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Study Of The Pan-African Shear Zone In Wohlthat And Orvin Mountains During 28th Indian Antartic Expedition

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ABSTRACT

A detailed geological mapping programme to understand the major Pan-African shear zone in Wolthat and Orvin Mountains, East Antarctica was undertaken to evaluate the kinematics involved and significance of shear zones in the implied collisional tectonics that brought about amalgamation of Gondowanaland. An attempt had been made to localise the major shear zone in the Zweissel mountain area through helicopter drop points. Though, the major shear zone could not be traced but a few local shears have been studied. The field work was carried out by taking 19 helicopter drop points in Zweissel Mountains. A total of 28 rock samples were collected from the study area for detailed petrography and geochemical analysis. With the available time slot and logistic support, sincere efforts were given to locate and study the shear zones in the study area. Out of 19 drop points (location) studied, only in three locations, the authors could study some minor locally developed shear zones. The regional extension of these shear zones could not be traced along its strike continuity because of snow/ice cover and logistic constraints. Due to unpredictable weather condition, time and logistic constraints, the study was carried out only in the selected drop points, with limited area coverage and restricted time frame of maximum 30 minutes each point. With this type of working conditions it should be understood that the data generated for each point is factual for that particular point and may or may not have a regional implication. It is strongly recommended that, for more comprehensive and detailed shear zone studies of the area, detailed geological mapping, in a small area, by taking foot traverses with camping facility is necessary.

1. INTRODUCTION

The Zweissel area occurs in the southernmost parts of the Petermann Ranges between Latitude 71°51' to 72°05' S and longitude 12°05' to 12°40' E. It comprises of isolated nunataks and peaks near the polar ice cap with an average height of 2700m above msl. The hills have a general NW-SE trend and exhibit subdued topography. It is bound towards East by the Gruber Mountains and towards West by the Humboldt mountains. The Prayer-Weyprecht Mountains are situated about 50 km to the southeast of the area. Antarctica is divided into Phanerozoic West Antarctica and Archean-Proterozoic East Antarctica. East Antractica mostly comprises Precambrian crystalline rocks which have undergone a complex geological history involving several phases of deformation and related metamorphism and plutonism (Grew, 1978; Tingey, 1991; Sengupta, 1988; Ravich and Kamenev, 1975). The Wolthat mountains forming southern part of the Circum East Antarctica Mobile Belt (CEAMB) of Yoshida, 1995, is divided into three sectors i) The Gruber Massif consisting mostly of anorthosites and related intrusives in the East (Mukerji et al., 1988; Pant et al., 1991), ii) Humboldt Mountains composed mainly of ortho-para gneisses with older metamorphic enclaves and younger intrusions in the West (D'Souza et al., 1995, 1997) and iii) Petermann Ranges composing chiefly ortho-para gneisses and younger intrusives in the central part (Kaul et al., 1991; Pant et al., 1991).

The rocks of the Wolthat Mountains record a poly-deformational history where an earlier (Grenvillian) granulite facies metamorphism is superimposed by later (Pan-African) amphibolite facies metamorphism (Sengupta, 1988, 93; D'Souza et al., 1995; Mikhalsky et al., 1997; Ravikant et al., 1997). Pelitic and semipelitic schists and mafic intrusives that occur as enclaves within the dominant felsic gneisses preserve record of the Grenvillian 900-1100 Ma event. The Pan-African 500-540 Ma event is represented by the folitated ortho and para-gneisses alongwith related mafic to acidic intrusives. Intrusive anorthosite, granitoids and alkaline intrusives form the last phases of plutonic activity.

The geological studies that started as reconnoitory appraisal in earlier expeditions by Geological Survey of India, eventually gave way to regional systematic mapping. The studies carried out by Kaul et al., 1991; Bejarnia et al., 1995; D'souza et al., 1995 & 1997; indicated that central Dronning Maud Land (cDML) occupied a central stage in the processes that involved formation of mega-continents like Rodinia and Gondowanaland. Shear zones as such are known to be inherent features of orogenic cycles like the one responsible for having brought about amalgamation of Gondowanaland through continent- continent collision during Pan-African orogeny. Shear zones have played an important role in the exhuming high grade rocks in Central Dronning Maud Land, East Antarctica. Shear zone in the Zweissel mountain area appear to be the loci of widespread fluid infiltration that first caused the exhumation of the rock and subsequent cooling. The major WNW-ESE striking shear zone has been identified to be passing through south of Orvin, south of Humboldt and Zweissel area (D'souza et al., 1997).

2. GEOLOGY

The geological mapping, on 1:50000 scale, of Anorthosite-Mangerite-Charnockite-Granite (AMCG) suite of rocks in Zweissel area of Wohlthat Mountain Range was continued in the 28th Indian Antarctic Expedition. An area of about 150 km^2 (including ice/snow covered areas) was covered during the field work. The geological map is shown in fig. 2.1.

The Wohlthat Mountain Range typically represents a granite-gneiss country which is intruded by voluminous younger granites and charnockite. The multi phase intrusion of pegmatite, aplite, quartz and basic dykes represents the culmination of igneous activity in the region. There are older enclaves of amphibolite and diorite occurring within the gneissic country. The gneisses and granitoids are distinctly separable in the field by their mode of occurrence. The anorthosite massif in Gruber Mountains and the AMCG suite of rocks in Zweissel are supposed to be coeval.

Structure: Two distinct phases of deformations could be identified in the field. The noncoplanar F_1 and F_2 fold axial traces are the manifestations of the D_1 and D_2 phase of progressive deformations, respectively. The trend of F_1 folds varies from 210-240°/sub horizontal to 30° NW. The trend of pervasive gneissosity (S1) varies from 210 to 235°/30-40°NW to sub horozontal and is coplanar with axial traces of the tight isoclinal F1 folds (fig. 2.3a). The trend of F2 folds, generated due to folding of S1 gneissosity planes, varies from 300-325°/30° NE to sub vertical (fig. 2.3a, b & c). Minor fault planes trending NS, cutting across the S1 gneissosity and having sinistral shift, are also observed in the Zweissel area. At some locations small scale locally developed minor shears were identified. The width of these shears varies from 10 centimeters to 1.5 meters. Some of these shears could be traced for 100 to 150 meters along their strike continuity. The trends of these shears vary from NS to NW-SE to even EW. The mylonitic foliations in the mylonitised granite gneisses, exposed in the eastern and west-central part of the study area, trend NS and NW- SE respectively (fig. 2.3d). Based on the study of S-C mylonitic fabric in the gneisses, the sense of movement along the shears is sinistral.

Stratigraphy: following stratigraphy can be proposed for the Study area

Pegmatite/quartz/aplite/epidote veins (Younger intrusives)

Porphyritic granite/leuco granite (Granite)

Charnockite

Biotite rich granite gneiss/quartzo feldspathic gneiss (Granite gneiss)

Amphibolite/diorite (Older enclaves)

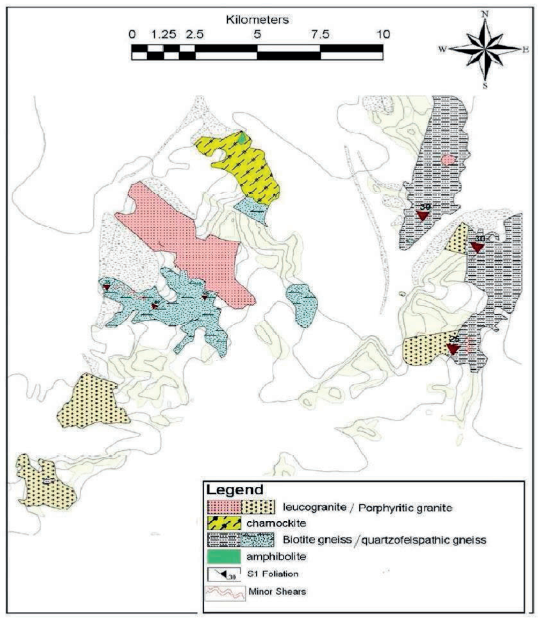

Fig.1.1 Geological map of Zweissel, cDML, EastAntarctica

Fig. 2.3 (a) Tight isoclinal F1 fold and open upright F2 fold in granite gneiss. (b) Section view of inclined F2 fold. (c) Plane view of F2 fold in granite gneiss. (d) δ porphyroblasts in the mylonitised gneiss.

