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GEOLOGY OF PARTS OF ORVINFJELLA CENTRAL DROWNING MAUD LAND, EAST ANTARCTICA

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Abstract

The Orvin mountains in the Central Dronning Maud Land (CDML), East Antarctica expose a polydeformed and polymetamorphosed sequence of high grade granulitic rocks intruded by undeformed charnockite and granite, Two main suites of rocks viz. older metamorphic suite and the younger intrusive suite were recognised in the area. The metamorphic suite consists of quartzofeldspathic gneiss and layered tonalitic gneiss with boudinaged two pyroxene granulites and amphibolite, intruded by grieissic charnockite. The undeformed charnockite and *hb-bt* granite with dykes of granite and aplite constitute the younger intrusive suite. The gneissic charnockite and granite are the most predominant lithounits of the investigated area. The petrographic and chemical studies indicate that the gneissic charnockite is of intrusive and magmatic nature emplaced at mid crustal level under granulite facies conditions. The undeformed charnockite and the granite have a close spatial association and show intrusive relationship with the older metamorphites. They are mainly coarse grained, porphyritic rocks with megacrysts of K-feldspar and carry flourite at times. Granites and charnockites are quartz monzonitic to granodioritic in composition and are meta-aluminous, comparable with post- tectonic granites of A-type affinity. Evidences of decharnockitisation showing retrogressive transformation of charnockite to granite is observed in the area. The area records a complex tectonic and metamorphic history. At least three phases of deformation associated with three metamorphic events are evident. The emplacement of gneissic charnockite is synchronous with D2 deformation and M2 metamorphism. A later metamorphic event of amphibolite facies has caused retrograde effect on granulites. The emplacement of granite post dates the D3 deformation and seems to be co-eval with Pan-African activity (500Ma). The comparison of metamorphites of the area with the similar granulitic rocks reported from Sor Rondane and Muhlig- Hofmannfjella in CDML suggests an age of 1100 Ma to these rocks.

Introduction

As part of ongoing Indian programme aimed at elucidating the geology of East Antarctica, geological studies covering areas around Kurze, Skorvestallen, Holtedahl and Fenris Hill ranges, in Orvinfjella, CDML were carried out during the 15th Indian Scientific Expedition to Antarctica. The work forms part of the summer task assigned to GSI team for the austral summer of 1995- *96.* The area investigated constitutes the central part of Orvin Mountains and is located around 165 km southwest of Indian Station Maitri. It is bounded by Conrad mountains of Orvinfjella in the east and Muhlig-Hofmannfjella in the west. An area of 3750 sq km was mapped on 1:50,000 scale between 71° 25'- 72° 15' South latitude and 07° 58'- 09° 30' East longitude. An attempt has been made in this paper to unravel the geology of the area through field, petrographic and geochemical evidences.

Geomorphology

The Orvinfjella constitutes a prominent chain of mountains in CDML and has a broad E-W trend. The individual hill ridges in this chain in turn have a general N-S trend. The terrain with typical cold desert conditions exhibits a jagged topography caused by the combined action of wind and glaciers. Generally, the hills are discontinuous as they are dissected by several intervening glaciers. Steep-scarps and deep wind-trenches are common features on the eastern side of the ridges, while platformal glacier moraines and gentle slopes on the western side make the approach possible to the exposures. The altitude of the area varies from 1600m to 2900m with Ulvettanna peak in Fenrisfjella forming the highest peak (2931m above the msl) in the area.

Regional set-up

The Orvinfjella exposes a complex of Proterozoic high grade metamorphic rocks intruded by younger granite plutons in the East Antarctic Craton. Geologically, the area mapped lies on the eastern side of Jutulstraumen-Penck-'sokket Rift zone (Neethling, 1972) which is a prominent regional structure that separates a Proterozoic platformal sequence to the west from the high grade metamorphic terrain to the east in CDML. High grade granulitic rocks and rocks of upper amphibolite facies are characteristic litho-constituents generally found in these areas. The mapped area in particular exposes an older metamorphic suite comprising quartzo-feldspathic orthogneiss, amphibolite and pyroxene granulite intruded by charnockite which is deformed and metamorphosed to gneissic charnockite'. This older sequence forms the basement for the younger intrusive suite mainly consisting of Hb-Bio granite and charnockite (undeformed). Minor .dykes of granite and veins of pegmatite, aplite and quartz are the latest igneous manifestations in the area.

Previous Work

Though no detailed geological account of the area investigated is available, considerable geological information in the adjoining western Muhlig-Hofmannfjella and H.U.Sverdrupfjella is given by Ravich and Soloviev (1969), Ravich and Kamenev (1975), Grantham *et al.* (1988), Ohta *et al.* (1990), Groenwald *et al.* (1991) and Allen (1991). While Shiraishi *et al.* (1991) have given a detailed account on the geology of Sor-Rondanefjella in the east, a wealth of geological information on the lesser known CDML has been brought out by Indian geologists during successive Indian Antarctic expeditions since 1982. Kaul *et al.* (1991) have given a detailed account on the petrographic and structural characteristics of Gruber and Petermann ranges in Wohlthat moun tains in CDML. Joshi and Pant (1995) have described the petrochemistry and evolution of charnockites in Petermann area. Poly deformed, high grade granulite facies rocks represented by pelitic granulites, quartzofeldspathic gneisses, minor calc- silicate gneisses and pyroxene granulites have been described by Ravindra *et al.* (1994) from south Humboldt Mountains. D'Souza *et al.* (1996) have reported three dominant lithounits named as metamorphites, foliated charnockites and porphyritic granite from Dallmannfjellet in east Orvin mountains and have deciphered foliated charnockites as intrusives into the metamorphites. Further, they are of the opinion that the foliated charnockite is of magmatic origin and has intruded either before or during M2 metamorphism, while the porphyritic granite is related to the Pan-African activity. While giving a geological account of the Conrad mountains, which is the eastern adjacent part of the present area of investigation, Bejarniya *et al.* (1996) have also observed that the foliated charnockite which forms the most dominant lithounit of the area is intrusive into layered tonalitic gneiss of amphibolite facies and has been emplaced syntectonic to D2 event. Emplacement of porphyritic hornblende biotite granite (I-type), charnockite veins and veins of pegmatite and fine grained granite in Conrad mountains are reported to be Post D3 events.

Geology of the Area

The geological map of the area studied is given in **Fig.1.** Based on the field and petrographic studies the various litho-units encountered in the area are grouped into two distinct suites viz. i) Older Metamorphic suite and ii) Younger Intrusive suite. Following is the lithostratigraphic sequence recorded in the area.

	Aplite and minor quartz veins
Younger	Pegmatite
Intrusive suite	Granite dyke
(Palaeozoic)	Hb-bt Granite
	Charnockite

GEOLOGICAL MAP OF PART OF ORVIN MOUNTAINS, CENTRAL DRONNING MAUDLAND, EAST ANTARCTICA

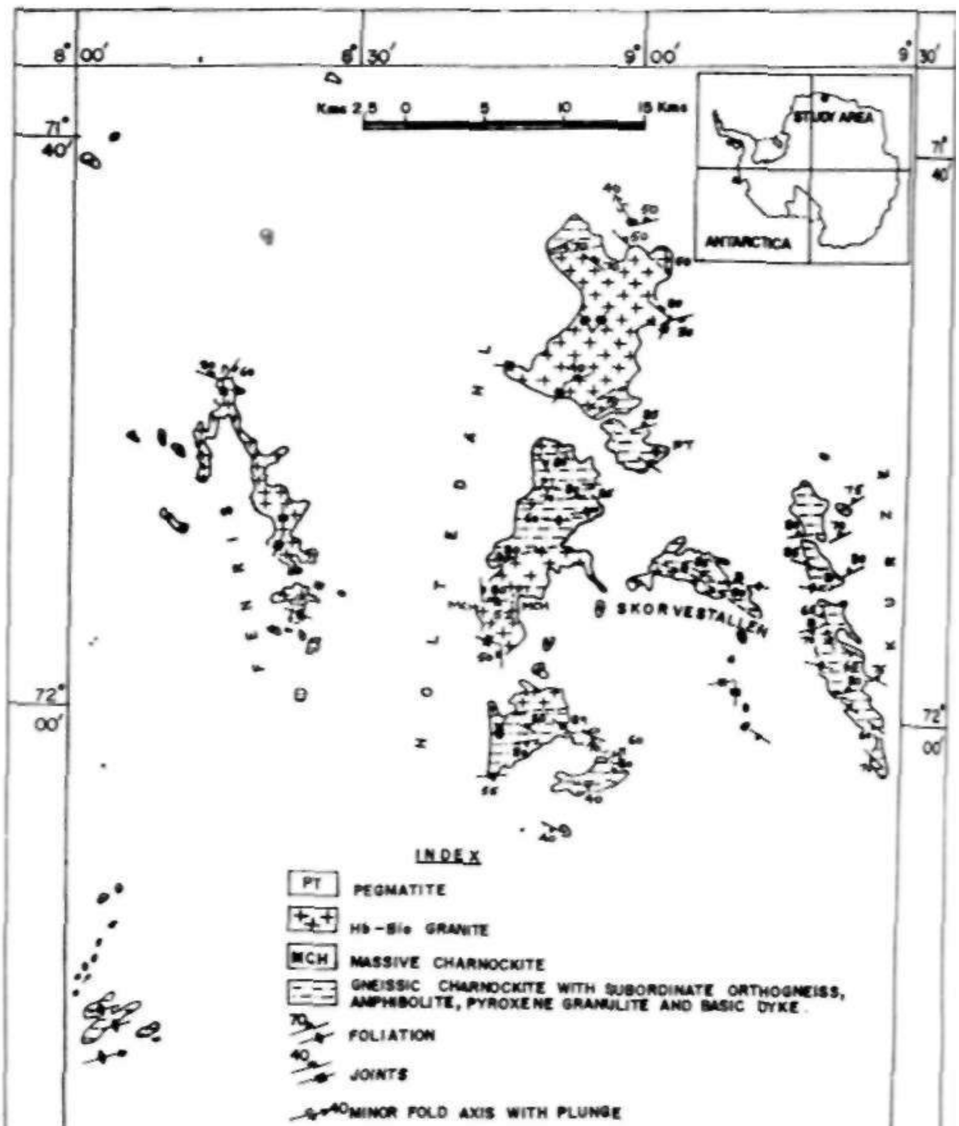


Fig. 1: Geological map of the study area

Older Metamorphic suite (Proterozoic)	Gneissic Charnockite associated with subordinate quartzofeldspathic and tonalitic gneisses, two pyroxene-granulite, amphibolite and gabbro dykes

