On the Amphibolities from the Indian Research Station at Antarctica

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In the *Dakshin Gangotri* landmass, dykes, pockets and lenticular outcrops of massive weathered amphibolites are noticed within the gneisses.

Mineralogically three zones have been established in order of increasing grades, *viz., Zone A:* Amphibolite with sphene but without diopside; *Zone B:* Amphibolite with both sphene and diopside; *Zone C:* Amphibolite with diopside but no sphene.

From modal analysis, it is concluded that zone 'A' is plagioclase rich (62%) amphibolite (hornblende 36%) whereas zone 'C' is hornblende rich (67 to 68.4%) amphibolite with plagioclase content 29% and zone 'B' is with plagioclase ranging from 29 to 38% and hornblende varying from 56 to 63%.

The boundaries between the zones are parallel to the strike of foliation of the gneisses indicating simultaneous metamorphism with deformation.

INTRODUCTION

The amphibolites form very few exposures around the Indian Research Station at Antarctica and are scattered in parts of the area. Mostly they form weathered massive, lenticular exposures and occur as dykes, veins, small pockets, lenses of small dimension within gneisses. They are well foliated and lineated by parallel alignment of streaky prismatic grains of hornblende. The amphibolites show a northwesterly trend parallel to the strike of the foliation of the gneisses. The amphibolites show sharp or gradational contact with the gneisses. Layers of amphibolites are ptygmatically folded in migmatitic outcrop. Quartz veins occupy the joint planes in amphibolite. Gradation of texture (or structure) from granoblastic to gneissose and at places to schistose was seen in the same body of amphibolite.

CLASSIFICATION

On the basis of mineralogical assemblages, that is the presence of sphene and appearance of diopside, three zones have been established. These, in order of increasing grade, are as follows:

Zone A: Amphibolite with sphene but without diopside.

Zone B: Amphibolite with both sphene and diopside.

Zone C: Amphibolite with diopside but no sphene and quartz.

Zone A: Amphibolite with sphene but without diopside

The following mineral assemblages were observed in the amphibolites of this zone:

(i) Hornblende-plagioclase-quartz-sphene-apatite-opaque ore.

(ii) Hornblende-plagioclase-sphene-apatite-opaque ore.

Megascopic characters: The specimens of this group of amphibolite are dark coloured, medium grained and show granoblastic texture.

Microscopic characters: *Hornblende* forms sub-idioblastic, short prismatic and poikiloblastic grains. It is pleochroic with X = light yellowish green, Y = olive green, Z = green; Z>Y>X; N_2 = 1.671±.004, and composition is $Mg_{66}Fe_{34}$ (Table I). Z C = 23°.

It shows triple point contact ('Y' shaped) with the surrounding grains and contains inclusions of quartz, plagioclase, apatite and granules of opaque ore.

Plagioclase forms subidioblastic to xenoblastic and short prismatic to tabular grains with lobed grain boundaries. Composition from maximum extinction X' 010 is An_{55} (labradorite; Table II). Some grains show lamellar twinning, clouded due to dusty inclusions. It is altered to sericite along the cleavage and contains inclusions of plagioclase, quartz, hornblende, sphene, apatite and opaque ore. Plagioclase is rimmed by hornblende.

Quartz grains are xenoblastic, few with undulatory extinction. Quartz grains occur as inclusions within hornblende and plagioclase. Quartz is absent in some specimens.

TABLE I

Optical properties of hornblende from amphibolite.

Zone	Scheme of pleochroism			Absorption	ZAC	N_Z	Composition
	X	Y	Z				
A	**Light yellowish green**	**Olive Green**	**Green**	**Z>Y>X**	**23°**	**1.671± .004**	**$Mg_{66}Fe_{34}$**
B	**Light yellowish green**	**Olive green**	**Very dark green**	**Z>Y>X**	**10°**	**1.671± .004**	**$Mg_{66}Fe_{34}$**
C	**Light yellowish green**	**Olive green**	**Green**	**Z>Y>X**	**13°**	**1.667± .005**	**$Mg_{70}Fe_{30}$**

TABLE II

Optical properties of plagioclase from amphibolite.

Zone	X' 010as determined in the zone normal to 010 on Universal Stage			Anorthite %			Average anorthite content
A	28°	29°	30°	51.5	53	55	53
A		30°			60		50
B	30°	36°	37°	60	63.5	65	63
B	33°	35°	35°	60	62.5	68.5	616
B	25°	33°		47	60		53.5
C	29°	29°	36°	53.5	53.5	63.5	57

*Sphene f*orms subidioblastic and prismatic grains; it is feebly pleochroic, colourless to pinkish. Sphenc occurs as inclusion within hornblende and plagioclase and also occupies intergranular spaces, between hornblende and plagioclase as independent grains.