Description of rock types: The rock types exposed in Zweissel area are classified into four major types. 1. Granites are of two types porphyritic granite and medium to fine- grained leucogranite occurring as intrusive within the granite gneiss. 2. Granite gneisses are of two types-biotite rich granite gneiss and quartzo feldspathic gneiss. 3. Charnockite occurs as small enclaves (2-5 meters) in granites as well as mappable out crops within the gneissic country and 4. Enclaves of amphibolite and diorite are common within the granitoids as well as in the gneisses. Younger intrusives of quartz, aplite, epidote and pegmatite veins along with mafic dykes represents the last phase of magmatic activity in the area.

Porphyritic granite contains anhedral phenocrysts (1-7cm long) of K-feldspar in a medium- grained groundmass (fig. 2.5a). The groundmass - phenocryst ratio is about 2:3. At places a crude magmatic foliation represented by alignment of phenocrysts was observed.

Enclaves of gneisses are found in the porphyritic granite. The contact between porphyritic granite and granite gneiss is sharp.

The leucogranites are medium to fine-grained and occur as intrusive veins and sheets. At places the leuco granite is highly mylonitised. It exhibits sharp and discordant contact with diorite, biotite rich granite gneiss and quartzo feldspathic gneiss (fig. 2.5b, e & f).

The granite gneiss country, exposed at many places, comprises of biotite rich granite gneiss and quartzo feldspathic gneiss. The biotite gneiss is dark grey to black in colour, medium to fine grained, well foliated and weathered rock associated mostly with the quartzo feldspathic gneiss. The contact between quartzo feldspathic gneiss and biotite rich granite gneiss is sharp and concordant (fig. 2.5c). It contains enclaves of amphibolite and diorite and is intruded by granite, pegmatite/quartz/aplite veins. Medium grained, greasy looking, moderately foliated charnockite occurs as small enclaves as well as mappable bodies within the granite and gneiss country. The younger intrusive bodies of quartz, pegmatite, aplite and epidote veins are abundant in the study area. Several generations of these intrusives cutting across the gneisses and granites in all directions (fig. 2.5 d).

3. PETROGRAPHY

Based on petrographic studies of the various rock types, collected during 28th expedition, from the Zweissel area of Wohlthat Mountain Range of cDML, East Antarctica, three major litho units namely granite gneiss, charnockite and granite could be delineated. The granite gneiss is further divided into two sub units namely biotite rich granite gneiss and quartzo feldspathic gneiss, based on their mineral content. Similarly the granite has been divided into two sub units namely porhyritic granite and leuco granite based on their texture. The detailed petrographic description of each rock type is given below-

Granite: The porphyritic granite consists of quartz, plagioclase (oligoclase-andesine), microcline, biotite as major mineral phase and amphibole, apatite, zircon, sphene, opaque (magnetite/ ilmenite), monazite, muscovite (few) and epidote as accessory phase. Two textural types of microclines were identified viz. as phenocrysts and as ground mass showing cross hatched twining. Plagioclase is also seen in two textural forms; as euhedral inclusion in phenocryst (few) and as small subhedral to anhedral grains in ground mass. Biotite occurs as two textural types; as ground mass and as corona around ilmenite (fig.3.1a) representing a cooling texture. Biotite grains show partial alteration, along the grain boundary and cleavage, due to rehydration, to chlorite. Sericitic alteration of feldspar is common. Myrmekitic texture, comprised of quartz-plagioclase-biotite symplectitic intergrowth, is invariably present along the grain boundaries of microcline also representing the cooling texture (fig.3.1b). The porphyritic granite shows typical granitic texture. There is no sign of deformation micro fabrics observed although there is a crude alignment of phenocrysts observed on the megascopic scale.

The leuco granite consists of quartz, microcline, plagioclase (oligoclase-andesine) and biotite as major mineral phase and apatite, zircon, monazite, epidote as accessory phase. The average modal (by visual estimation) quartz, microcline and plagioclase volume percentage is 35%, 35% and 25% respectively in the leuco granite. Biotite grains show partial alteration, along the grain boundary and cleavage, due to rehydration, to chlorite. The mylonitised leuco granite exhibits quartz ribbons and a strong preferred alignment of quartzo feldspathic minerals on microscopic scale (fig. 3.1c).

Fig. 2.5 (a) Porphyritic granite showing crude alignment of feldspar phenocrysts. (b) Sheet like intrusion of leuco granite in diorite. (c) biotite rich granite gneiss and quartzo feldspathic gneiss. (d) Innumerable injection of quartz, pegmatite and aplite veins in the granite gneiss. (f) Sharp contact between intrusive leuco granite and biotite rich granite gneiss.

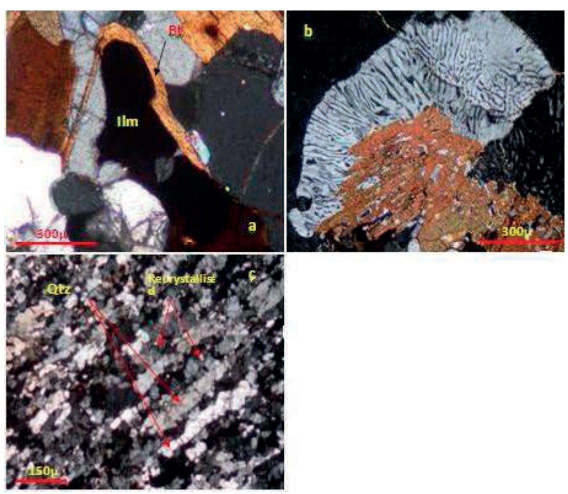

Fig. 3. 1 (a) Corona of biotite around ilmenite in the porphyritic granite. (b) Symplectitic intergrowth of quartz-plagioclase-biotite in the porphyritic granite. (c) Quartz ribbons and recrystalised feldspar grains showing strongly developed mylonitic foliation in mylonitised leuco granite.

The recrystalised quartz and feldspar grains, surrounding quartz ribbons, are also aligned in the direction of shear movement i.e. NW-SE. Due to lack of presence of mafic minerals, mylonitic foliation is often not accentuated in hand specimen.