Metamorphic Suite

It mainly comprises a migmatitic ensemblage of banded quartzo- feldspathic gneiss, layered tonalitic gneiss, boudinaged pyroxene-granulite and amphibolite representing the basement which is intruded by gneissic charnockite. The entire part of Kurze area, northern part of Skorvestallen, central and southern parts of Holtedahl and Fenris are made of older metamorphites. The gneissic charnockite constitutes the most dominant unit among metamorphites and occupies nearly half of the area mapped. Owing to repeated deformation and metamorphism suffered by the older metamorphites, the interrelationship between these units becomes difficult to ascertain due to their occurrence as interlayered alternating bands showing concordant relationship. However, occurrence of enclaves and xenoliths of gneiss and pyroxene granulites within the gneissic charnockite (Fig.2), suggests an intrusive relationship between these units. Further, the field characteristics such as concordant contact, conformable sheet like morphology, absence of chilled margin and thermal aureole, predominant diffused contact and development of migmatite on regional scale indicate that the gneissic charnockite is essentially a deep-seated intrusion into basement gneisses and granulite, emplaced under granulite grade conditions. Minor dykes of gabbroic composition were seen cutting the metamorphites in Skorvesstellen area.

Intrusive Suite

The undeformed charnockite, granite, dykes of fine to medium grained granite, pink aplite, pegmatite and minor quartz veins constitute the intrusive suite. Among these, the granite forms the most dominant lithounit and occupies nearly one-third of the area. A major part of northern and southern Holtedahl and almost entire Fenrisfjella in the north, are occupied by granite. The undeformed charnockite is closely associated with granites both in time and space and has a general diffused contact with granite as recorded in Holtedahl and Fenris. Except for colour variation, there hardly exists any macroscopic difference between granite and charnockite in this area. Morphologically, the granite exhibits sharp and pinnacled peaks forming a jagged topography **(Fig.3).** A sharp intrusive and discordant contact with a few mm of chilled margin is seen between granite and gneissic charnockite **(Fig.4)** The contact between the granites and migmatitic gneiss is also sharp and discordant **(Fig.5).** Differential weathering and erosion is commonly seen along the contact at times resulting in formation of gullies.

Fig. 2: Boudinaged mafic dykes within the gneissic charnockite concordant with the present day gneissocity

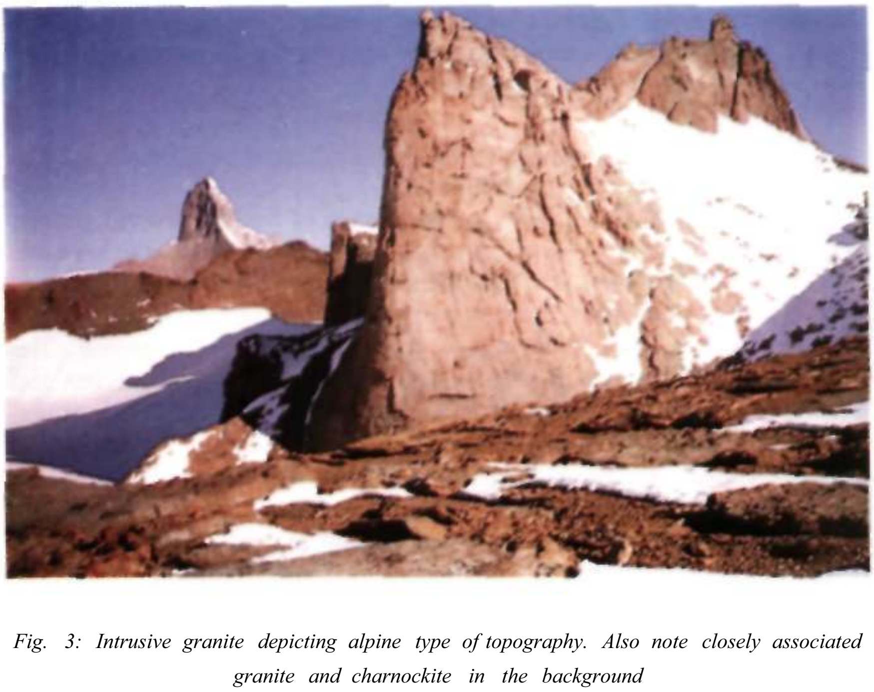


Fig. 3: Intrusive granite depicting alpine type of topography. Also note closely associated granite and charnockite in the background

Fig. 4: Granite intruding the gneissic charnockite

Fig. 5: Granite intruding the migmatised gneisses

Enclaves and xenoliths of both orthogneiss and gneissic charnockite are abundant in the granite as noticed along the contact zones in Holtedahl and Fenris ranges. Such abundance of xenoliths, presence of sharp and discordant contact, chilled margins, massive and porphyritic texture, and local development of migmatite point towards shallow intrusive nature of the granite. The granite dykes and the network of aplite dykes seen criss-crossing the Holtedahl granite, indicate that these dykes occupy the joints and fractures that were developed in a cooling pluton while magma was still there at near-solidus to subsolidus stage. (Clarke, 1992). This view is supported by the fact that the chemistry of granitic dykes almost resembles the host granite into which they are emplaced. Pegmatites and minor quartz veins are other constituents of the intrusive suite.

Petrography

The mineral assemblages in the order of abundance for the major lithounits is shown in **Table-1,** The *orthogneiss* is mainly represented by banded quartzofelspathic and layered tonalitic gneisses. The gneisses are medium to coarse- grained, grey coloured and often show bands of light and dark minerals. They show gneissose texture with platy and elongated ribbon quartz **(Fig.6)** and biotite defining the foliation. Plagioclase is often saussuritised and shows bent twin lamellae, and in some rocks it is almost completely replaced by perthitic feldspar. Often, hornblende exhibits poikiloblastic texture with inclusions of opaque and plagioclase. Secondary silica exhibiting foam texture and occupying interstitial position swerves around phenocrysts indicating its later crystallization.

Table 1: Mineral assemblages of main lithounits (Mineral symbols after Kretz. 1983)

Rock	Mineral Assemblage
Granite	2Qtz+Kfs+Perthite+Bt+Pl+Opaque+Zrn+Ap+Aln
	1 Qtz+Kfs+Pl+Hbl+Bt+Zrn+Ap+Sp+Opaques
Charnockite	Qtz+Pl+Kfs+Perthite+Hbl+Bt+Opx+Opaque+Ap+Zrn
Olivine Gabbro	Cpx+Opx+Pl+Ol+Opaques+Hb+Rt
Gneissic charnockite	2 Qtz+Pl+Opx+Cpx+Hb+Opaques+Grt+Rt+Ap
	1 Qtz+Kfs+Perthite+Pl+Opx+Cpx+Grt+Bt+Zrn+Ap+Opaque
Orthogneiss	2 Qtz+Pl+Hbl+Kfls+Bt+Opaque+Sp+Ap
	1 Qtz+Kfls+Perthite+Pl+Grt+Bt+Opaque+Zrn+Ap
Amphibolite	Hbl+Pl+Qtz+Bt+Cpx+Opaques+Zm+Ap
Pyroxene Granulite	Cpx+Opx+P1+Hbl+Bt+Opaques+Rt

Fig. 6: Ribbon quartz in migmatised gneiss defining Se foliation plane (x40)

The *pyroxene granulite* is dark coloured and medium-grained showing well developed granular texture. Both clino- and orthopyroxene along with plagioclase constitute the dominant minerals of the rock with accessory hornblende, biotitc, garnet and opaques. Tourmaline and allanite are also seen in some of the sections. Intergrowth of biotite and plagioclase as retrogression products of pyroxene was noticed. *Amphibolite* is medium-grained, granular and dark coloured. The rock shows granoblastic texture and mainly consists of hornblende and plagioclase with biotite. quartz, apatite, zircon and opaque as accessories. In some sections relict grains of clinopyroxene are seen. Hornblende shows annealing and the rock appears absolutely fresh, perhaps indicating its development after pyroxene granulite under upper amphibolite fades condition.

The *gneissic charnockite* is medium to coarse-grained, earthy to dull brown in colour, well foliated and shows compositional banding of alternating mafic and felsic minerals. Generally the foliation is defined by the preferred orientation of quartz (often ribbon type) felspar and pyroxene. Leaching of iron-oxide in the form of yellow limonite along the cracks of minerals is a common phenomenon and it imparts a dull brown to rusty brown colour to the rock. Wide variation is seen in its composition from basic to acid types. Quartz, plagioclase (andesene), clino- and orthopyroxene are the main constituents of the basic type while K-felspar (mainly perthitic) adds to the major constituents in the intermediate types.The modal composition of the rock is as under.

