supracrustal rocks, and its magmatic history have been described by Mukerji et al. (1988) and Ravikant et al. (2011). Mukerji et al. (1988) point out the alkali enrichment and silica-rich nature of these anorthosites while drawing a similarity of these anorthosite to those of Adirondack (USA) and Perinthatta (India). Ravikant et al. (2011) have classified the rocks marginal to the anorthosite massif as ferro-monzoiorite and ferro-monzonite. They postulate that the magma from which the anorthosite crystallized has been contaminated by crustal material that now occurs as enclaves within it. The marginal ferromonzodiorite represent hybridization of injected primitive ferrodiorite magma with preexisting crustal material resulting in hybrid ferromonzodiorite.

The Petermann ranges and Zwiesel Mountains located west of the Gruber Mountains occur as three parallel elongated ranges (Figure

2). The rocks here comprise low pressure granulites with minor calc-silicates, intrusive charnockite suite and A-type granites (Joshi et al., 1991; Joshi and Pant, 1995; Bejarniya et al., 1995; Dharwadkar et al., 2016). The charnockites have been described as comprising rocks varying from ferrogabbro- ferromonzogabbro- monzonite-monzosyenite to charnockite derived from a probable source of distinct magma enriched with lower crust or mantle.

The Humboldt Mountains occupying the western margin of Wohlthat Mountains reveal that the dominant lithounits exposed in the area are complexly deformed high grade metamorphites comprising interbedded two-pyroxene granulites, khondalites, amphibolites, charnockites and calc silicates (Pant, 1991; Ravindra et al., 1989; Ravindra et al., 1994; Bejarniya et al., 1995; D'Souza et al., 1995; Ravindra and Pandit, 2000). The rocks have undergone granulite facies metamorphism. The garnet is largely grossularite. Biotite is titaniferous and iron rich. PGM bearing meta-ultramafites have been reported from northern parts of Humboldt (Ravindra et al., 1989), based on the EPMA scan of the meta-ultramafite assemblages. Ravindra and Pandit (2000) also assign whole rock Rb-Sr isochron age of 514 ± 59 Ma to the granites exposed in Nordvestoya, in the northern parts of the Humboldt Mountains. Late Proterozoic granitic orthogneisses in the Payer-Weyprecht Mountains, south of Gruber and Petermann ranges, have been assigned an age of 749 ± 61 Ma by whole rock Rb-Sr (Ravikant et al., 1997). Similar orthogneisses appear to be present in the Skeids area in the Southern parts of Humboldt (D'Souza et al., 1995).

The Muhlig-Hofmannfjella Mountains, exposed towards the eastern parts of Central Dronning Maud land have been shown by D'Souza et al. (2006) as comprising basal gneisses, charnockites and intrusive granites. The granitoid pluton, essentially of monzogranite-quartz monzonite composition contains restites of orthogneisses and charnockites, which have been correlated with the Svarthmaren charnockites present in the western Muhlig-Hoffmanfjella that have been dated at 500 ± 24 Ma by Ohta et al. (1990).

Stabben – Jutulssessen in the Gjelsvikfjella area located in the farthest western parts of the CDML exposes predominantly para and orthogneisses represented by biotite gneiss, biotite-garnet gneiss, quartzo-feldspathic and granite gneiss (Dharwadkar et al., 2017). The orthogneiss consists of amphibolitic and biotite rich enclaves. Gabbro, syenite, minor granite, pegmatite and aplite form the intrusive suite. Chemically, the gneisses are of monzogranite-granodiorite composition whereas the mafic dykes have a basalt-andesite-rhyodacite composition. The area has undergone a complex geological history involving at least three deformational episodes with concomitant metamorphism. In the Stabben area, a non foliated intrusive gabbro pluton as well as intrusive syenite limits the gneisses. The para-gneisses represented by biotite and biotite-garnet gneisses may have a sedimentary protolith whereas the orthogneisses are igneous in origin. The mineral assemblage of K-feldspar-Plagioclase-Biotite with or without garnet indicates amphibolite facies peak metamorphic conditions for the orthogneiss. Occurrence of orthopyroxene within the amphibolitic enclaves suggests an earlier granulite-grade event. A peak temperature of formation of garnet of 483°C within the orthogneiss and 628°C for the same within diorite enclave has been obtained. Amphibolite facies metamorphism is indicated by feldspar crystallization temperature of $\sim 450^\circ\text{C}$. Recent geochronological studies assign an age of 1170 Ma to 970 Ma for the migmatites/gneisses and an emplacement age of 501 Ma for the Stabben gabbro and syenite.