Granite gneiss: The biotite rich granite gneiss consists of quartz, plagioclase (andesine), biotite, microcline and garnet as the major phase and apatite, zircon, monazite, ilmenite/magnetite, epidote as accessory mineral phase. The approximate modal volume percentage of quartz, plagioclase and microcline is 30%, 25% and 30% respectively where as the biotite modal volume varies from 7-10%. Plagioclases occur in four textural modes- as inclusions of small euhedral grain in garnet; as subhedral to anhedral grains in the ground mass; as thin corona around garnet (fig. 3.2a & b) and as small euhedral recrystalised grains around quartz ribbons, garnet and biotite grains. The last two modes are observed in the mylonitised biotite rich granite gneiss. Biotite occurs in three textural forms- as inclusion in garnet; as ground mass and as symplectitic intergrowth with plagioclase and quartz along the garnet grain boundary (fig. 3.2c). Garnets occur as rounded to semi rounded grains in the ground mass. Based on the petrographic studies it can be stated that biotite gneiss might have undergone at least two phases of metamorphism. The inclusion assemblage of plagioclase, biotite and quartz in garnet indicates a prograde event prior to the retrograde decompression/cooling events, defined by the textures like corona of plagioclase around garnet, symplectites of plagioclase-biotite-quartz along the grain boundary of garnet.

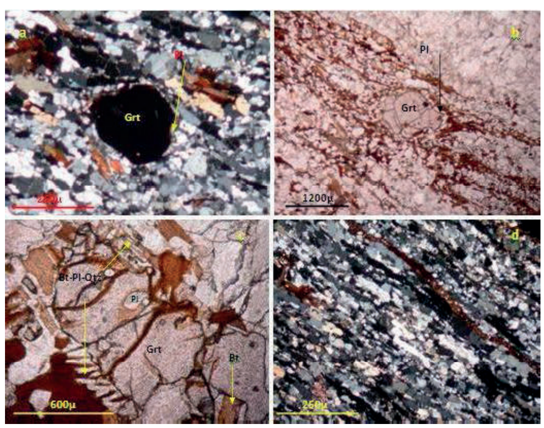

Fig. 3.2 (a) Coronal plagioclase around garnet and recrystalised plagioclase grains around biotite and quartz ribbon. (b) δ porphyroblast of garnet having partially developed corona of plagioclase around it. (c) Partial development of symplectitic intergrowth of biotite plagioclase-quartz along garnet grain boundary. (d) Photomicrograph of mylonitised quartzo feldspathic gneiss showing quartz ribbons and recrystalised quartz and feldspar grains.

The quartzo feldspathic gneiss consists of quartz, microcline, plagioclase (oligoclase-andesine) and biotite (few) as major phase and garnet (very few), apatite, zircon, epidote, monazite and muscovite as accessory mineral phase. The approximate modal volume of quartz, plagioclase and microcline is 35%, 25% and 35% respectively where as the biotite modal volume varies from 2-5%. The biotite grains show partial alteration to chlorite, along the grain boundary and cleavage, due to rehydration. The sericitisation of feldspars is also a common alteration phenomenon in the quartzo feldspathic gneiss. The mylonitised quartzo feldspathic gneiss exhibits quartz ribbons and strong preferred orientation of quartzo feldspathic minerals. Like mylonitised leuco granite, the recrystalised quartz and feld-spar grains, in the mylonitised quartzo feldspathic gneiss, are also aligned in the direction of shear movement (fig. 3.2d).

Charnockite: It consists of quartz, plagioclase (andesine-labradorite), microcline, biotite, orthopyroxene (hypersthene), amphibole (hornblende) and few clinopyroxene (diopside) as major mineral phase and apatite, epi-dote, monazite, zircon, ilmenite/magnetite as accessory minerals. Plagio-clase occurs in three textural modes viz. inclusion in orthopyroxene, as ground mass and as symplectitic intergrowth with biotite and quartz (fig.3.3a & b). Three textural modes of biotite are noted: occurring as inclusion in orthopyroxene, as ground mass and as corona around ilmenite, clinopyroxene and orthopyroxene (fig.3.3c & e). Within charnockite, orthopyroxene usually occurs as poikiloblastic grains. Another textural type of orthopyroxene is found as exsolved lamellae in clinopyroxene (fig.3.3d). Two textural types of clinopyroxenes noted, viz. as ground mass and as inclusion in orthopyroxene. Amphiboles occur in two textural modes; as ground mass and as corona around orthopyroxene and ilmenite (fig.3.3f). The inclusion assemblage of minerals like quartz, plagioclase and biotite in orthopyroxene indicate a possible prograde metamorphic event in the charnockite. The corona of biotite around ilmenite/magnetite, amphibole around ilmenite/magnetite and orthopyroxene and symplectitic intergrowth of plagioclase-biotite- quartz can be represented as the retrograde decom-pression and cooling events in the charnockite. In addition to the above mentioned major rock types, there are small occurrences of amphibolites and diorites observed in the study area. These units occur as small en-claves and restites in the gneiss and granite country. Amphibolite consists of plagioclase, quartz, biotite, amphibole and few clinopyroxene as major minerals and ilmenite/magnetite, apatite, zircon and epidote as accessory minerals. Diorite consists of plagioclase, biotite, amphibole and few py-roxene and quartz with accessory mineral phases of apatite, zircon, ilmenite/magnetite and sphene.

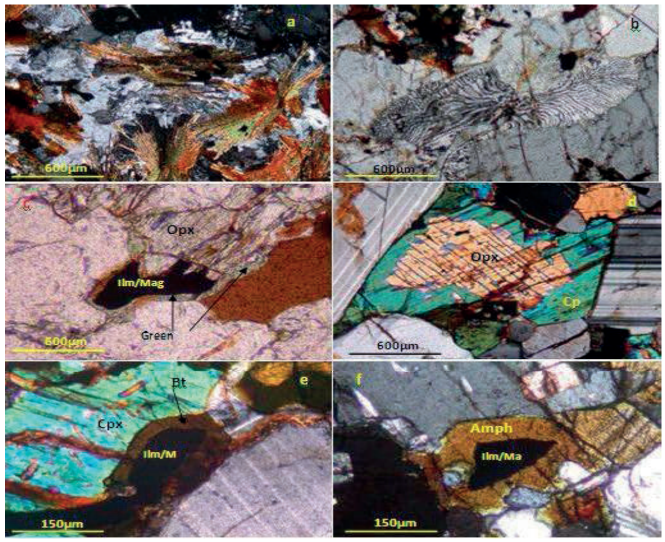

Fig. 3.3 (a) Symplectitic intergrowth of plagioclase-biotite-quartz. (b) Symplectitic intergrowth of plagioclase and quartz (myrmekite). (c) Corona of green amphibole around ilmenite/ magnetite and clinopyroxene. (d) Exsolved lamellae of orthopyroxene in clinopyroxene. (e) Corona of biotite around ilmenite/magnetite adjacent to clinopyroxene. (f) Corona of amphibole around ilmenite/magnetite

Microstructural study of minor shear: The microstructures within the minor shear zone includes the development of quartz ribbons, quartz subgrains, garnet mantled type porphyroblasts, some mica fish like biotite grains etc. At one place, sinistral movement is indicated by sinistrally disposed ribbon quartz grains (fig. 3.4b). The mylonitic banding in form of recrystallised quartzo-feldspathic band (1000-2000μm) interbanded with relatively biotite rich band (200-400μm) (fig. 3.4a). A strong single foliation fabric is observed in all the sections (fig. 3.2d). There is a definite grain size reduction in the mylonites. The original bigger quartz and feldspar grains are reduced by the various mechanism of grain size reduction. The progressive deformation may have resulted in recovery of some of the reduced grains. Thus, there are many recovered quartz grains along with recrystalised grains (fig. 3.4c). There is a preferred alignment of these recrystallised grains which again signifies the ongoing deformation. The prophyroblasts are mainly garnet crystals set against quartzo-feldspathic and phyllositicate groundness. As such, the rotation of the garnet porphyroblasts are depicted by the swirl of the groundmass grains in the vicinity of the bigger clasts (fig. 3.2b). The garnets are all mantled type with dominance of development of long tails. (fig. 3.2b & 3.4a and d). There are indications of brittle breakdown of garnet porphyro blast during the ongoing deformation (fig. 3.4d).