Mineral	**Percentage**
Plagiocalse	60.40 - 68.20
Pyroxene	10.03- 12.62
Biotite	3.00- 16.89
Quartz	0.40 - 9.93
K-feldspar	2.60 - 11.48
Opaques	1.79-2.55

Modally. the gneissic charnockite can be classed as charnoenderbite. Two sets of exsolution lamellae of Cpx parallel to 100 and 001 planes were seen along the cleavage planes of Opx (Fig.7). The lamellae parallel to 001 becomes very coarse and is at high angle to the other. The development of exsolution lamellae indicate crystallisation at high temaperature and magmatic parentage. Hornblende is occasionally a break-down product of pyroxene where it preserves the relict pyroxene in its core. In some cases myrmekite replacing K-feldspar was noticed. Apart from being the main constituent, quartz also occurs interstitially indicating its later origin.

Gabbro dykes are dark coloured medium to coarse-grained predominantly comprising clinopyroxene, orthopyroxene and plagioclase with accessory oli-

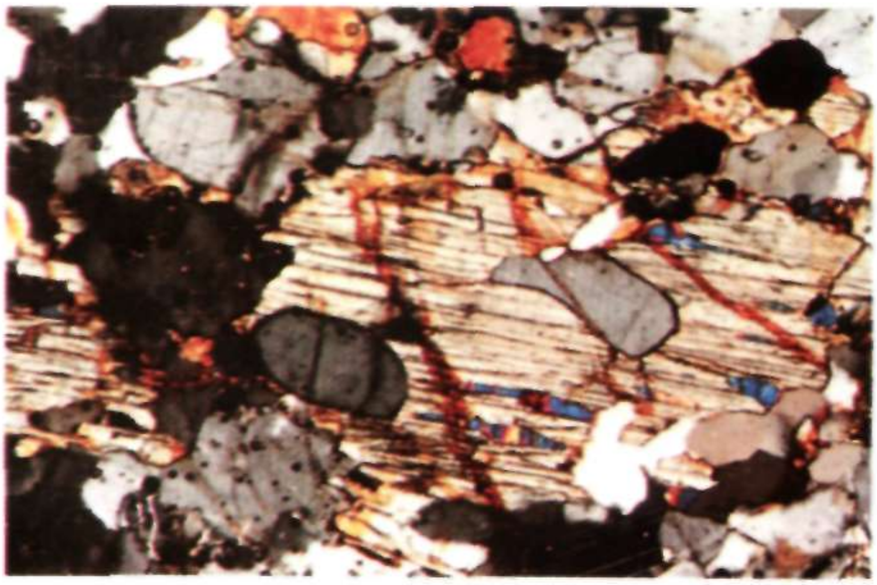


Fig. 7: Orthppyroxene showing exsolution lamellae of cpx along cleavage plane in gneissic charnockite with included apatite (x 40)

vine, hornblende, ilmenite and rutile. Green hypersthene constitutes the orthopyroxene and shows retrogression to hornblende. Both plagioclase and hypersthene show undulose extinction suggesting deformation.

The *charnockite* (undeformed) is medium to coarse-grained, massive and varies in colour from grey to greenish grey and brown. Quartz, plagioclase and K-feldspar are the major constituents with minor hornblende, orthopyroxene, biotite and little apatite and opaque. Hornblende is subhedral, green in colour and shows poikilitic texture with inclusions of plagioclase and relict hypersthene. In one of the sections, only hornblende and biotite could be seen perhaps indicating two stages of retrogression, viz. i)Pyroxene to amphibole and ii)Amphibole to biotite. Well developed myrmekitic growth is seen along the border of K-feldspar (generally perthitic) and plagioclase indicating the eutectic crystalliszation (Fig.8). It is also observed that myrmekite affects biotite indicating late reaction of the early formed minerals with the melt. Both green and brown biotite were seen where the green variety (titanium bearing) are patchy and the brown types are flaky in appearance. It is quite likely that the breakdown of amphibole has contributed titanium to the green biotite. Modally, the rock falls under the charnockite field and the modal composition of the rock is listed below.

Mineral	**Percentage**
Quartz	23.53
K-feldspar	67.55
Opx	5.00
Plagioclase	1.64
Biotite	1.65
Opaques & accessories	0.63

The *granites* which constitute the major part of the studied area exhibit diversity in colour and texture. Three main granite plutons were mapped in the area. The spatial extension and the distinctive features of these plutons is shown in **Table-2.** In general, the granites are medium to coarse grained and often porphyritic with megacrysts of K-feldspar measuring 5-10 cm at times. Colour variation is common among these granites. Two prominent colour variants found are grey and rusty brown and they can be distinctly seen in Fenris range where the granite forms sharp peaks (Fig.3). The major constituent minerals are quartz, K-feldspar, plagioclase, hornblende, boitite and accessary apatite, zircon, sphene and opaque. The K-feldspar is mainly represented by string, patchy or flame perthite **(Fig.9)** which often replaces plagioclase and contains inclusions of the latter. Reaction rim of quartz around plagioclase **(Fig.10)** and development of myrmekite along the borders of alkali feldspars are the common petrographic features noticed among granites, indicating slow cooling of magma. Hornblende is strongly pleochroic from yellowish green to dark green and poikilitically encloses the early formed quartz and flourite **(Fig.ll)** The

Fig. 8:Myrmekittic intergrowth of quartz and plagioclase in granite (x100)

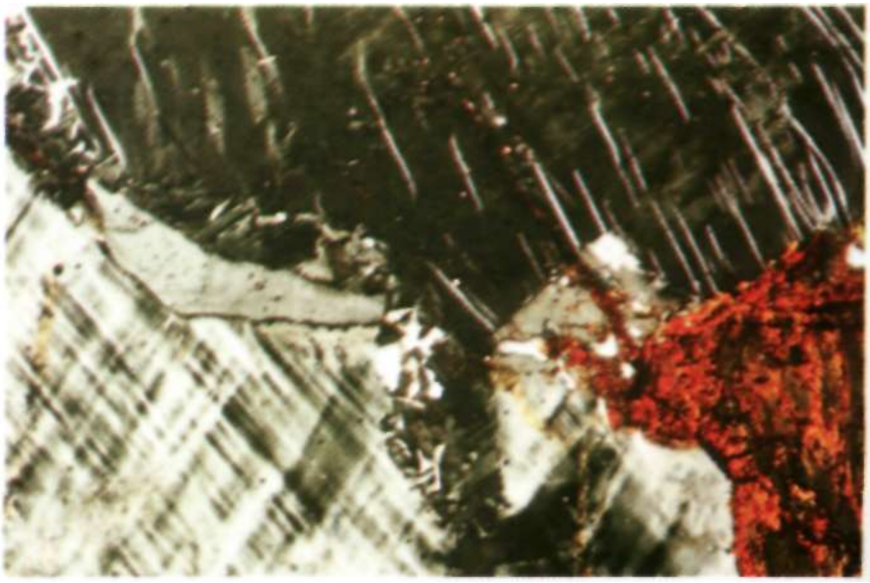


Fig. 9:String perthite, microcline and hornblende in granite. Note the intergrowth of feldspar and quartz at the margin in granite (x 40)

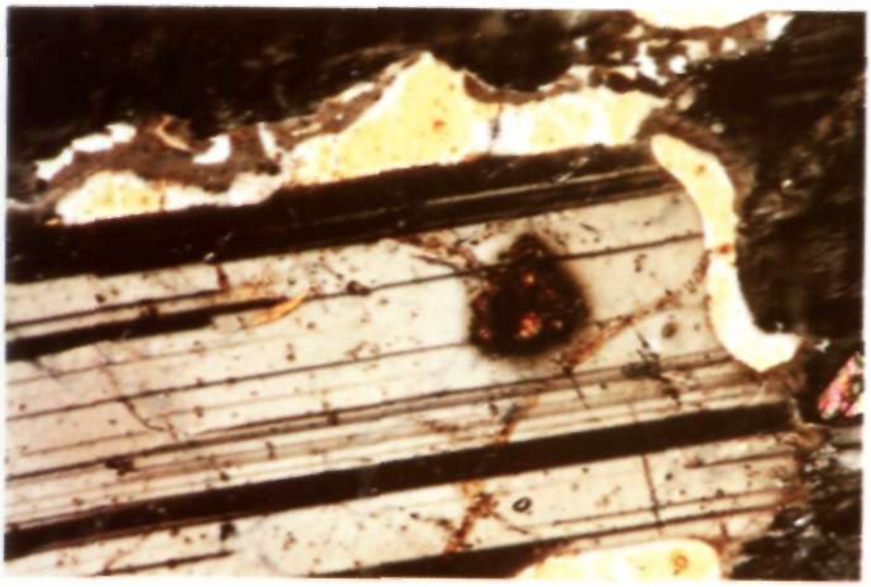


Fig.10: Plagioclase with silicic run in contact with perthite in granite (x 40)