Apatite is idioblastic to subidioblastic and prismatic grains; occurs as inclusion within hornblende and plagioclase.

Opaque Ore is few, xenoblastic. Granules of opaque ore occur as inclusion within hornblende and feldspar.

Texture: The amphibolites of this group is medium grained and mostly equigranular. Hornblende, plagioclase and quartz grains are interlocked showing granoblastic texture.

Zone B: Amphibolite with both sphene and diopside

The following mineral assemblages were observed in the amphibolites of this zone:

(i) Hornblende-plagioclase-diopside-sphene-quartz.

(ii) Hornblende-plagioclase-diopside-sphene.

(iii) Hornblende-plagioclase-diopside-sphene-epidote.

Megascopic characters: The specimens of this group of amphibolites are dark coloured, medium-grained consisting of hornblende, other mafic minerals, feldspar and quartz. Elongated prismatic grains of hornblende form a strong foliation. Streaky layers of hornblende alternate with the granoblastic aggregate of feldspar and quartz showing gneissose structure.

Microscopic characters: *Hornblende* forms subidioblastic, prismatic and poikiloblastic grains. It is pleochroic with X = light yellowish green, Y = olive green, Z = very dark green; Z>Y>X; N,= 1.671 ± .004 and composition is Mg_{66} Fe_{34} (Table I). Z C = 19". Some of grains show twinning and contain inclusions of plagioclase, hornblende, sphene and granules of opaque ore. Elongated grains of hornblende are arranged parallel to the foliation plane (Fig. 1).

Plagioclase forms subidioblastic to xenoblastic and short tabular grains with lobed gram boundaries. Composition from maximum extinction X' 010 is $An_{„}$ (Table II). Some grains show zoning parallel to the margin of the grains and show lamellar twinning. Dusty inclusions in plagioclase form clouding. At places grains are altered to sericite mostly along the twin planes and show mosaic structure having sharp and straight boundaries.

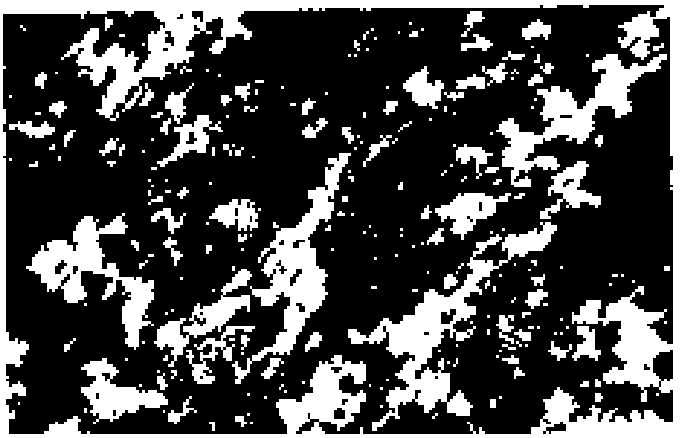

Fig.1. Photomicrograph showing elongated grains of hornblende arranged parallel to each other showing foliation in amphibolite (Crossed nicols, 20X)

Diopside form subidioblastic and elongated prismatic grains. Diopside is faint green coloured, non-pleochroic, N_v = 1.692 ± .005, Z c = 31°. Diopside is replaced marginally by hornblende in places. In some specimens diopside partially encloses plagioclase and hornblende. Their average $2V_2$ is 52.5, and the composition is $Ca_{44}Mg_{41}Fe_{l5}$.

Quartz grains are only few, xenoblastic, with undulatory extinction, show lobed and concavo-convex contact and occur as inclusions within plagioclase and hornblende.

Sphene forms idioblastic to subidioblastic and prismatic grains, feebly pleochroic from pinkish brown to pink. Sphene is enclosed by hornblende and plagioclase and also occupies intergranular spaces between hornblende and plagioclase is independent grains.

Apatite is idioblastic to subidioblastic, prismatic and small needle like grains. Apatite occurs as inclusion within hornblende and plagioclase.

Opaque ores occur as a few subidioblastic to xenoblastic, octahedral and dusty granular grains. Grains are randomly distributed and fine grained dusty grains occur along the cracks and cleavages of plagioclase and hornblende.

Epidote forms subidioblastic to xenoblastic prismatic grains; it is pleochroic from colourless to pinkish and show variegated interference colour. Epidote occupies the fractures and closely associated with sphene and occurs as inclusion within plagioclase.