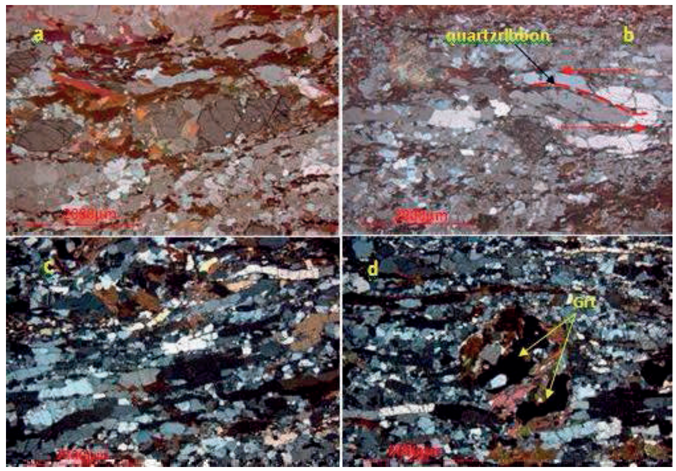

Fig. 3.4 (a) Mylonitic banding in form of recrystallised quartzo-feldspathic band interbanded with relatively biotite rich band. (b) Sinistral movement is indicated by sinistrally disposed ribbon quartz grains. (c) Recovered quartz grains along with recrystalised grains. (d) Brittle breakdown of garnet porphyroblast.

4. GEOCHEMISTRY

About 11 represntative granite samples, ten granite gneiss, four charnockite and two samples of amphibolite were analysed for major and trace elements by conventional X-ray Fluroscence method at the PPOD laboratory of GSI at Banglore. The REE analyses were carried out at ICPMS Lab at GSI, Hyderabad. The results of the analyses is shown in Table no. 1a, b & 2a, b. Table 3 shows the CIPW norms.

In the R1-R2 multicationic plot (Fig 1) by De la Roche et al (1980), the gneisses as well as the most granites (both porphyritic and leuco varieties) classify as granites. Few of the granites plot in the quartz-monzonite-monzonite fields. The charnockites show a spread in composition from syenodiorite to tonalite to monzogabbro.

The AFM plot (after Irvine & Baragar, 1971) shows that the granites as well as gneisses show tholeiitic character and highly evolved nature. The charnockites show mixed tholeiitic- calcalkaline nature with lower degree of differentiation whereas the amphibolite shows distinct calc-alkaline nature [Fig 2]. The granites and gneisses show a distinct peraluminous nature in the alumina-alkali index plot by Shand (1943) [Fig 3]. This may be a result of the higher differentiation of the granitoids. The A/NK Vs A/CNK values vary between 1.06 and 2 indicating enrichment in alumina suggesting a role of crustal contamination.

Most of the granites and the charnockites show high K calc-alkaline to shoshonitic affinity in the SiO_2-K_2O plot after Pecerillo and Taylor (1976) whereas Sample Z-2A (granite) plots in the tholeiitic field. The gneissic rocks show a spread from calc-alkaline to the high-K calc-alkaline series [Fig 4]. In the R1-R2 multication tectonic discrimination plot by Batchelor & Bowden(1975), the gneissic rocks show a spread from Pre-plate collision to Late-orogenic indicating their diverse origin during various stages of deformation whereas the granites plot in the late-orogenic field. The charnockites plot in the post-collision-uplift field [Fig 5]. In the major element tectonic discrimination plots after Maniar and Piccoli (1985) the granites show rift-related granite-continental epirogenic/plate orogenic granite affinities whereas the gneisses show Island Arc affinities [Fig 6a & b].

As observed from the bivariant harker plots [Fig 7] of various major elements against silica, TiO_2, CaO, MgO, FeOt and Al_2O_3 show decreasing trend with increase in SiO_2 content with variable spread in values. The TiO_2 content is generally low varying from 0.06 to 2.6 (except Z- 3 -5.96). The Na_2O content (about 3%) is fairly constant across all rock types except Z-2A which has higher (7.59%) Na_2O content. The rocks of Zweissel area are enriched in K_2O where the granites have higher content and tight clustering as compared to the gneisses.

It is evident from the trace element/incompatible element plot [Fig 8] of the Zweissel lithotypes versus chondrite values (chondrite values after Thompson, 1982) that the Zweissel lithologies are generally enriched in the lighter incompatible elements as compared to heavier fractions. The granites and gneisses show prominent ridges of La, Nd, Sm & Hf indicating enrichment of both lighter as well as heavier fraction. The prominent troughs of P and Ti suggest higher contribution of crustal material in the source. The amphibolite (Z-20) shows depletion in Hf and Ta and enrichment in La, Ce, Nd and Tb. In contrast, the amphibolite (Z-2B) shows a prominent Sm trough and enrichment in Hf.

The Chondrite normalized patterns of the granitoids and mafics from Zweissel area shown in Fig 9. The granites and gneisses usually show a prominent negative Eu anomaly. Some samples (Z- 24B) show a positive Eu anomaly where as samples Z-14A shows a flattish Eu signature. The La/Lu values show higher spread with granites showing a range of range from 12 to 605 while the range for gneisses varies from 37 to 665. The La/Lu values for charnockites vary from 63 to 95 indicating a flattish LREE-HREE trend.

Table 1a: Major and trace element data for granites and granite gneisses from Zweissel area.

Sample	Z-2A	Z-4B	Z-11	Z-14A	Z-15B	Z-17B	Z-17C	Z-18	Z-5C	Z-14B	Z-16A
Lithology						Granite					
SiO2	63.8	67.53	67.8	61.55	72.87	68.93	71.95	68.56	70.59	71.25	70.55
TiO2	0.06	0.57	0.39	0.98	0.14	1.34	0.23	0.64	0.39	0.38	0.5
Al2O3	20.9	15.41	14.6	15.94	13.7	11.73	14.69	14.71	13.88	13.57	13.6
Fe2O3	0.45	3.28	3.55	7.55	1.75	8.96	2.52	3.43	2.61	2.83	4.06
MnO	0.01	0.01	0.03	0.09	0.04	0.03	0.01	0.05	0.03	0.03	0.06
MgO	0.01	0.39	0.26	0.55	0.04	1.68	0.08	0.42	0.27	0.21	0.52
CaO	4.32	1.36	1.78	2.99	1.18	0.2	1.29	1.47	1.2	1.33	1.83
Na2O	7.59	2.67	2.77	2.81	4.31	0.89	3.15	2.92	2.94	2.85	2.42
K2O	0.63	6.76	6.74	5.67	4.54	4.05	4.71	5.93	5.72	5.81	4.45
P2O5	0.03	0.16	0.08	0.27	0.04	0.02	0.05	0.21	0.09	0.15	0.16
Treace elements (in ppm)											
Cr	1	1	1	11	8	87	1	1	17	1	27
Ni	26	19	9	7	1	62	1	4	7	1	11
Be	3.06	0.52	2.88	2.33	4.33	0.98	1.09	4.5	3.91	2.6	0.48
Ge	1.14	0.98	2.47	1.86	0.88	1.21	2.49	1.83	1.03	2.04	1.11
Mo	1.02	0.76	0.36	1.53	0.02	0.72	1.23	0.55	0.4	0.65	0.17
In	0.06	0.04	0.09	0.1	0.09	0.07	0.23	0.14	0.06	0.13	0.05
Sn	5.76	1.84	0.74	1.47	4.75	1.24	2.61	3.3	1.99	6.75	0.19
Hf	4.56	13.13	13.6	14.87	3.63	6.5	17.6	15.33	8.63	3.89	3.86

Contd....