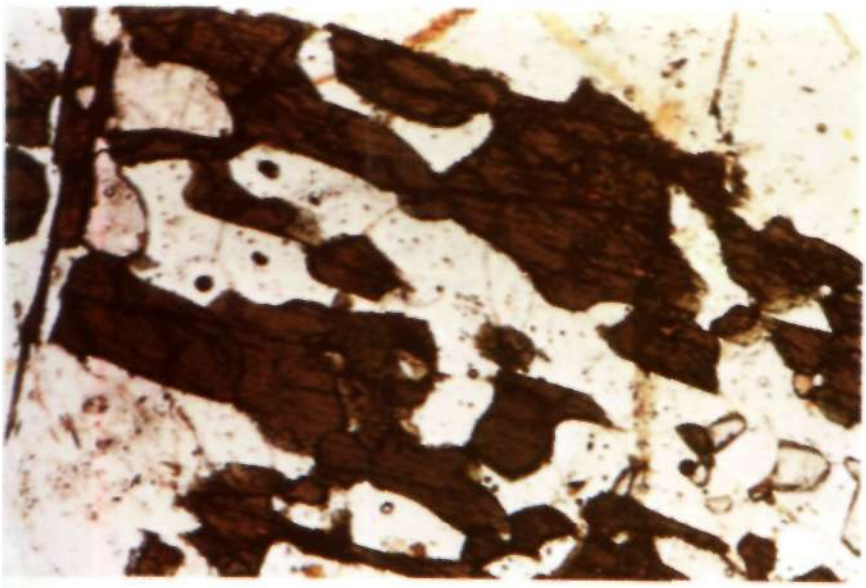


Fig. 11: Hornblende poikilitically enclosing early formed quartz and fluorite in granite (x 40)

Table 2 : Granite suites and distinctive features

Name of Granite	Area (sq km) (estimated)	Distinguishing feature	
		Physical	Chemical
Fenris	350	Brown and grey, porphyritic with megacysts of K- feldspar	Relatively* low silica, high alkalies, high TiO_2 and P_2O_5 and low FeO and CaO, A/CNK=<1
Holtedahl (North)	125	Mainly brown and porphyritic with megacysts of K-feldspar	Average silica, high alkalies, low MgO and CaO and average FeO, A/CNK=<1
Holtedahl (South) and Skorvesterlen	225	Mainly grey, porphyritic and occasionally contains fluorite	Wide variation in SiO_2 and alkalies and other oxides, A/CNK=<1
Total	695		

comparison with respect to average composition or metalummous granites (Chayes, 1985)

hornblende in turn is enclosed by K-feldspar which was last to crystallise. In some sections, formation of late stage brittle fractures were observed and these fractures acted as conduits for fluids that have caused retrogression of amphiboles to biotite. Metamictic allanite is a significant accessary in some of the granites (Fig.12).

Minor amount of hypersthene which often shows retrogression to amphibole is noticed in some of the granites. Occurrence of patches and xenoliths of charnockite within the granite showing diffused contact perhaps indicate that the charnockites might have been brought up by the invading granitic magma. However no unequivocal origin can be assigned to the charnockite at present. Conspicuously, it is observed that at places the charnockite shows retrogression to granite, locally as seen in Holtedahl and Fenris Hill ranges. This phenomenon of decharnockitisation could be due to flushing of H_2O along the weak planes. This view is corroborated by the fact that wherever an aplite vein traverses the charnockite, a clear cut bleached zone on either side of the vein is seen (Fig.13) where breaking down of charnockite into granite is observed. Ravindra Kumar and Chacko (1986) have also reported such bleached zones and 'breaking down of charnockite along leucocratic veins in gneissic charnockite in Southern Kerala, India; where the charnockite is retrogressively converted to gneiss by the influx of water-rich fluids. Retrogressive transformation of banded charnockite to leptynite is reported from Trivandrum region, South Kerala by Santosh and Yoshida (1986).

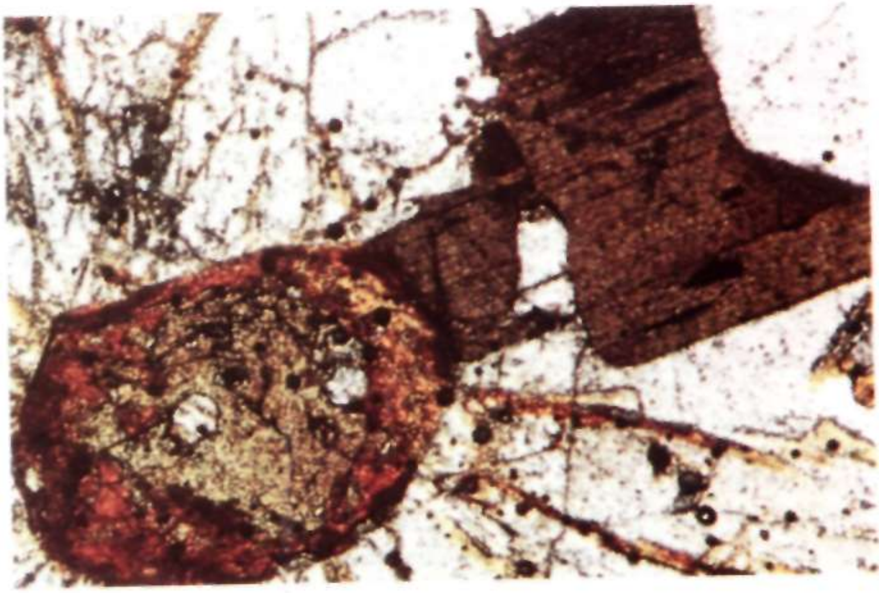


Fig. 12: Photomicrograph of megacrystic allanite with radial craela within granite (PL x 40)

Fig. 13: Aplite vein cutting through charnockile. Note the bleached zone in contact indicating rehydration of charnockite

Besides the main batholithic granites there are a number of dykes of both grey and leucogranite cutting the granites. These dykes are fine to medium grained and are generally depleted in mafic mineral content, but for which their mineral composition remains.same as that of granites. Podiform pegmatite with unusually large crystals of quartz and feldpars and sheets of biotite charac-- teristically occurs among the granites. A network of pink aplite veins occas- sionally carrying fluorite represent the last phase of igneous activity in the area. Fluorite is also recorded in some of the pegmatite and granites indicating pneumatolitic activity subsequent to granite emplacement.

Geochemistry

A total of 27 rock samples comprising 15 granites, 8 gneissic charnockites and 4 charnockites were analysed and the results along with CIPW norms are given in Table-3. Except Na_2O all the major oxides and trace elements were analysed using ICP-AES model No. BJY 70C by adopting BRGM (France) procedure at GSI's chemical laboratory, Faridabad. The procedure involves cintering of 1 gm dried sample of 200 mesh in zirconium crucible with 3 gm of flux i.e. Sodium Peroxide. The cintered mass was taken in a plastic tube in 72 ml of water and 28 ml of HC1 (1:1). The BRGM standard samples were used as reference samples for analysing all the 34 elements. Analysis of Na_2O was carried out using Atomic Absorption spectrophotometer.

Table-3 shows the major and trace elements of granites. Considerable variation both in major and trace element chemistry is seen. The granites show relatively lesser $Si0_2$ (varying from 61.6%-71.4%), Al_2O_3 (12.5%-15.4%) and very low MgO (0.1 to 0.7%). The total alkalies range from 6.8 to 11.0 and Na_20/K_20 ratio varies from 0.58 to 1.31, indicating a wide variation in the alkali contents. Conspicuously, majority of these granites show enrichment in some of the trace elements such as Ba, Sr, Zr, Nb and Ce. Granites are exceptionally rich in Ba in particular whose value ranges from 1135 ppm to more than 4000 ppm. The higher values of Ba and Sr could be attributed to their partitioning behaviour with K-feldspar and plagioclase respectively. Though the concentration of Ba and Sr in the feldspars could not be ascertained through scanning in the present case, however such concentration of Ba and its zoning in megacrysts of K-feldspar in granites has been reported by Long and Luth, (1986). The development of megcrysts of K-feldspars in granite and also at times along the contact of granite and gneisses indicate that they grew from a water-rich fluid phase under subsolidus conditions (Dickson and Sabine, 1967, Mehnert, 1969).

Using Na_2O/K_2O discrimination ratio, (Fig.14) the granites are mainly classified into adamellite and granodiorite. Majority of the granites plot in quartz monzonite and granodiorite fields in $CaO-Na_20-K_20$ diagram (Fig.15).

Table 3 : Major and Trace Element Analysis and Normative Mineralogy of Granite (Wt %)

	HOLTEDAHLF (NORTH)					HOLTEDAHL (SOUTH)						FENRIS			
Sample No.	26A	44C.1	55	57	58	65	74B.1	75	86	H4.1	H6.C	F15	F18.1	F29.2	F30)
Element															
Si02	64.40	65.00	65.00	68.10	67.80	68.70	64.50	60.90	71.40	66.70	61.60	65.40	63.20	68.10	65.70
TiO_2	0.53	0.26	0.23	0.27	0.39	0.32	0.57	0.75	0.20	0.41	0.79	0.69	0.66	0.34	0.70
Al_2O_3	12.50	14.20	14.20	13.60	14.20	13.50	14.30	15.40	12.70	14.20	13.20	14.20	15.20	13.10	13.90
FeO	4.86	3.33	3.15	3.33	2.43	3.24	4.05	3.78	2.70	3.24	4.95	2.70	2.79	3.78	2.97
MnO	0.05	0.03	0.04	0.04	0.02	0.03	0.04	0.04	0.03	0.03	0.05	0.04	0.03	0.04	0.03
MgO	0.20	0.10	0.10	0.10	0.50	0.10	0.40	0.50	0.10	0.20	0.50	0.70	0.70	0.10	0.70
CaO	2.40	2.60	2.60	2.40	2.10	2.30	3.50	4.40	1.70	2.80	3.30	2.20	2.40	2.50	2.10
Na_20	3.40	3.60	3.50	4.10	3.30	5.90	3.10	3.30	5.00	2.80	3.20	6.00	4.20	3.20	3.90
K_20	4.00	4.80	4.50	4.90	4.40	4.50	3.70	3.40	5.00	4.80	3.60	5.00	5.50	4.60	4.70
$P2O_5$	0.20	0.09	0.08	0.09	0.16	0.06	0.24	0.34	0.03	0.15	0.27	0.25	0.26	0.08	0.25
K_2O Na_20	7.40	8.40	8.00	9.00	7.70	10.40	6.80	6.70	10.00	7.60	6.80	11.00	9.70	7.80	8.60
K_2O Na_20	1.1765	1.3333	1.2857	1.20	1.3333	0.7627	1.1935	1.0303	1.00	1.7143	'1.125	0.8333	1.3095	1.4375	1.2051
A/CNK	0.87	0.89	0.92	0.82	1.01	0.72	0.92	0.90	0.75	0.95	0.87	0.73	0.88	0.88	0.90
Fe/(Fe+ Mg)	0.93	0.96	0.94	0.94	0.73	0.94	0.85	0.80	0.93	0.90	0.84	0.68	0.69	0.95	0.70
Trace / Rare Elements (in ppm)															
La	96	547	275	251	121	160	89	98	428	67	89	177	169	145	138
Li	27	13	18	16	43	20	15	17	10	14	15	13		20	17
Be	4	3	3	3	3	3	3	3	2	3	52	2	2	4	2

Contd.