Weddell Sea region

Reconnaissance of the Filchner Ice Shelf and Berkner Island area along with Littlewood, Bertrab and Moltke nunataks in the Weddell Sea area was undertaken during 1989-90 Antarctic season. While nunatak Littlewood exposes rhyolites, granites and acid volcanic and basic rocks intruded by dolerite dykes have been mapped in Bertrab nunatak (Raina, et al. 1995). The Moltke nunatak exposes limestone interbedded with foliated lithic arkose rock.

Larsemann Hills

The Larsemann Hills area along the east Antarctic margin of Prydz Bay, encircling the Ingrid Christensen Coast, lies along the northern extension of the eastern Indian Cratonic belts of Bastar, EGMB, Singhbhum, etc. of the East Gondwanaland - East Antarctica tectonic framework. Preliminary geological studies undertaken by Beg and Asthana (2012) and Nath et al., (2011, 2016) indicate that there are three distinct genetically different suites of rocks exposed in the study area - i) an igneous suite composed of granitoids (tonalite, granodiorite and Progress Granite), ii) metamorphosed igneous suite (garnetiferous granite-granodiorite gneiss and pyroxene granulites) and iii) the metamorphosed sedimentary suite (sillimanite gneiss and mgt±sill±cord bearing metapelites). Structural analysis has revealed that the pervasive and persistent regional foliation planes (S1 and S2) are near-parallel and are the result of two phases of deformation DF₁ and DF₂ respectively. There is a third phase of folding F₃ documented in the study area which represents the DF₃ deformation.

The rocks in the Larsemann Hills region document a diachronous geological evolutionary history that shows a Palaeoproterozoic felsic/gneissic basement over which supracrustal sequence of pelitic, psammitic paragneisses were deposited (Pandit, 2016). The rocks have undergone two major phases of metamorphism at ca ~ 1 Ga and during early Palaeozoic- the latter, a medium to low pressure granulite facies metamorphism at ~ 7 kbar pressure and 800-850°C temperature. A detailed work on the complicated basement-cover rocks of the Larsemann Hills area, their relationship and the time frame was carried out by Ghosh et al. (2017).

Crustal Evolution and India-Antarctica correlation

The East African Orogen (EAO), is an ~ 3000 km long orogen, extending from Jordan and Israel in the North (Arabian Nubian Shield, ANS) to Madagascar–Mozambique in the South. The EAO has been suggested to extend into East Antarctica through the Lutzow-Holm Bay and to CDML. A large number of individual cratonic segments viz., India (in the East) and Kalahari, Sahara etc (in the West) were sutured in the world's largest Neoproterozoic orogen. Orogen styles within EAO varies from N to S. ANS is an accretion-type orogen with an oblique convergence of bounding plates; the orogen involving the Cabo Delgado Nappe Complex is opined to be a hot- to ultra-hot orogeny whereas, Madagascar- Tanzania is considered to be of the Himalayan type. The passage of EAO in these regions is not very well established mainly because of the paucity of continuous rock exposures. Following Jacobs et al. (1998), there have been a number of workers who have attempted to fill in the missing information (Jacobs and Thomas, 2002; Jacobs et al., 2003, 2008; Mikhalsky et al., 2006; Pant et al., 2013 etc.).

Several contributions have been made by Indian geoscientists of late towards understanding the crustal evolutionary history of parts of Central Dronning Maud Land (CDML) and the Larsemann Hills and their correlation with the Indian landmass vis-a-vis their position in Gondwanaland. The southern extension of the East African Orogen (EAO) comprising Mesoproterozoic rocks of Grenvillian orogeny (Stern, 1994) into the coastal mountain ranges of CDML (Jacobs et al., 1998; Jacobs and Thomas, 2002 etc.) through the NNW-SSE trending rocks of Schirmacher Oasis, Humboldt Mountains and the isolated exposures of various nunataks between the Schirmacher Oasis and Wohlthat Mountains (such as Baalsrudfjellet), has been recognized by many workers (Ravikant et al., 2007; Baba et al., 2006; Pant et al., 2013; Roy et al., 2017, and references therein).