Table 1a : Contd....

Sample Litho logy	Z-5A	Z-5B	Z-15A	Z-16B	Z-17A	Z-20A	Z-20B	Z-22A	Z-24A	Z-24B
					Granite	gneiss				
Hf	6.7	3.29	11.71	3.8	3.14	3.54	9.09	6.48	7.41	6.73
Ta	3.02	1.42	3.17	6.13	4.72	9.85	8.66	6.93	6.13	6.56
W	715	320.9	174.7	414.9	284.8	522.6	434.8	330	297.3	323.9
Tl	0.19	0.29	0.17	0.18	0.14	0.27	0.63	0.22	0.2	0.38
U	4.78	0.85	0.51	0.95	1.45	1.32	10.29	1	1	0.86
Th	15.7	5.44	2.41	2.75	2.81	3.12	149.4	5.12	8.37	0.6
FeOt	4.04	1.58	7.81	5.66	4.34	2.48	1.27	4.15	10.68	1.32
A/NK	1.81	1.4	1.81	1.59	1.87	1.39	1.24	1.49	1.83	1.17
A/CNK	1.16	1.1	0.98	1.22	1.2	1.18	1.11	1.27	1.31	1.01
K2O/Na 2O	0.62	1.2	1.36	1.06	0.71	2.02	1.61	1.17	1.37	2.16

Contd....

Table 1a : Contd....

Sample	Z-5A	Z-5B	Z-15A	Z-16B	Z-17A	Z-20A	Z-20B	Z-22A	Z-24A	Z-24B
Lithology					Granite	gneiss				
SiO2	68.6	71.7	59.71	68.69	70.61	73.84	73.31	69.01	57.26	73.9
TiO2	0.59	0.21	2.19	0.91	0.55	0.28	0.07	0.59	1.4	0.28
Al2O3	14.6	14.7	14.99	13.53	13.95	12.75	13.8	14.27	15.6	12.65
Fe2O3	4.49	1.76	8.68	6.29	4.82	2.76	1.41	4.61	11.87	1.47
MnO	0.04	0.02	0.1	0.06	0.06	0.04	0.03	0.04	0.15	0.02
MgO	1.38	0.33	1.75	1.17	0.9	0.29	0.01	0.63	3.01	0.17
CaO	2.52	1.55	3.88	1.4	2.28	0.88	0.76	0.9	1.89	0.91
Na2O	3.47	3.57	2.66	3.06	3.09	2.4	3.27	3.29	2.72	2.72
K2O	2.16	4.28	3.62	3.23	2.18	4.85	5.28	3.86	3.73	5.88
P2O5	0.04	0.08	0.71	0.05	0.11	0.09	0.02	0.26	0.06	0.04
Treace elements (in ppm)										
Cr	17	4	28	46	7	1	10	1	111	1
Ni	21	21	18	47	21	7	1	1	29	23
Be	1.8	1.2	1.15	0.47	1.68	1.27	0.8	2.17	0.71	0.23
Ge	1.23	1.03	1.67	0.8	0.91	1.46	1.69	1.15	2.16	0.53
Mo	1.83	0.4	0.29	0.46	0.05	0.18	1.04	0.06	0.61	0.26
In	0.06	0.02	0.12	0.03	0.06	0.1	0.03	0.09	0.13	0.02
Sn	1.73	0.26	1.22	0.17	3.28	1.38	0.73	6.11	0.59	0.36

Contd....

Table 1a : Contd....

Sample Litho logy	Z-5A	Z-5B	Z-15A	Z-16B	Z-17A Granite	Z-20A gneiss	Z-20B	Z-22A	Z-24A	Z-24B
Hf	6.7	3.29	11.71	3.8	3.14	3.54	9.09	6.48	7.41	6.73
Ta	3.02	1.42	3.17	6.13	4.72	9.85	8.66	6.93	6.13	6.56
W	715	320.9	174.7	414.9	284.8	522.6	434.8	330	297.3	323.9
Tl	0.19	0.29	0.17	0.18	0.14	0.27	0.63	0.22	0.2	0.38
U	4.78	0.85	0.51	0.95	1.45	1.32	10.29	1	1	0.86
Th	15.7	5.44	2.41	2.75	2.81	3.12	149.4	5.12	8.37	0.6
FeOt	4.04	1.58	7.81	5.66	4.34	2.48	1.27	4.15	10.68	1.32
A/NK	1.81	1.4	1.81	1.59	1.87	1.39	1.24	1.49	1.83	1.17
A/CNK	1.16	1.1	0.98	1.22	1.2	1.18	1.11	1.27	1.31	1.01
K2O/Na 2O	0.62	1.2	1.36	1.06	0.71	2.02	1.61	1.17	1.37	2.16

Table 1b: Major and trace element data for charnockite and amphibolite from Zweissel area.

Sample lithology	Z-3	Z-4A	Z-8	Z-14C	Z-2B	Z-20C
		Charnockite			Diorite / Amphibolite	Amphibolite
SiO2	44.7	49.2	53.7	61.56	50.77	45.01
TiO2	5.96	2.63	2.21	1.25	4.52	1.73
Al2O3	9.12	11.9	13.9	14.52	14.92	13.26
Fe2O3	19.98	19.3	11.9	8.24	11.8	11.78
MnO	0.31	0.26	0.15	0.11	0.2	0.15
MgO	6.23	1.87	3.13	3.26	3.66	10.14
CaO	8.69	6.89	5.42	3.43	6.21	7.14
Na2O	2.05	2.72	2.79	3.16	2.54	0.5
K2O	0.51	2.87	3.71	2.92	3.12	5.19
P2O5	1.38	1.15	1.24	0.19	0.46	2.13
Trace elements(in ppm)						
Cr	57	17	7	125	54	195
Ni	16	1	37	27	37	99
Be	1	1.3	1.8	0.49	1.54	4.31
Ge	3.47	3.57	2.7	1.31	1.9	4.44
Mo	3.88	4.35	1.21	0.47	1.87	0.17
In	0.25	0.24	0.2	0.06	0.1	0.45
Sn	2.96	2.48	2.13	0.56	5.19	6.16
Hf	8.38	8.36	6.56	8.61	16.8	1.37
Ta	3.22	0.68	1.75	4.56	2.61	1.69
W	97	83.4	150	324	482.2	72.1
			0			
Tl	0.05	0.09	0.16	0.09	0.16	0.17
U	0.73	0.95	1.95	0.87	7.56	8.48
Th	2.17	1.88	7.49	3.77	6.56	37.23
FeOt	17.98	17.4	10.7	7.41	10.62	10.6
A/NK	2.32	1.56	1.61	1.74	1.97	2.06
A/CNK	0.46	0.59	0.75	0.99	0.79	0.68
K_2O/Na_2O	0.25	1.06	1.33	0.92	1.23	10.38

Table 2a: REE data for granites and granite gneisses from Zweissel area.