Table 3 — Contd.

V	<10	<10	<10	<10	28	<10	11	20	<10	<10	17	27	31	<10	31
Cu	45	30	32	34	31	38	45	44	25	37	50	31	28	34	36
Zn	180	138	122	120	108	109	141	117	83	106	135	86	67	156	84
Sr	276	433	437	446	321	401	379	539	204	358	362	792	1077	340	755
Y	98	126	85	91	28	94	68	53	77	66	55	65	36	73	29
Zr	477	393	309	525.	263	466	328	333	368	380	602	338	352	419	350
Nb	343-	356	354	324	278	311	466	578	217	372	437	294	309	349	277
Ba	1896	3194	3530	3894	1871	3198	1707	1808	1114	1947	1687	3310	>4000	2121	2887
Ce	247	854	525	502	207	355	200	201	645	176	192	352	309	283	297
Pb	22	32	26	<10	33	29	90	<10	48	18	16	23	27	235	51
CIPW Norm															
q	21.32	18.23	19.77	19.12	24.90	15.12	22.10	17.22	21.79	23.78	19.17	9.51	10.94	24.36	18.46
or	23.64	28.37	26.60	28.96	26.01	26.60	21.87	20.10	29.55	28.37	21.28	29.55	32.51	27.19	27.78
ab	28.77	30.46	29.61	34.69	27.92	44.31	26.23	27.92	37.45	23.69	27.07	45.16	35.54	27.07	33.00
an	7.07	8.54	9.91	4.30	10.02		14.26	17.26		12.11	11.09		6.53	7.86	6.65
c					0.36										
di	3.67	4.25	3.17	7.30		10.65	1.84	2.61	7.61	1.29	3.60	8.91	4.37	4.22	2.37
hy	6.73	3.79	4.09	•2.23	5.10	0.23	6.62	5.67	0.97	5.16	7.27	1.23	3.68	4.51	4.74
mt															
a	1.01	0.49	0.44	0.15	0.74	0.61	1.08	1.42	0.38	0.78	1.50	1.31	1.25	0.65	1.33
ap	0.48	0.23	0.21	0.23	0.38	0.16	0.59	0.83	0.08	0.37	0.65	0.63	0.67	0.19	0.62
zr	0.10	0.08	0.06	0.11	0.05	0.09	0.07	0.07	0.07	8.00	0.12	0.07	0.07	0.08	0.07
sp	0.07	0.03	0.05	0.04	0.12	0.05	0.04	0.05	0.03	0.04	0.04	0.03	0.03	0.05	0.05

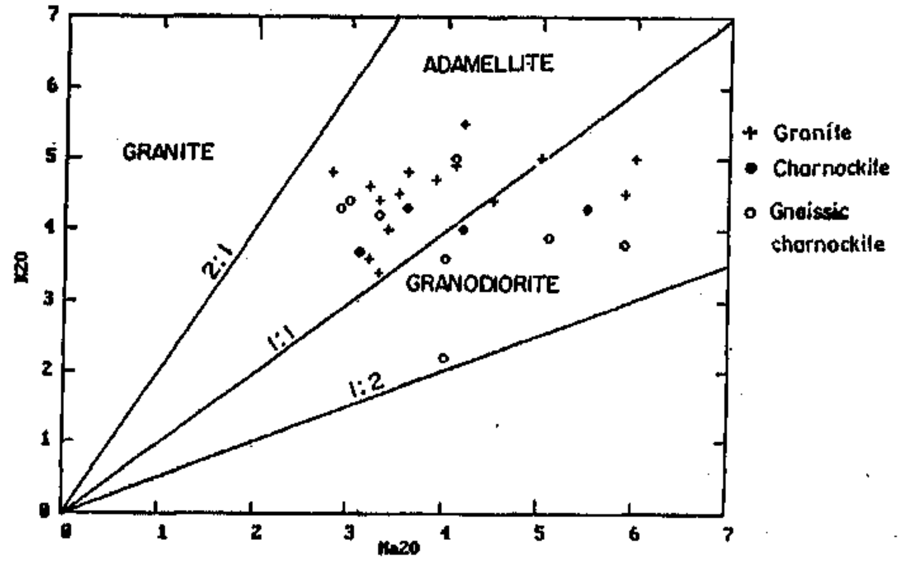
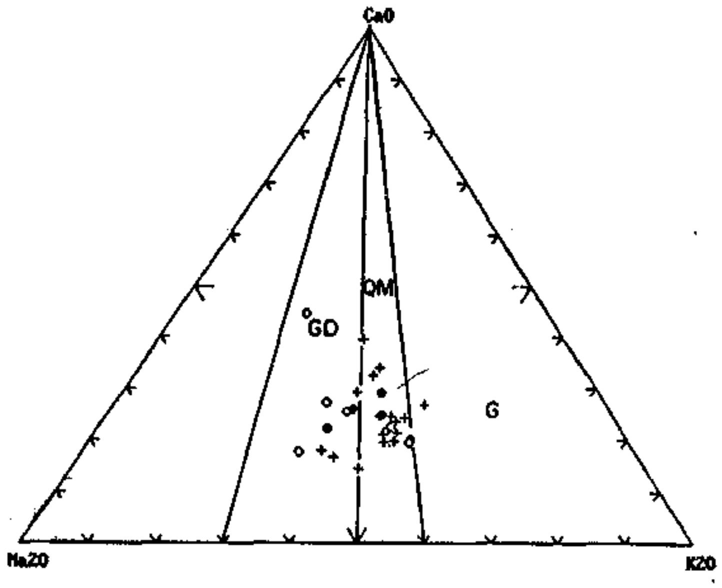


Fig. 14: Rock classification based on Na_2O-K_2O variation diagram



Fig, 15: CaO-Na_2O-K_2O classification (after Barker and Arth, 1976). GD-granodiorite, QM-quartz monzonite, G-granite

The granites are overwhelmingly metaluminous in nature as indicated by the Alumina Saturation Index (ASI) values (Fig.16) and on AFM diagram the granites plot in Calc-Alkaline field indicating their crystallisation under crustal cover (Fi'g.17). Applying different discrimination diagrams the magmatic nature and the late-orogenic origin of these granites is confirmed (Fig.18). The chemical composition and behaviour of charnockite closely resembles that of granite suggesting their common parentage and evolutionary history.

Harker type variation diagrams showing behaviour of major oxides with respect to SiO_2 are shown in Fig.19. A crude sympathetic relationship is observed with K_2O indicating enrichment of potash with the increasing silica as the crystallisation progressed. The distinct antipathetic behaviour of $Ti0_2$, P_2O_5, MgO, FeO and CaO indicates the steady depletion of these oxides in the melt and their early fractionation. The overall chemical signature of the granite points towards an undepleted protolith and a definite igneous origin.

Table-4 gives the major and trace element analysis and CIPW norms of charnockite and gneissic charnockites. The chemistry of gneissic chamockites shows that the rocks vary in composition from basic to intermediate type. The $Si0_2$ content ranges from 56.6%-71.1% and Al_2O_3 from 11.4%-14.2%. Slightly higher Fe_20_3, CaO and $Ti0_2$ are observed in relation to granites. The $Si0_2$ shows distinct antipathetic relation with MgO, CaO, Fe_20_3, $Ti0_2$ and P_2O_5 indicating differentiation of the magma. No definite trend could be made out with alkalies probably indicating crustal contamination at the time of emplacement. The chemical diversity in gneissic charnockites is further demonstrated through the Q-P diagram of Debon and Le Fort, 1983 (Fig.20). The rocks scatter in adamellite, granodiorite and quartz-monzodiorite fields indicating the fractionation of magma. However, both granites and charnockites show clustering in the granite field when they were plotted on normative feldspar variation diagram of O'Conner (1965) (Fig.21).

Like granites, the charnockites too are metaluminous and magmatic in nature but are slightly depleted in Ba and Sr. The depletion of such large incompatible elements (LILE) from the high grade rocks is attributed to their removal while the rocks were resident in the lower crust at the time of high grade metamorphism (Passchier *et al.,* 1990). Unlike granites which are mainly late orogenic, the gneissic charnockites are found to be syn-orogenic (Fig.18) which is also in agreement with the tectonic and metamorphic fabrics observed in these charnockites.