Both the CDML and Larsemann Hills regions expose Mesoproterozoic poly-deformed, magmato-metamorphic terrain of high-grade rocks that have undergone granulite grade of metamorphism. The southern extension of EAO is believed to have acted as a suture between the east and west Gondwana blocks during Neoproterozoic (Pant et al., 2013 and references therein). Based on electron microprobe dating of the monazite grains, Pant et al. (2013) have opined that metamorphic neocrystallisation began in Neoproterozoic at ~640-650 Ma time and continued up to 580 Ma. The 500-600 Ma magmatic activity is widespread in CDML.

Based on similarities of granulites representing 660 Ma-600 Ma (Stern, 1994) to those of Schirmacher (Ravikant et al., 2004, 2007; Baba et al., 2006), the EAO has been extended to Antarctica through Schirmacher. The rocks of Schirmacher have been shown to be late Neoproterozoic. There are differences in the interpretation of the metamorphic paths in Schirmacher Oasis, from isobaric heating-isothermal decompression-isobaric cooling (Ravikant and Kundu, 1988) to isobaric cooling during retrograde metamorphism (Baba et al. 2006). Nonetheless there is a general consensus about the clockwise P–T–t paths and the timing of peak metamorphism to be significantly younger than was envisaged earlier (Baba et al., 2008, 2010), thus establishing an affinity with the EAO. Structurally, the NE-SW trending shear zones and mylonites in Schirmacher that show flow planes parallel to the regional foliation of East African Orogeny are believed to have evolved during the late phase of D2/M2 to early D3/M3 tectonothermal event. Based on the regional setting, the nature and timing of these shear zones and their association with the retrogressive amphibolite facies metamorphism, these zones are suggested to be a part of exhumation (D'Souza et al., 2011; Pant et al., 2017b).

The intervening ~100km vast ice covered stretch between Schirmacher Oasis in the North and Wohlthat Mountains in the South is by and large devoid of much geological information excepting for those from a few isolated small hill tops which rise above the Polar Ice sheet. One such nunatak is Baalsrudfjellet. The rocks exposed in Baalsrudfjellet consist of an inter-banded sequence of quartzo-feldspathic gneiss, pyroxene granulite, metapelite with intrusives like lamprophyre and quartz veins. The mineral assemblage of pl+qtz+bt+grt+opx+amph indicates granulite facies peak metamorphic conditions. The bulk composition of quartzo-feldspathic gneiss is comparable with upper crust with a moderate REE enrichment. Tectonic discrimination plots indicate a syn-collision setting for the quartzo-feldspathic gneiss. The metapelite is represented by the mineral assemblage qtz+bt+pl+grt+sil. The peak metamorphism for metapelite is estimated at 635°C at 6-7Kbar pressure. Two-pyroxene geothermometry indicates a peak temperature of 730°C at 6-7Kbar.

The oldest date obtained from monazite within the metapelite of ~584 Ma indicates that the area is part of EAO. Based on lithological, metamorphic, structural, geochronological similarities the EAO has been hypothesised to pass through the nunatak (Roy et al., 2017).

The P-T fluid histories inferred from the study of calc-silicate rocks of Baalsrudfjellet have been correlated with those from Kerala Khondalite Belt (KKB) and the Highland complex of Sri Lanka (D'Souza et al., 2012). The calc-silicate rocks interlayered with the metasedimentary units show a mineral assemblage of forsterite-spinel-calcite-dolomite-plagioclase-biotite and scapolite-wollastonite-diopside-plagioclase with development of coronal garnet. The mineral assemblages and the reaction textures have helped to constrain the P-T fluid history which suggests metamorphism at temperatures of 900°C under high pressure (~9 kbar) conditions. The calc silicate rocks and the marble show the effect of amphibolite facies retrogression under the influence of high H₂O content and reduced XCO₂ value.