Sample	Z-2A	Z-4B	Z-11	Z-14A	Z-15B	Z-17B	Z-17C	Z-18	Z-5C	Z-14B	Z-16A
lithology					Granite						
La	27.8	50.25	405.4	117.1	12.84	34.2	44.07	155	27.34	41.77	28.43
Pr	7.57	10.67	72.41	27.3	3.43	8.44	14.22	38.38	6.52	11.48	6.97
Nd	31.4	43.07	258.6	107.8	15.44	34.91	69.31	146.4	25.25	50.54	29.4
Eu	0.31	1.99	1.92	4.32	0.3	0.98	2.46	1.23	0.9	2.2	1.18
Sm	8.55	6.27	35.16	17.89	5.36	6.73	14.46	23.13	4.86	9.71	5.79
Tb	2.38	0.59	5.15	2.69	2.29	1.64	2.68	3.35	0.89	1.86	1.7
Gd	8.1	3.95	26.51	13.49	6.96	6.55	12.28	16.45	4.04	8.39	6.13
Dy	10.6	1.47	16.56	9.01	10.97	6.6	9.52	10.97	3.3	6.81	7.6
Ho	1.98	0.23	2.66	1.5	2.17	1.21	1.59	1.82	0.6	1.15	1.5
Er	6.08	0.69	7.35	4.2	6.86	3.63	4.47	5.09	1.82	3.26	4.65
Tm	1.01	0.09	0.9	0.57	1.12	0.55	0.63	0.67	0.27	0.46	0.73
Ce	61	98.03	645.7	222.3	25.34	68.45	97.65	344.7	203.8	88.73	56.53
Yb	6.44	0.6	5.02	3.49	7.1	3.42	4	3.73	1.72	2.86	4.65
Lu	0.91	0.11	0.67	0.53	1.03	0.51	0.65	0.52	0.25	0.41	0.66
La/Lu	30.6	456.8	605.1	221	12.47	67.06	67.8	298	109.4	101.9	43.08

C0ntd....

Table 2a:C0ntd....

Sample	Z-5A	Z-5B	Z-15A	Z-16B	Z-17A	Z-20A	Z-20B	Z-22A	Z-24A	Z-24B
lithology	Granite	gneiss								
La	34.05	23.78	45.35	16.85	14.04	26.79	179.63	30.62	32.8	15.37
Pr	8.3	4.96	13.25	4.35	3.3	6.56	46.34	8.08	8.02	1.8
Nd	34.22	18.91	60.52	18.56	14	27.34	177.03	34.55	34.3	6.1
Eu	1.24	0.7	1.75	0.76	0.99	0.95	1.35	0.97	1.53	2.28
Sm	7.19	3.51	12.15	3.56	2.97	6.25	33.9	7.22	7.6	1.04
Tb	1.67	0.73	1.98	0.84	0.73	1.6	4.02	1.56	1.98	0.5
Gd	6.38	2.91	9.64	3.32	2.9	6.01	23.03	6.48	7.45	1.4
Dy	6.94	2.81	6.67	3.49	3.28	6.21	10.2	5.56	8.52	2.83
Ho	1.27	0.5	1.09	0.67	0.69	1.07	1.31	0.91	1.7	0.67
Er	3.72	1.47	3.02	2.1	2.29	3.14	3.07	2.61	5.29	2.23
Tm	0.55	0.22	0.41	0.34	0.38	0.47	0.3	0.39	0.84	0.36
Ce	69.41	43.54	102.62	32.86	27.11	52.93	377.98	63.35	63.88	19.51
Yb	3.46	1.37	2.46	2.2	2.49	3	1.68	2.38	5.47	2.32
Lu	0.51	0.19	0.36	0.33	0.37	0.44	0.27	0.35	0.82	0.35
La/Lu	66.76	125.2	125.97	51.06	37.95	60.89	665.3	87.49	40	43.91

Table 2b: REE data for charnockite and amphibolite from Zweissel area.

Sample	Z-3	Z-4A	Z-8	Z-14C	Z-2B	Z-20C
lithology		Charnockite			Diorite/ Amphibolite	Amphibolite
La	65.95	69.75	78.67	25.4	25.72	486.65
Pr	20.95	21.89	22.26	5.74	6.06	111.07
Nd	101.5	106.1	99.49	24.13	25.36	455.69
Eu	2.69	4.94	2.47	1.93	1.22	10.38
Sm	20.6	22.08	20.99	4.26	4.75	56
Tb	3.64	4.07	4.42	0.8	1.97	5.93
Gd	17.12	18.47	18.39	3.65	5.48	36.59
Dy	12.59	14.46	16.91	3.18	10.25	15.46
Ho	2.11	2.49	3.01	0.64	2.2	2.31
Er	5.7	6.81	8.41	2.08	7.08	6.56
Tm	0.76	0.94	1.16	0.35	1.14	0.78
Ce	149	153.9	170.3	48	48.69	863.78
Yb	4.64	5.89	6.8	2.42	7.53	4.63
Lu	0.69	0.93	0.94	0.4	1.16	0.63
La/Lu	95.58	75	83.69	63.5	22.17	772.46

Table 3: CIPW norms of rocks from Zweissel area.

Sample	lithology	Q	C	Or	Ab	An	Di	Wo	Hy	Ol	Il	Hm	Tn	Ru	Ap	Sum
Z-2A/28		8.12	0.00	3.72	64.22	21.07	0.00	0.00	0.02	0.00	0.02	0.45	0.12	0.00	0.07	97.82
Z-4B/28		23.08	1.61	39.95	22.59	5.70	0.00	0.00	0.97	0.00	0.02	3.28	0.00	0.56	0.38	98.15
Z-11/28		22.08	0.00	39.83	23.44	7.44	0.00	0.00	0.65	0.00	0.06	3.55	0.61	0.11	0.19	97.96
Z-14A/28		17.04	0.39	33.51	23.78	13.07	0.00	0.00	1.37	0.00	0.19	7.55	0.00	0.88	0.64	98.42
Z-15B/28		28.16	0.00	26.83	36.47	4.63	0.21	0.15	0.00	0.00	0.09	1.75	0.23	0.00	0.09	98.61
Z-17B/28	Granite	45.38	5.57	23.93	7.53	0.86	0.00	0.00	4.18	0.00	0.06	8.96	0.00	1.31	0.05	97.83
Z-17C/28		32.86	2.18	27.83	26.65	6.07	0.00	0.00	0.20	0.00	0.02	2.52	0.00	0.22	0.12	98.68
Z-18/28		25.70	1.32	35.04	24.71	5.92	0.00	0.00	1.05	0.00	0.11	3.43	0.00	0.58	0.50	98.35
Z-5C/28		28.88	0.89	33.80	24.88	5.37	0.00	0.00	0.67	0.00	0.06	2.61	0.00	0.36	0.21	97.73
Z-14B/28		29.70	0.53	34.34	24.12	5.62	0.00	0.00	0.52	0.00	0.06	2.83	0.00	0.35	0.36	98.42
Z-16A/28		35.20	1.86	26.30	20.48	8.03	0.00	0.00	1.30	0.00	0.13	4.06	0.00	0.43	0.38	98.16
Z-5A/28		32.76	2.06	12.76	29.36	12.24	0.00	0.00	3.44	0.00	0.09	4.49	0.00	0.55	0.09	97.84
Z-5B/28		31.01	1.55	25.29	30.21	7.17	0.00	0.00	0.82	0.00	0.04	1.76	0.00	0.19	0.19	98.22
Z-15A/28		21.46	1.34	21.39	22.51	14.61	0.00	0.00	4.36	0.00	0.21	8.68	0.00	2.08	1.68	98.33
Z-16B/28		33.93	2.57	19.09	25.89	6.62	0.00	0.00	2.91	0.00	0.13	6.29	0.00	0.84	0.12	98.39
Z-17A/28		38.38	2.62	12.88	26.15	10.59	0.00	0.00	2.24	0.00	0.13	4.82	0.00	0.48	0.26	98.56
Z-20A/28	Granite gneiss	39.25	2.17	28.66	20.31	3.78	0.00	0.00	0.72	0.00	0.09	2.76	0.00	0.24	0.21	98.19
Z-20B/28		32.49	1.37	31.20	27.67	3.64	0.00	0.00	0.02	0.00	0.06	1.41	0.00	0.04	0.05	97.96
Z-22A/28		32.97	3.67	22.81	27.84	2.77	0.00	0.00	1.57	0.00	0.09	4.61	0.00	0.55	0.62	97.47
Z-24A/28		18.80	3.80	22.04	23.02	8.98	0.00	0.00	7.50	0.00	0.32	11.87	0.00	1.23	0.14	97.70
Z-24B/28		33.48	0.25	34.75	23.02	4.25	0.00	0.00	0.42	0.00	0.04	1.47	0.00	0.26	0.09	98.04