Structure and Metamorphism

The area records a complex tectonic and metamorphic history. The different tectonic fabrics noticed in the area correlates well with the reported regional structure in CDML (Bejarniya *et al.,* 1992). The older metamorphites show

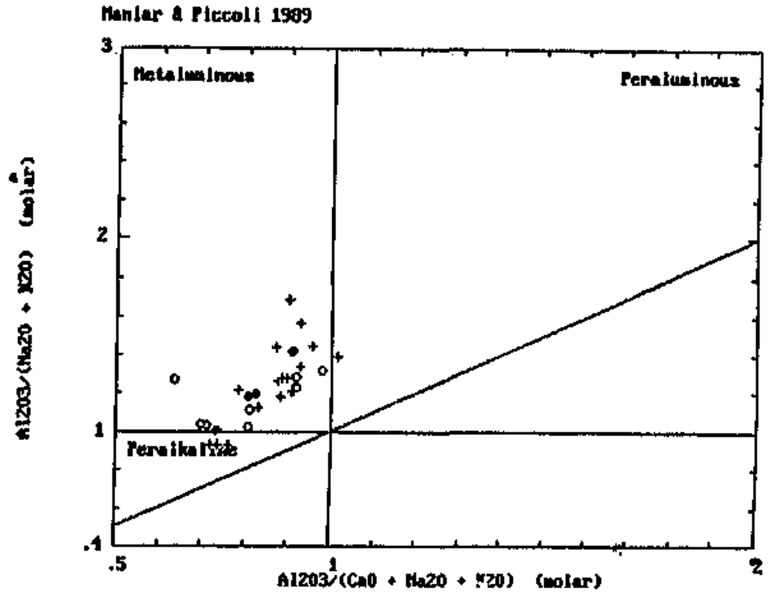


Fig. 16: Shand's Index showing classification of granites based alumina-saturation index

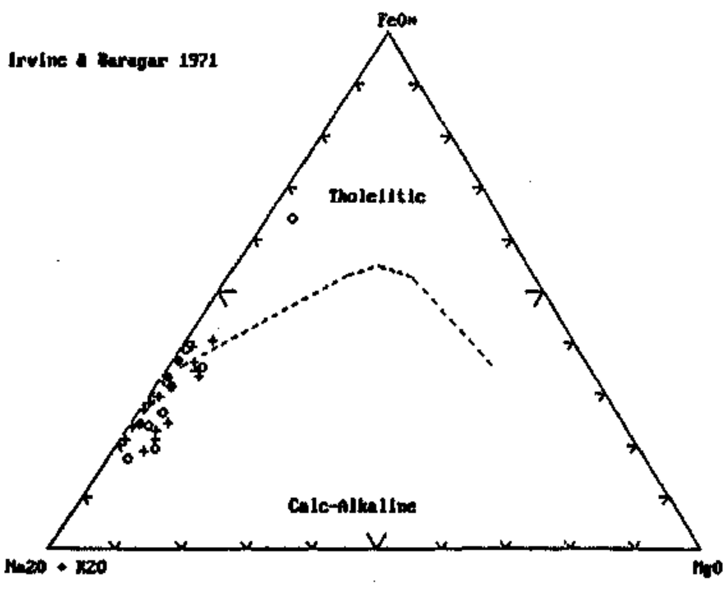


Fig. 17: A-F-M- diagram after Irvine and Bargar (1971)

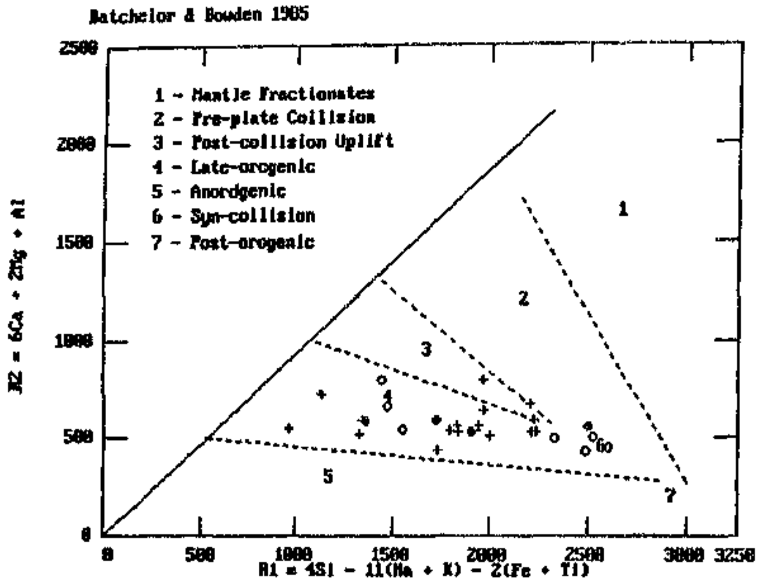


Fig. 18: Tectonic discrimation diagram, The symbols used as (R_1- R_2) after Batchelor & Bouden (1985) for the intrusive rocks

polydeformation and exhibit well developed foliation and gneissosity. Mainly three phases of deformation are evident. The foliation (S2) is defined by preferred alignment of minerals particularly biotite and ribbon quartz in the gneissic charnockite. Compositional banding defined by alternate layers of mafic and felsic minerals, defines the foliation in the orhtogneisses. The general trend of the foliation is ENE-WSW dipping steeply. Evidences of the earliest deformation (D1) are recorded in the form of isoclinal intrafolial folds (Fl) with axial planar S1 foliation mostly preserved in enclaves and xenoliths found in migmatitic gneisses. The subsequent deformation (D2) has caused pervasive foliation (S2) on regional scale and resulted in refolding of Fl into tight isoclinal folds (F2) roughly along ENE-WSW axis. Open folds (F3) with NW-SE axis plunging steeply towards south indicate the third deformation (D3) which predates the emplacement of the granites. As such, no imprint of regional tectonic fabric could be seen among granites, though minor shearing is evident at places. However, petrographic studies reveal presence of tensional cracks and bending of plagioclase twin lamellae in some of the granites. A minor fault trending N-S with steep easterly dip and causing displacement of amphibolite band was recorded in Southern Holtedahl.

A steeply dipping ductile shear, about a metre wide, in conformity with the regional foliation and showing development of mylonite, was seen in the

Table 4 : Major and Trace Element Analysis and Normative Mineralogy of Charnockites (Wt.%)

Sample No.	49	50	H3.2	H5.2	5	14	30.3	47.2	68.1	92	F6	F23
Elements												
SiO_2	68.60	64.80	64.10	66.30	56.60	70.20	71.10	69.30	71.00	65.60	70.80	70.10
TiO_2	0.28	0.04	0.57	0.43	1.72	0.64	0.38	0.35	0.25	1.04	0.26	0.03
Al_2O_3	12.90	12.60	13.30	13.80	11.40	13.50	10.80	14.20	12.80	13.10	12.40	11.90
FeO·	3.42	4.59	3.87	3.15	12.42	3.42	4.86	2.52	1.62	5.31	2.34	2.97
MnO	0.04	0.06	0.04	0.03	0.16	0.04	0.06	0.04	0.03	0.06	0.02	0.03
MgO	0.10	0.10	0.30	0.20	0.80	0.50	0.10	0.80	0.30	0.80	0.30	0.10
CaO	2.80	2.60	2.90	2.80	5.00	2.50	2.60	2.10	2.20	3.40	1.80	1.80
Na_2O	3.10	3.60	4.20	5.50	4.00	4.10	4.00	5.90	3.30	5.10	2.90	3.00
K_2O	3.70	4.30	4.00	4.30	2.20	5.00	3.60	3.80	4.20	3.90	4.30	4.40
P_2O_5	0.07	0.09	0.19	0.14	0.63	0.18	0.08	0.06	0.05	0.29	0.06	0.07
	0.07	0.09	0.19	0.14	0.63	0.18	0.08	0.06	0.05	0.29	0.06	0.07
$K_2O + Na_2O$	6.80	7.90	8.20	9.80	6.20	9.10	7.60	9.70	7.50	9.00	7.20	7.40
K_2O/Na_2O	1.19	1.19	0.95	0.78	0.55	1.22	0.90	0.64	1.27	0.76	1.48	1.47
A/CNK	0.90	0.82	0.80	0.73	0.63	0.80	0.71	0.80	0.91	0.69	0.97	0.91
Fe/Mg	0.95	0.96	0.87	0.89	0.89	0.79	0.96	0.63	0.75	0.78	0.81	0.94
	0.95	0.96	0.87	0.89	0.89	0.79	0.96	0.63	0.75	0.78	0.81	0.94
Trace / Rare Elements (in ppm)												
La	435	398	95	100	62	53	40	78	28	78	86	159
Li	17	14	15	13	<10	14	17	23	10	<10	12	<10
Be	4	2	3	3	<2	2	3	4	<2	<2	2	3
V	<10	<10	<10	<10	39	23	<10	50	21	51	<10	<10
Cu	48	37	43	27	44	25	29	37	29	32	32	31
Zn	154	155	128	98	285	91	144	86	45	105	66	107
Sr	337	397	312	326	120	136	108	139	109	144	72	142
Y	133	87	81	66	133	51	75	45	<20	112	<20	156
Zr	421	520	410	338	963	293	788	207	58	252	137	257

Contd.

Table 4 — Contd.