The metamorphic neocrystallization began in Neoproterozoic time (~640 to 650 Ma) and continued upto ~580 Ma extending for ~60 Ma and was marked by the development of low to intermediate pressure granulite-grade assemblages, partial melting and generation of in situ crystallization of granitic melt by biotite dehydration melting (Pant et al. 2013). The protracted metamorphism was overprinted by a strong thermal imprint at ~540 Ma which is correlatable with large scale charnockite and A-type granite emplacements. Extensive pan-African thermal imprint in the Wohlthat Mountains is represented by anorthosite (~600 Ma), charnockite and anorogenic granite. The range of ages for the younger charnockites and anorogenic granites is within 500–550 Ma (Mikhailsky et al., 1997) signifying a possibility of multiple phase of AMCG magmatism in Dronning Maud Land. The Humboldt Mountain granulites, like Schirmacher Oasis and Baalsrudfjellet Nunatak indicate an initial isobaric heating (continental collision and crustal thickening) reaching upto the sillimanite stability field followed by unroofing, thus, defining clockwise P–T–t paths. The younger magmatic activity, spread on both East and West of the narrow zone of ~640 Ma granulites, shows anorogenic characteristic (Joshi et al., 1991; Joshi and Pant, 1995) and appears to be unrelated to the granulites. The zone of ~640 Ma granulite grade metamorphism is inferred as the remnant of suture between East and West Gondwana (Pant et al., 2013).

Dharwadkar et al. (2017) have recorded the presence of orthopyroxene within the amphibolitic enclaves in Gjelsvkfjella Mountains, in the western margin of CDML, suggesting an earlier granulite grade event. Geochronological studies assign an age of 1170 to 970 Ma for the migmatites/gneisses and an emplacement age of 501 Ma for the Stabben gabbro and syenite.

The Larsemann Hills in the Prydz Bay region of East Antarctica offers a key setting for correlation between the East Antarctica and the Eastern Ghat Belt of eastern India. The study of Grenvillian (~1000 Ma)-Pan-African (~500 Ma) high grade tectono-metamorphic evolutionary history of the Prydz Bay, including Larsemann Hills and its adjoining areas like Sostrene Islands, Bolingen Islands, Brattstrand Bluffs, Rauer Islands, Vestfold Hills etc. is significant in the present-day reconstruction and correlation with India and east Antarctica.

The major rock types exposed in the Larsemann Hills area are: garnetiferous granite; granodiorite gneiss; orthopyroxene bearing granite representing the metamorphosed acid igneous suite; pyroxene granulite representing the metamorphosed basic igneous suite and

the metapelite representing the metamorphosed sedimentary suite. Small scale quartz-feldspathic melts (migmatite) are also preserved at a few locations. The post tectonic igneous suite is represented by small patches of granitoids. Relicts of older amphibolites and mafic enclaves occur as rafts and enclaves within the garnetiferous gneiss (Mandal and Roy, 2008; Nath et al., 2011).

The reconstruction of metamorphic history by Nath and Shah (2013) reveals that the earliest phase of metamorphism (M₁) is represented by the inclusion assemblage of quartz-biotite-plagioclase-ilmenite/magnetite in amphibole suggesting a prograde metamorphic event. The M_{1b} phase is well represented by the inclusion assemblage magnesio-hastingsite/pergasite-quartz-plagioclase-biotite ± ilmenite in Opx/Cpx and also Opx/Cpx corona around amphibole, ilmenite and plagioclase (zoned), suggesting a progressive prograde metamorphic event along with a deformational phase represented by preferred orientation of mineral grains. The peak metamorphic grade M₂ assemblage has been defined by the mineral association of Opx-Garnet±biotite±ilmenite±quartz where the amphibole is totally an absent phase and garnet appears (possible P-T condition may be T >850°C, P >5 kb). The M₃ metamorphic event is largely explained by near-isothermal decompression and cooling phenomenon represented by inclusion assemblage of Opx-Cpx-garnet in green amphibole, biotite, plagioclase, ilmenite, presence of symplectites of biotite-chlorite-muscovite/sericite-plagioclase-quartz and biotite-Opx; corona of biotite, cordierite around ilmenite/spinel/sillimanite and the inclusion of Bt-Hbl-Opx-Ilm-Mag-tourmaline in Prismatine etc.

The mineral assemblages and inclusion of sillimanite in garnet and cordierite, and amphibole in pyroxenes have helped in building the metamorphic history of the Larsemann Hills region. 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. 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.