C0ntd....

Table 3:Contd....

Sample	lithology	Q	C	Or	Ab	An	Di	Wo	Hy	Ol	Il	Hm	Tn	Ru	Ap	Sum
Z-3/28		11.11	0.00	3.01	17.35	14.18	0.29	0.00	15.38	0.00	0.66	19.98	13.77	0.00	3.27	99.01
Z-4A/28		11.32	0.00	16.96	23.02	11.67	5.33	0.00	2.19	0.00	0.56	19.30	5.74	0.00	2.72	98.80
Z-8/28	Charnockite	11.46	0.00	21.92	23.61	14.36	0.00	0.00	7.80	0.00	0.32	11.85	3.12	0.77	2.94	98.15
Z-14C/28		20.33	0.38	17.26	26.74	15.78	0.00	0.00	8.12	0.00	0.24	8.24	0.00	1.13	0.45	98.65
Z-2B/28	Diorite/Amphibolite	8.25	0.00	18.44	21.49	20.09	0.00	0.00	9.12	0.00	0.43	11.80	5.43	2.08	1.09	98.23
Z-20C/28	Amphibolite	0.00	0.00	30.67	4.23	18.61	0.00	0.00	20.10	3.61	0.32	11.78	2.04	0.73	5.05	97.14

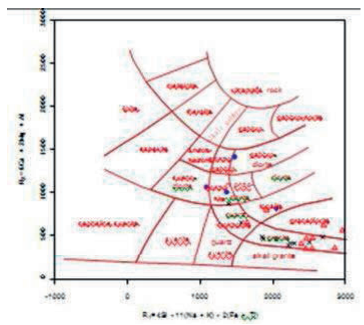

Figure 1 R1-R2 multi cationic classification plot for the granitoids of Zweissel (after De la Roche et al., 1980) x-granites, open triangles-gneisses, filled circles-charnockites (for all figures)

Figure 2 A-F-M plot of different lithotypes (after Irvine & Baragar, 1971

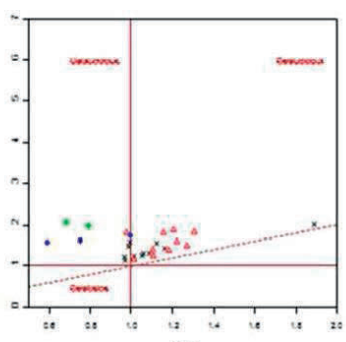

Figure 3 Alumina index plot of Zweissel lithologies (after Shand, 1943)

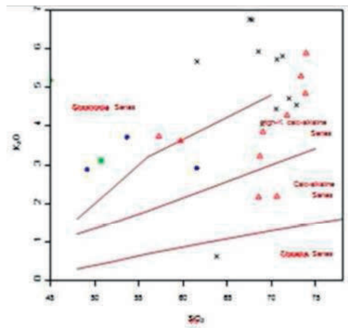

Figure 4 Alkali staturation plot of Zweissel rocks (after Pecerillo & Taylor, 1976)

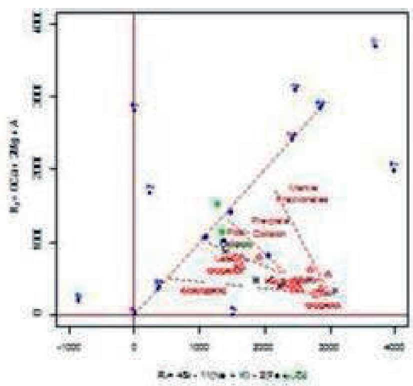

Figure 5 R1-R2 multication plot of rocks from Zseissel Mountains (after Batchelor & Bowden, 1985)

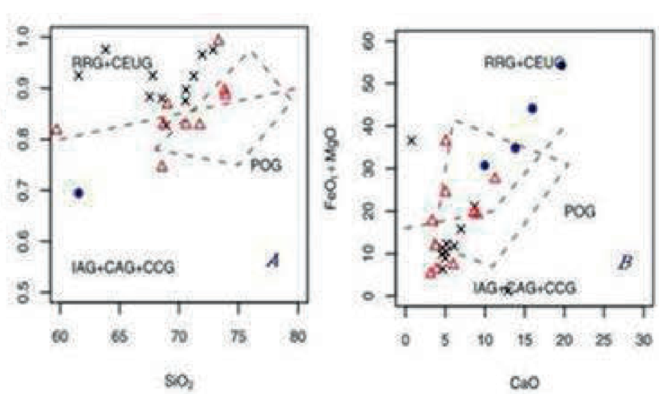

Figure 6 Selected major element tectonic discrimination plot of rocks from Zwseissel Mountains (after Maniar & Piccoli, 1989)

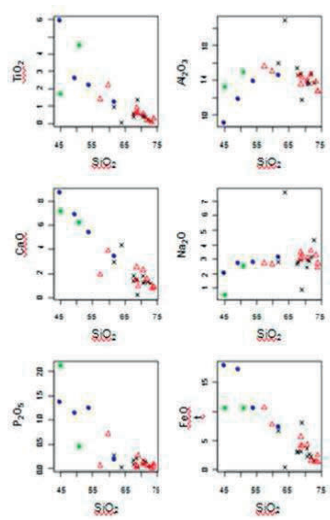

Figure 7 Bivariant plots of the major elements versus SiO_2

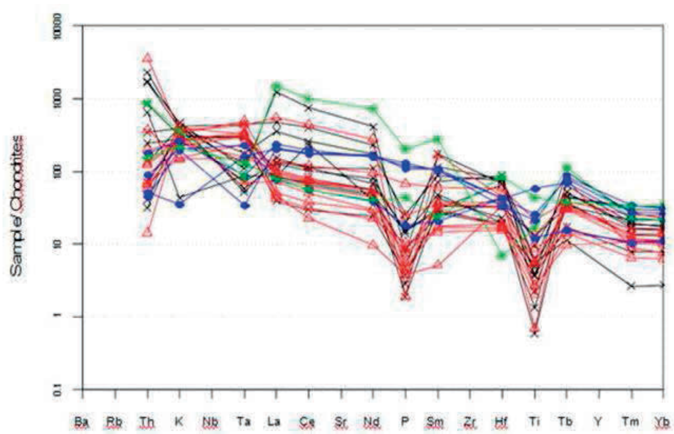

Figure 8 Trace element/incompatible element plot of Zweissel lithotypes as a function of chondrite values (chodrite values after Thompson, 1982)