Nb	398	361	399	370	661	325	359	264	276	440	238	259
Ba	2244	3216	1586	226	732	829	1113	578	678	756	863	1449
Ce	849	785	230	1630	174	117	103	156	74	207	167	327
Pb	31	90	13	<10	<10	10	<10	36	23	<10	32	36
CIPW Norms												
q	28.28	19.32	16.88	12.21	8.46	20.75	27.11	14.90	30.09	12.50	31.58	30.15
or	21.87	25.42	23.64	25.42	13.00	29.55	21.28	22.46	24.82	23.05	25.42	26.01
ab	26.23	30.46	35.54	46.53	33.84	34.69	33.84	49.92	27.92	43.15	24.54	25.38
an	10.49	5.60	5.65	0.25	6.65	3.66	0.86	1.00	7.73	1.32	8.15	6.06
c												
di	3.29	6.88	7.05	10.84	12.56	6.78	10.55	7.80	2.63	12.05	0.57	2.51
hy	4.43	5.16	3.34		15.69	3.06	3.12	2.18	2.02	3.94	4.36	3.94
mt												
il	0.53	0.08	1.08	0.82	3.27	1.22	0.72	0.66	0.47	1.98	0.49	0.59
ap	0.16	0.22	0.46	0.33	1.50	0.43	0.19	0.16	0.13	0.68	0.14	0.18
zr	0.08	0.10	0.08	0.07	0.19	0.06	0.06	0.04	0.01	0.05	0.03	0.05
sp		0.04	0.04	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.03

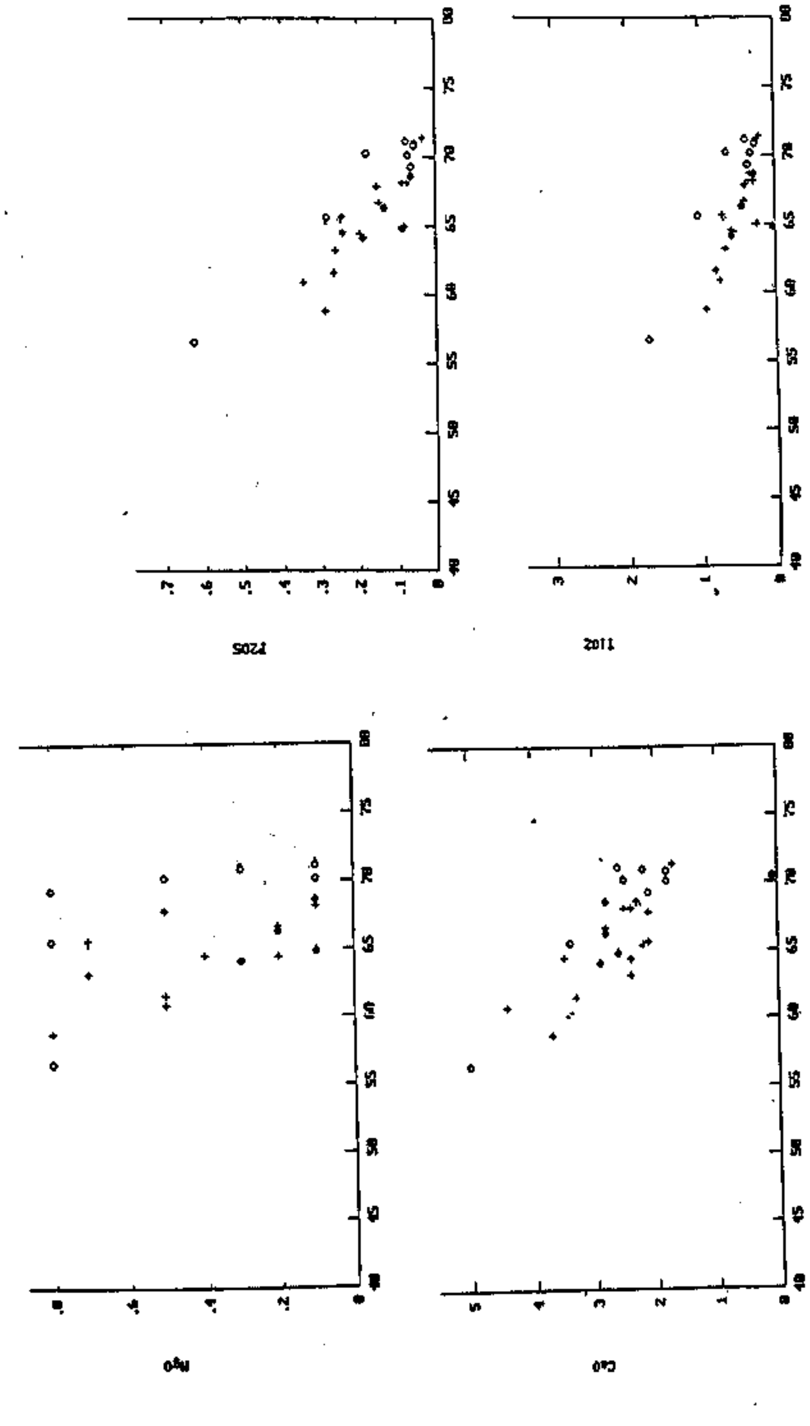


Fig. 19: Marker's variation diagram, of Granite, charnockite and gneissic charnockite (Contd)

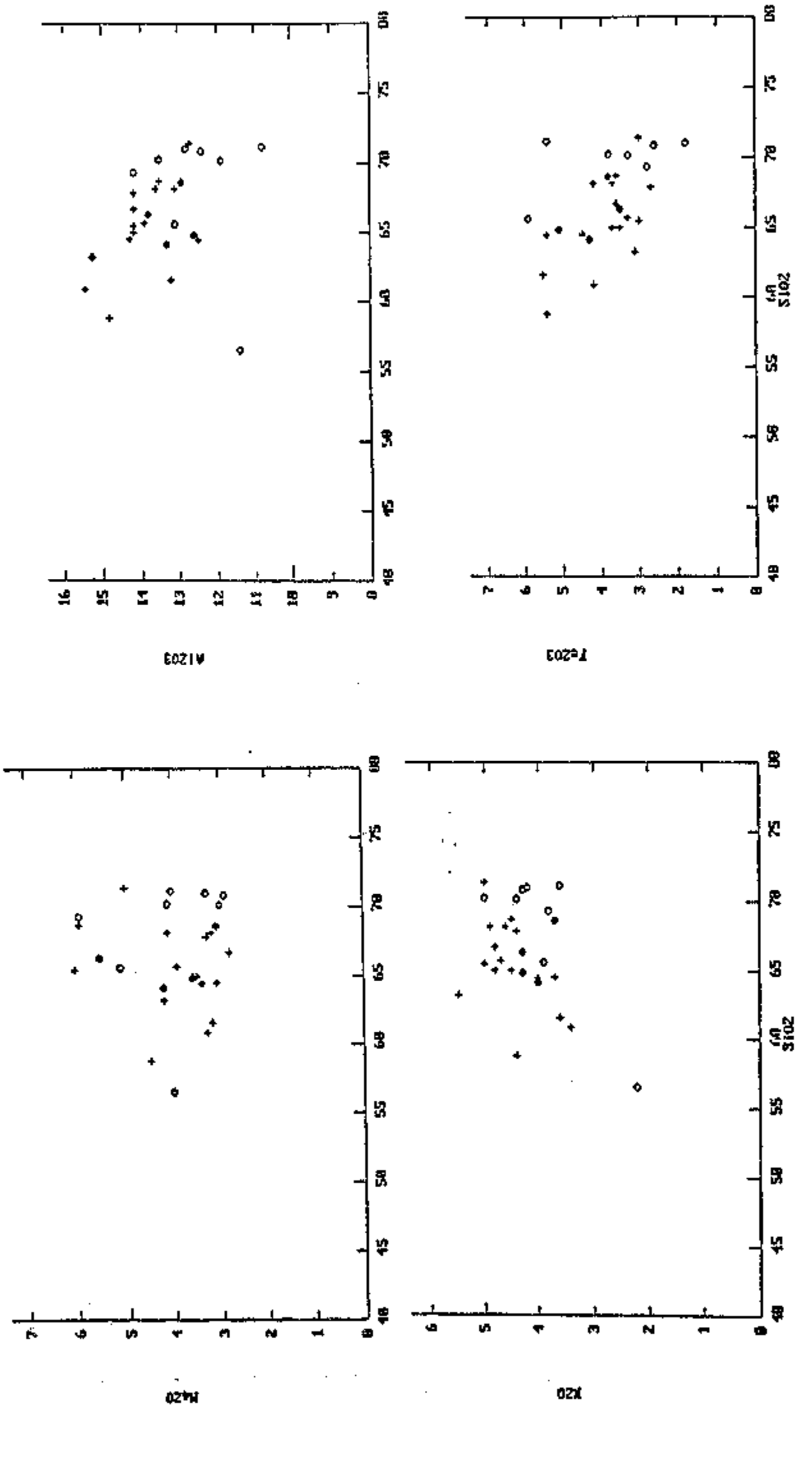


Fig. 19: Marker's variation diagram of Granite, charnockite and gneissic charnockite