A similar thermobarometry has been noted in the of the metamorphites of the Anantagiri-Araku areas of the Eastern Ghats with exsolution of pigeonite at ~950°C, clinopyroxene in orthopyroxene and vice versa at 750-820°C and formation of garnet at around 700-725°C, 7 kb. This indicates a nearly isobaric cooling path subsequent to peak metamorphic conditions. Subsequent retrograde events that occurred at a lower temperature of ~523°C in 490±14 Ma 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.

U-Pb-Th chemical dating of monazite reveals that the prograde isobaric heating might have been triggered at the waning stage of the Grenvillian Orogeny (~850-900 Ma), where heat budget was provided by the process of crustal thinning. This process might have continued up to 600-550 Ma to reach the peak condition with the high P-T sustained by the crustal rejuvenation related to collision tectonics during Pan-African Orogeny. The post peak retrograde phases represented by the isothermal decompression commenced at 550 Ma and culminated at ~490 Ma through isobaric cooling.

Geomorphology

Geomorphologic studies constitute an integral part of the geoscience investigations in CDML (Ravindra, 2001; GSI, 2006a;

Ravindra, 2013) and Larsemann Hills area (Asthana et al., 2013a and b).

The Schirmacher Oasis and Larsemann hills display a rolling topography constituted by low-lying hills, devoid of sharp peaks as opposed to interior parts of CDML which exhibit typical alpine morphology with sharp peaks, horns etc. A thin moraine cover is omnipresent in Schirmacher, displaying the retreating ice mass over the Oasis subsequent to the Last Glacial Maximum. Larsemann Hills are believed to have been ice-free much earlier (Kiernan et al. 2009). Glacial striations and polishing are evident on hard rocks at both places. The sharp vertical escarpment, faulting and comparatively higher relief on the northern margin is displayed in Schirmacher, suggesting an isostatic rebound that caused the uplift of the ice-free oasis. Several erosional and depositional landforms such as honey comb weathering, cavernous pits, en-echelon pattern of *Rôche moutonnée* and depositional features e.g. moraines, patterned ground etc. have been mapped in Schirmacher Oasis (Ravindra, 2013). The hundred-odd melt water lakes of Schirmacher have also attracted the attention of many workers. These lakes have been classified genetically as proglacial, landlocked and epishelf lakes (Ravindra, 2001). The alignment of most of these lakes have been found to follow some lineaments which define the palaeo course of the glaciers moving from ice sheet to the shelf, in general NNE or NW directions. The two contrasting polar and periglacial environments of Schirmacher and Larsemann Hills of East Antarctica have been discussed by Asthana et al. (2013a,b).

Landscape evaluation of Humboldt and adjoining area in Wohlthat Mountain by Ravindra et al. (1991) has shown both polar and alpine type of morphologic set up. The vast stretch of highly crevassed ice sheet separates the Wohlthat massif from Schirmacher Oasis, with occasional nunataks in between, depicting the typical polar environment. The sky line is constituted by sharp serrated ridge tops with *arêtes* and jagged peaks and horns in the Gruber, Petermann, Humboldt and Orvin Mountains that rise abruptly to 2188m above the m.s.l. at Hjørnehorn.

Shrivastava et al. (2012) have identified four distinct geomorphological units in the Schirmacher region, viz. the shelf, piedmont zone, the mountain barrier or the structural hills and the Polar ice plateau. They have also identified a number of dry glacial valleys and about 122 small remnant glaciers on the upper mountain slopes.

Geophysical studies

Gravity, magnetic and GPS studies are useful in finding out the structural features, plate motions and crustal deformation of the continent. Verma et al. (2003) describe the 95 line-km magnetic traverses carried out on the ice shelf giving the structural model of the area around Dakshin Gangotri. The studies around Schirmacher Oasis include 13 multi-frequency electromagnetic (EM), magnetic, and radiometric traverses. Helicopter-borne magnetic and helicopter-supported gravity surveys over Schirmacher and the area lying between Schirmacher and Wohlthat Mountains have yielded gross features of the subglacial topography, with the maximum thickness of the ice in the region being about 3.5 km to the south of Schirmacher. The Moho thickness has been found to vary from 38 km below the Humboldt Mountains to about 32 km below the Schirmacher, reflecting the gradual reduction of the crustal thickness from the continental margin below the Wohlthat Mountains towards the deep ocean.