Texture: The amphibolites of this group are medium-grained, almost equigranular. Elongated prismatic grains of hornblende are arranged in parallel fashion exhibiting a strong foliation. Feldspar and quartz grains show granoblastic aggregate. It shows alternations of hornblende rich layers, plagioclase-rich layers and in one case diopside rich layer.

Zone C: Amphibolite with diopside but not sphene and quartz

The following mineral assemblage was obtained in amphibolites of this zone: Hornblende-plagioclase-diopside.

Megascopic characters: The specimens are dark coloured, medium grained consisting of hornblende, other mafic minerals and feldspar. The rocks show relict sub-ophitic texture. At places hornblende rich layer alternate with granoblastic aggregate of quartz and feldspar showing faint gneissose structure.

Microscopic characters: *Hornblende* forms subidioblastic large prismatic grains. It is pleochroic with X = light yellowish green, Y = olive green, Z = green; Z>Y>X; N_z = 1.667±.005, and composition is Mg_{70} Fe_{30} (Table I). Z C = 13°. Hornblende grains show triple contact with the surrounding grains and tend to enclose plagioclase. Hornblende contains inclusions of granules of opaque ore, apatite and alters to biotite.

Plagioclase occurs as subidioblastic and short tabular grains with lobed grain boundaries. Composition determined from maximum extinction angle X' 010 is $An_{63.5}$ (Table II). Some grains show zoning parallel to the margin of the grain and lamellar twinning. Dusty inclusions form clouding. Plagioclase encloses granular hornblende and alter to sericite and muscovite.

Diopside forms subidioblastic and prismatic grains. Diopside is faint green coloured and non-pleochroic; Z C = 35°. Diopside occurs as a relict mineral and replaced by hornblende; partially encloses plagioclase and contains inclusions of opaque ore.

Opaque ore occur as idioblastic to subidioblastic, octahedral and prismatic grains. Grains occur as inclusion within hornblende and as dusty inclusion within plagioclase.

Biotite is present as flaky prismatic gram Biotite replace hornblende

Apatite forms idioblastic to subidioblastic, prismatic and subelliptical grains Apatite occurs as inclusion within hornblende

Texture. The amphibolite of this group is medium grained, almost equigranular Grams are interlocked showing granoblastic texture Diopside encloses plagioclase partially forming blastophitic texture

MODAL COMPOSITION

The modal composition of the specimens from three zones of amphibolites have been presented in Table III

TABLE III

Modal composition (volume %) of amphibolite of Dakshin Gangotri Antarctica

Minerals	Zone A		Zone B			Zone C	
Hornblende	36 0	63 0	59 0	56 3	59 0	68 4	67 0
Plagioclase	62 0	29 0	38 0	32 0	38 0	29 0	29 0
Diopside	**X**	4 2	1 0	2 8	**X**	0 1	2 0
Quartz	1 4	3 4	1 4	5 7	**X**	**X**	**X**
Sphene	0 3	**X**	0 2	1 0	0 5	**X**	**X**
Apatite	0 3	**X**	**X**	0 2	**X**	0 3	**X**
Biotite	**X**	**X**	**X**	**X**	0 5	**X**	**X**
Phlogopite	**X**	**X**	**X**	**X**	0 4	X	X
Calcite	**X**	X	**X**	**X**	0 2	**X**	**X**
Zircon	**X**	X	X	X	0 1	**X**	**X**
Chlorite	X	X	**X**	**X**	1 3	**X**	**X**
Opaque Ore	**X**	0 4	X	2 0	**X**	12	20
Total	100	100	100	100	100	100	100

x = not present

The table shows that the zone A with sphene but without diopside is rich in plagioclase amount Plagioclase of this zone is present in 62% Quartz is only 1 4%a Sphene is present in trace amount

The zone B with both diopside and sphene comprises amphibohtes which are richer in hornblende percent than the zone A In this zone, percentage of hornblende is lower than the zone A and it ranges from 29 to 38 Diopside is present in 1 to 4 2% only Percentage of quartz (1 4 to 5 7%) is low Amount of sphene varies from 0 2 to 1 0

The zone C with diopside but no sphene is distinctly a hornblende rich amphibolite Hornblende varies from 67 to 68 4% and it is fairly high in comparison to the zone A and zone B

Comparatively plagioclase decreases in amount and it is 29%. With the increase of hornblende percentage, diopside gradually decreases in amount in this zone compared to zone B and it is 0.1 to 2.0% only.

Apparently, from the modal composition it has been concluded that the zone A is fairly a plagioclase rich amphibolite and zone B is intermediate between zone A and zone C. In presence or diopside, hornblende percentage gradually increases in the zone B and reaches its maximum in the zone C where sphene is absent and diopside abruptly decreases in amount.