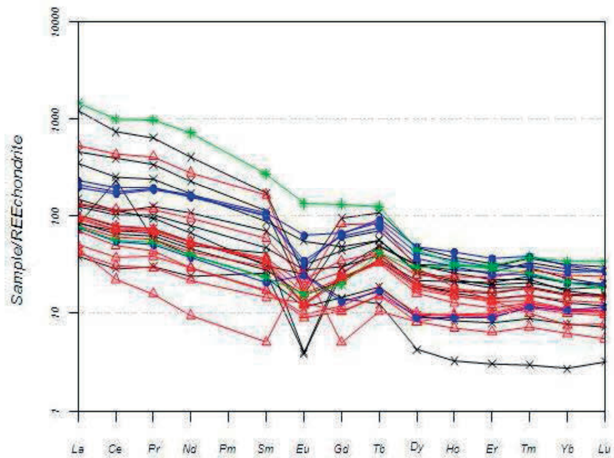

Figure 9 REE plot of Zweissel lithotypes as a function of chondrite values (chondrite values after Nakamura, 1974)

5. DISCUSSION

Quartzo-felspathic gneisses and biotite gneisses form the country rock in the area under investigation. These gneisses are intruded by voluminous charnockite, porphyritic granite and leucogranite. Pegmatite, aplite and basic dykes form the culminating phases of intrusive activity in the Zweissel area. The entire ensemble indicates a plutonic- metamorphic domain during the evolution of this part of Wohlthat Mountains, central Dronning Maud Land (cDML). On the basis of field and petrographic criteria, following stratigraphic succession can be envisaged for the area:

Pegmatite, aplite, basic dyke
Porphyritic granite, leucogranite
Charnockite
Biotite gneiss, quartzo-feldspathic gneiss with amphibolitic and dioritic enclaves

The coarse to medium grained biotite gneiss occurring as the country rock shows granulose to gneissic, inequigranular texture. The mineral paragenesis suggests peak amphibolite facies conditions during prograde metamorphism. The sharp and usually conformable contact between the quartzofelspathic gneiss and biotite rich granite gneiss suggests differences in their protoliths. The quartzofelspathic gneiss may have granitic protolith whereas the biotite gneiss may have a sedimentary origin. The intense deformation-metamorphism undergone by these rocks have completely altered their nature and obliterated the original contact relationships. In the normative R1-R2 multicationic plot (Fig 1) by De la Roche et al (1980), the gneisses as well as the granites (both porphyritic and leuco varieties) classify as granites. Few of the granites plot in the quartz-monzonite monzonite fields. The charnockites show a spread in composition from syenodiorite to tonalite to monzogabbro. The gneisses are mostly peraluminous attesting to the higher role of crustal contamination in their formation. The granites and charnockites are metaluminous in nature with A/CNK ratios between 1 and 2. In the AFM plot it is observed that the granites show highly evolved nature where as the gneisses show a spread in differentiation usually in the tholeiitic field.

In the $FeO_t/(FeO_t+MgO)$ Vs SiO_2, discrimination diagram of Maniar and Piccoli (1989), the granites plot in the RRG+CEUG field whereas the gneisses show a mixed tectonic regime from island arc to rift related continental granite fields (Fig 6A). But in their FeO_t+MgO Vs CaO diagram the rocks indicate IAG + CAG + CCG field (Fig 6B). They have attributed such mixed signatures to complex craton stabilizing accretionary process. The granites as well as gneisses predominantly show mixed S-Type characters such as: i) metaluminous-peraluminous nature ii) medium to low Na_2O content iv) presence of normative corundum, v) presence of igneous (mafic) xenoliths vi) linearity of trends in bivariant diagrams versus SiO2 and vii) near absence of meta sedimentary enclaves. This alongwith the restitic garnet in this rock unit points towards garnet granulite, eclogite or assimilation of crustal contaminant (Sawka, 1990). Granites with negative Eu anomalies, high concentration of REE and high LREE/HREE ratios require sources with abundant amounts of garnet, amphibole or pyroxene in the source rock (eg-quartz diorite, tonalite, siliceous granulite , Henderson, 1984). Hence the Zweissel granitoids may have, in part, evolved from partial to complete reworking of earlier crust.

The porphyritic as well as leuco- granite show intrusive relationship with the country gneiss. The undeformed granite intrusive is clearly post tectonic in origin. Presence of myrmekitic growths and perthite points towards extended cooling history in an undisturbed environment to allow the exsolution reactions to proceed. High total alkali content reflects syenitic affinity of this unit. These criteria suggest an intracratonic setting and 'A' type nature of the granite. Presence of late stage, undeformed granites and syenites is wide spread in cDML. The higher alkali enrichment with predominance of K over Na as well as evolved REE patterns point towards crustal contamination of the granites in comparison with the gneiss. Maniar and Piccoli's (op cit.) tectonic discrimination plots suggest mixed characters indicative of complex cratonisation processes. In the R1-R2 multi-element discrimination diagram of Batchelor and Bowden (1985), the Zweissel granites plot in the late orogenic field with syn-collision affinities of the biotite gneiss and quartzofelspathic gneiss. The charnockites plot in the post collision field.

The gneissic unit of Zweissel area is comparable in occurrence and character with the foliated, syntectonic granite described in the Skeids area by D'Souza et al (op cit.) except for the absence of modal pyroxene in Zweissel gneiss. They assign igneous origin to the Skeids gneiss unit and give a syn-deformational (D2) status with development of strong, pervasive S2 foliation. Bejarniya et al (op cit) describe an orthogneiss unit with similar occurrence and character from the Paver-Weyprecht Mountains which lie to the southeast of the Zweissael area. They have also assigned syn-tectonoic origin to the orthogneiss unit and describe the regional foliation as S2 cleavage axial planar (to F2) associated with the D2 deformation.

The charnockite shows typical granitic (equigranular, hypidiomorphic) texture with both orthopyroxene and clinopyroxene as major phases. Orthopyroxene often encloses plagioclase, biotite and clinopyroxene suggesting peak metamorphic grade of granulitic facies. The temperature required for metamorphism may have been derived during the emplacement of later granitic plutons. Biotite coronas over orthopyroxene and ilmenite and symplectic intergrowths of plagioclase-biotite-quartz represent retrograde decompression and cooling events during their evolution.

6. CONCLUSION

Based on the studies done during 28th expedition, following conclusions may be drawn-

1. Four major groups of rocks delineated are- granite (porphyritic granite and leucogranite), granite gneisses (biotite rich granite gneiss ans quartzo feldspathic gneiss), charnockite and older enclaves (amphibolite/ diorite).

2. The minor shears studied, in the field as well as in the microstructural studies, indicate a sinistral sense of shearing. The variation in their strike direction can be explained by further detail investigation in the study area.

3. Based on petrographic studies it can be inferred that the peak metamorphic event, represented by the inclusion assemblage of quartz, plagioclase and biotite in orthopyroxene; biotite and quartz in garnet, is followed by a decompression and cooling event represented by biotite and amphibole corona over orthopyroxene and ilmenite and symplectitic intergrowth of plagioclase, biotite and quartz.

4. The linear inter element variation amongst different granitoids suggest that they may be cogenetic with the bulk composition of the monzonite which reflects significant crustal contamination.

5. The mafic enclaves may be of completely different origin and may represent remnants of the early country rocks in to which the later granitoids intruded.

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