Analyzing the GPS data from fifty sites in Antarctica, including that from Maitri Station (MAIT), Ghavri et al. (2017) estimate the velocity of movement of Antarctic plate to be less than about 4mm / year in the eastern part of East Antarctica and about 20mm/year in the western part of West Antarctica. The estimated velocity of movement at Maitri is about 8 ± 1 mm/year, towards north.

The crustal and lithospheric structure beneath the Antarctic ice have been deciphered using Space-borne gravimetry and other geophysical and geological information (Ravikumar et al., 2018). In general, the oldest Archean and Proterozoic crust of East Antarctica has a thickness of 45 km where as the youngest rifted continental crust of the West Antarctic Rift System has a thickness of 25 km. Structural variability is reflected both in the thickness and the physical properties of the crust. Other significant features such as the mantle differences between east and west Antarctica, and the thinning of the lithosphere in west and its thickening in east Antarctica similar to that of other stable cratons, have also deciphered from the geophysical data.

The study of geomagnetic processes and monitoring of reverse magnetic flux in the outer core of the Earth at Maitri attain significance because of the station's ideal location in a sub-auroral region. Indian scientists have been operating a Fluxgate Magnetometer (FM) at Maitri for recording variations in the three orthogonal components of the surface geomagnetic field, X, Y and Z or the Daily Variations (DV). Round-the-year collection of magnetic data commenced in 1986-87, while the three-stations magnetometer network has been intermittently operational for short periods between 1991 and 1997 for estimation of the velocity of current system moving over Maitri. Continuous recording of the geomagnetic field and magnetic pulsations (from two stations) is being carried out since 1991. The data are being recorded in both analogue and digital forms. Apart from FM, a Riometer has also been installed to record the radio signal strength of the cosmic radio noise at ground. Nearly three decades of experimental geomagnetic data has revealed the importance of Maitri as ideally suitable for now-casting geo-space weather and the interplanetary weather studies (Rajaram, et al. 2001).

Intermittent recording of the absolute values of total magnetic field (F) by a Proton Precession Magnetometer (PPM) and the comparison of the results with data of PPM and FM have shown a rapidly declining magnetic field over the past 75 years at Maitri and other southern hemisphere stations. The magnetic flux at Maitri has been reported to decline to 60 nT /yr from 120nT/yr during 1995-96 (Pathan, et al. 2009). In addition, cosmic noise absorption (CAN) has been measured using imaging Riometer to get an insight into D-region ionospheric conditions its dynamics (Sinha, et al. 2017).

Concluding remarks

The Indian geoscientific studies in Antarctica have witnessed a steady and sustained growth over the past nearly four decades, ever since the First Indian Scientific Expedition to Antarctica (1981-82). From summer-time reconnaissance around the Schirmacher Oasis during the initial years, the country's Indian Antarctic program has slowly reoriented itself into long-term national plans in tune with international priority settings. The establishment of a national institution (NCPOR) devoted to a leadership role in the study of the polar regions and two year-round Antarctic research bases (Maitri in the Schirmacher Oasis and Bharati in the Larsemann Hills) have led to many multi-institutional and co-operative multi-national scientific

activities spread over a larger spatial extent. Considering that Antarctica was a keystone of Gondwana of which the Indian landmass was an intrinsic part, the prime focus of the geological and geophysical studies by Indian scientists has been naturally on the crustal evolution and geodynamics of the Antarctic continent and a best fit model for India and Antarctica prior to the Gondwana amalgamation and split. Concurrently, the scope of other geoscientific investigations has also widened to include such frontier areas of study as the palaeoclimatic evolution of Antarctica as decipherable from the proxy records of ice cores and marine and lake sediment archives (for example, see Meloth, this volume, for a comprehensive review of Indian contributions to Antarctic paleoclimatic studies), the role of subglacial morphology and bedrock geological structure on the dynamics of the glaciers, crust and mantle thickness determinations through remote sensing and geophysical techniques etc. Looking ahead, India's research endeavours in Antarctic geosciences are poised to realign themselves to a portfolio of cross-disciplinary and multi-national initiatives in tune with the roadmap for the Antarctic and Southern Ocean sciences for the next two decades and beyond, as outlined by the 1st Scientific Committee on Antarctic Research (SCAR) Antarctic and Southern Ocean Science Horizon Scan (Kennicutt II et al. 2014a, b).

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