METAMORPHISM

Amphibolites of the investigated area form few exposures which are scattered in different parts of the area. Amphibolites show a northwesterly trend and lie either parallel or sub-parallel to the foliation or banding in the paragneisses. In the migmatitic outcrops veins of amphibolite cut across the foliation or banding of the metamorphic gneisses.

Amphibolites show the following mineral assemblages:

I. Hornblende-plagioclase-sphene (± quartz).

II. Hornblende-plagioclase-diopside-sphene-quartz.

III. Hornblende-plagioclase-diopside.

The typical assemblage hornblende-plagioclase-diopside (± quartz) indicates metamorphism of the amphibolites under sillimanite-almandine-orthoclase subfacies of almandine-amphibolite facies of Fyfe *et al.* (1958). Presence of sphene indicates more calcic composition. This basic assemblage hornblende-plagioclase-diopside does not correspond to hornblende granulite sub-facies of granulite facies, as sphene is stable upto almandine-amphibolite facies only (Turner, 1968). Absence of muscovite in the interlayered paragneisses evidently indicates metamorphism of amphibolite under the silimanite-almandine-orthoclase sub-facies.

On the basis of mineralogical changes with temperature of metamorphism, Engel and Engel (1962) were able to draw three isograd near Emerville to Colton in North-west Adirondack Mountain. These, in order of increasing grade, are marked by

1. Disappearance of sphene in amphibolites (about 525°C).
2. Appearance of abundant diopside in amphibolite (about 550°C).
3. Appearance of orthopyroxenes (about 575 °C) giving the granulite assemblage.

The present authors have established three zones in the studied area on the basis of mineralogical assemblages. These zones are as follows:-

Zone A: Amphibolite with sphene but without diopside.

Zone B: Amphibolite with both sphene and diopside.

Zone C: Amphibolite with diopside but no sphene.

The boundaries between these zones are parallel to the strike of foliation of the gneisses Hence it has been concluded that metamorphism increases from low grade to high grade within the same sillimanite- almandine- orthoclase sub-facies.The zone A containing sphene only, is of lower grade whereas the zone B containing both diopside and sphene of higher grade.

The principal changes in optical properties of the minerals with increasing grade of metamorphism are observed. Anorthite content of plagioclase gradually increases from zone A (53.5) to zone B (63). Plagioclase is of labradorite (An_{53-63}) variety. Hornblende shows an increase in intensity of pleochroic colour from zone A to zone B. Colour of Z-direction ranges from bluish green (in zone B) to green (in zone A). In zone C hornblende shows decrease in intensity of pleochroic colour from zone B and here Z-direction shows green colour. But refractive index (N_z) of hornblende remains almost same in all the zones and it is 1.671 ±0.004 and in zone C, it is 1.667 ± 0.005.

Engel and Engel (1958) experimentally established a temperature about 525˚C where sphene disappears and a temperature 540°C where diopside appears, at Edwards in Northwest Adirondack Mountain.

Binns (1964) established three zones in the "Willyama Complex", with progressive increase in metamorphic grade. These zones have been revealed by regular variations in mineral assemblages. These zones extend parallel to the regional foliation and fold structure. In the lowest grade zone (zone A), basaltic rocks have been recrystallised to hornblende-plagioclase amphibolites, containing blue green hornblende, garnet and clinozoisite or epidote. Pelitic rocks are biotite-muscovite schists, often containing sillimanite and garnet. This zone is distinctly lower in grade than the rock types of the present area. The second zone (zone B) is characterised by hornblende-plagioclase amphibolites containing brown, brown-green hornblende and also garnet, cummingtonite and clinopyroxene. In the pelitic rocks muscovite is no longer stable, its place being taken by orthoclase in sillimanite and garnet bearing biotite gneisses. Bulk of the amphibolites of the present area and the orthoclase bearing gneisses appear to be equivalent to these rocks of Willyama Complex. In the highest zone (Zone C), orthopyroxene appears in rocks of basaltic composition. Clinopyroxene becomes more abundant and the basic lithology is a hornblende-two pyroxene gneiss. Pelitic rocks of this zone resemble those in the second.

The third zone is marked by the first appearance of orthopyroxene in basic rocks and hence called "orthopyroxene isograd". Temperature in the range 600˚-850˚C and pressures of about 8 kilobar are estimated during metamorphism. Fluid pressure appears to have been considerably lower than total rock pressure. Orthopyroxene bearing assemblages developed in the metadolerites of the present area appear to be equivalent in grade with the zone C rocks. These rocks in both the areas appear to have formed under low water pressure condition.

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