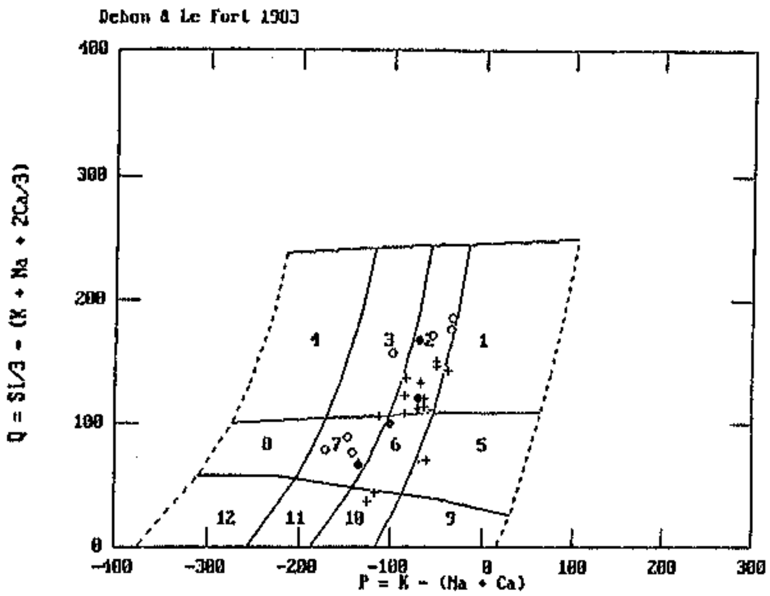


Fig. 20; A chemical mineralogical classification of plutonic rock after Debon and Le Forte 1983. The fields are — 1. Granite; 2. Adamalite; 3. Granodiorite; 4. Tonalite; 5. Quartz-Syenite; 6. Quartz monzonite; 7. Quartz-monzodiorite; 10. Monzonite

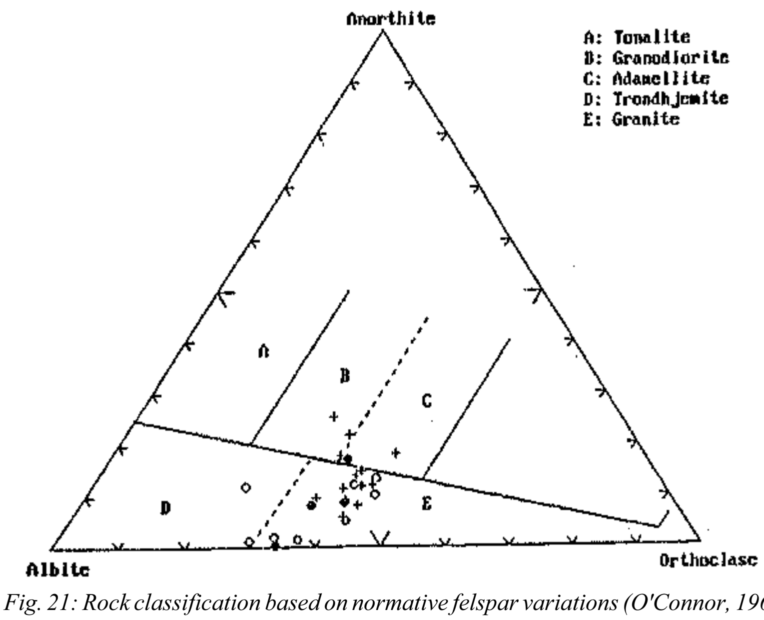


Fig. 21: Rock classification based on normative felspar variations (O'Connor, 1965). The fields are after Barker (1979)

orthogneiss in Kurze area. Minor shearing was also observed along the contact between the granite and migmatitic gneiss as recorded in Southern Holtedahl.

Impact of multiple metamorphism is evident in older metamorphites as evinced in their fabrics. The boudinaged pyroxene granulite and layered gneisses preserve the earliest metamorphism (Ml) of granulite grade synchronous with D1 deformation. The emplacement of gneissic charnockites and their subsequent deformation is attributed to syn-M2 metamorphism associated with D2 deformation. This seems to be the peak metamorphic event noticed in the area. The formation of biotite and quartz at the expense of orthopyroxene noticed in mafic granulites and the development of hornblende and quartz with the breakdown of pyroxene and plagioclase seen in gneissic charnockite indicate retrogression under amphibolite facies conditions, caused by influx of H_2O. Though no visible impact of regional metamorphism could be seen among younger intrusives, some effect of deuteric alteration in the form of leaching of iron imparting brown colour to granites is evident. Clouding of feldspar, development of biotite after hornblende and fracturing of mineral grains indicate late stage alteration and stress effects in the granites.

Mineralisation

Though no significant minerals of economic importance could be located, some sulphide mineralisation has been found within a large rolled boulder near the contact between granite and gneisses in the southern part of Holtedahl Range. Smaller blocks/boulders were seen strewn on the slope. However the insitu mineralised body could not be ascertained due to inaccessibility of the area further up hill. The mineralisation occurs as yellow, grey, granular mineral in the form of small veinlet, vugs and very fine dissemination in the greenish grey coloured gosanised calc-silicate rock. The metallic minerals constitute mainly pyrite and pyrrhotite with inclusions of chalcopyrite within pyrite.

The host calc silicate rock is fine to medium grained and has a mineral composition of diopside, epidote, sphene, zoicite amphibole, biotite, plagioclase, calcite, apatite, and pyrite. The rock has a granular texture predominantly consisting of equigranular mosaic of clinopyroxene and epidote. Intermittent zones of annealed epidote grains exhibit foam texture indicating recrystallisation. Pockets of zoisite and sphene are noticed sporadically. Brown biotite and green amphibole are present in the periphery of pyrite grains.

Pyrite, which is the major constituent of the ore, is intricately fractured in a near rectilinear grid pattern **(Fig.22).** Some of the fracture zones are formed by pulling apart of pyrite grains and the resultant interstitial space is filled by growth of epidote and fine chlorite. Rare pyroxene grains are found as inclusions in pyrite. Jagged outline of pyrite grains indicate its later replacement by chlorite. The pyrite grains form host to rounded inclusions of chalcopyrite and

Fig. 22: Photomicrograph of pyrite showing extension fractures. Some of the fractures are widened and filled by epidote and chlorite (x 40)

pyrrhotite. On the whole pyrrhotite and chalcopyrite do not constitute more than 2% of total sulphide minerals. Chemical analysis of two samples has shown copper values ranging from 40 to 60 ppm, Co 20 to 45 ppm, and Ni 45 to 55 ppm. One of the samples was also analysed for gold and has yielded 0.06 ppm gold.

The ore microscopic studies indicate that the mineralisation was subjected to brittle deformation causing pull-apart type of texture which was subsequently filled up by epidote and chlorite during retrograde metamorphism. The confinement of mineralisation along the contact between the foliated charnockite and the intrusive granite indicate that it post dates the granulite metamorphism and could be concomitant with granite emplacement. Near absence of mineralisation in these two rocks also points towards possible hydrothermal alteration along the weak zones resulting in the formation of characteristic hydrothermal minerals such as zoisite and epidote. Intense fracturing of ore minerals accompanied by their replacement by chlorite is indicative of tensional deformation and retrograde metamorphism.

Discussion and Conclusion

The Orvin mountains in the East Antarctic Craton expose a polydeformed and polymetamorphosed sequence of high grade granulitic rocks intruded by undeformed suites of charnockite and granite. The area records a complex history of tectonic and metamorphic activities. The mafic granulite and layered gneiss represent the high grade granulites emplaced at mid to deep crustal level, intruded by charnockites which were later deformed and metamorphosed to gneissic charnockites under the impact of regional metamorphism synchronous with D2 and M2 events. The rocks show an imprint of amphibolite facies associated with M3 metamorphism.

The petrochemistry of the gneissic charnockite and its field disposition support the view that it is an intrusive charnockite unlike the metamorphic charnockites found in Southern India and Sri Lanka. However, A.T.Rao *et al.* (1995) have correlated the Eastern Ghat Charnockites of India with that of Petermann charnockites described by Joshi and Pant (1995). The gneissic charnockites of the area can be correlated with the foliated charnockites described by Bejarniya *et al.* (1996) and D'Souza *et al.* (1996) from the adjoining Conrad mountains and Dallmannfjellet in CDML. Similar deformed and metamorphosed charnockites of igneous origin are reported from Mawson Coast in East Antarctica by Young and Ellis (1991).

There have been conflicting opinions on the origin of charnockite. The development of charnockite particularly of igneous origin is attributed to either direct crystallisation from a dry granitic magma (Wendlandt, 1981, Kilpatrick, and Ellis, 1992) or the restite material of a partial melting process in which water is removed by a melt phase (Fyfe, 1973, Nesbitt, 1980). The chemistry of the gneissic charnockite suggests that it could be product of undepleted magma produced by melting of mainly mafic to intermediate crust under low PH_2O conditions (Sheraton and Black, 1988).

Though the younger granites and the charnockite (undeformed) vary in their mineralogy and texture, they show a remarkable coherence in their chemistry. This chemical homogeneity and their close spatial association indicate that these younger suites might have been derived from a single parent magma. Charnockites indicate an early crystallization from an undepleted dry magma derived by melting of anhydrous granulitc-facies rocks. The granites of Orvinfjella with significant enrichment of trace elements such as Y, Zr, Nb, La and Ce are well comparable with late and post-orogenic intrusives with A-type affinities, reported by Sheraton and Black (1988). Joshi *et al.* (1991) have reported similar A-type granites from Petermann Ranges, East Antarctica. The undeformed charnockite of the area is comparable with the Svarthamaren charnockite reported from Muhlig- Hofmannfjella by Ohta *et al.* (1990).

Though no age data is available for the older metamorphitcs of the area, the correlation of the lithological ensemblage and structural continuities of Orvinfjella with that of Muhlig- Hofmannfjella in the west and Sor Rondane Mountains in the east allows an age of -1100 Ma for the older metamorphites and -500 Ma for younger intrusives. These correspond to the Grenvilean tectonic event and the Pan-African event in the region, respectively. The undeformed charnockite from Holtedahl mountains has been dated by Geochronology Division of GSI, recording an age of 483 ± 53 Ma.

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