CHAPTER - VII

METAMORPHIC HISTORY

CHAPTER-VII

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VII.1 Preamble

The rocks of the study area exhibit various phases of metamorphism as given below. These metamorphic events are correlatable with different tectonic and/or igneous events.

1. **Regional metamorphism (M1)**

Granulite facies during the Bhilwara cycle (Late Archaean ?): It was the manifestation of subduction of the igneous basement along with the pelitic and calcareous sedimentary cover rocks. This subduction facilitated deep burial of these rocks at sufficient depths (15-20 km ?) to achieve P-T conditions leading to granulite facies conditions

This metamorphic event can be further divided into three episodes of prograde metamorphism:

M1a. Rapid increase in pressure led to the development of staurolite in Fe-rich pelites (low temperature - medium pressure), presumably through chloritoid which is no longer preserved.

M1b. Subsequent increase in temperature caused the

(i) Metamorphism of pelitic and calcareous sediments together with the igneous rocks, which constituted the basement for the sediments, into pyroxene granulites.

(ii) Development of hercynite overgrowths over staurolite followed by development of sapphirine from hercynite.

(iii) Development of scapolite in calcareous rocks.

M1c. Cooling resulted in development of garnet overgrowth over spinel and sapphirine in pelitic rocks. This appears to be a minor event of anticlockwise P-T trajectory (Isobaric cooling (IBC).

Development of coronal garnet (andradite-grossular) in calc-granulites at the expense of scapolite, anorthite and clinopyroxene etc.

Development of mylonites due to extreme shearing along the basement-cover contact due to differential competency between basement and cover rocks appears to have taken place during M1a event.

2. **M2 event** :

Upliftment led to **decompression**, during pre-Delhi period. It comprised of

A. Near isothermal decompression (M2a), followed by

B. Near isobaric cooling (M2b)

A. M2a Isothermal decompression (ITD) resulted in the development of various types of symplectites viz. quartz-cordierite symplectites formed due to osumillite breakdown - development of plumose symplectites, quartz-feldspar symplectites, microcline-perthite symplectites, derivation of orthopyroxene-quartz symplectites from garnet breakdown, sapphirine-spinel symplectites, breakdown of staurolite to spinel-sapphirine (This is discussed in Chapter-IX on upliftment history).

The mechanism responsible for the upliftment was obduction of the granulites as tectonic slices or slivers which is described at length in Chapter-IX.

B. M2b Isobaric Cooling : The rapidly uplifted decompressed block gradually cooled without significant drop in pressure.

3 **Regional metamorphism (M3)**

synchronising with the Delhi orogeny caused the development of retrograde mineral assemblages with inclusions of M1 minerals viz. sillimanite, cordierite etc in porphyroblastic garnets and Superposition of the NNE-SSW regional foliation (S3) congruent to the orographic trend of the Aravalli Mountain Range. This metamorphic event indicates upper amphibolite facies as is evident from the mineral asssemblages of Delhi Supergroup rocks : absence of spinel, sillimanite in the metapelites, absence of scapolite in calc gneisses and calc schists, non-obliteration of volcanogenic structures viz. lapilli, vesicles, amygdules, pillow lava (in Deri Ambaji area- adjacent to the study area) etc All these point to the maximum upper amphibolite facies conditions of the M3 event of regional metamorphism (Deb et al., op cit) .

4. **Thermal Metamorphism** :

Emplacement of Erinpura granite (contact metamorphism -M4 event) led to the development of hornfelses. Superimposition of thermal metamorphism led to development of andalusite or cordierite (of second generation) in the metapelites (Desai et al, op cit).

As many of the early formed assemblages appear to be partially preserved or as these early minerals were consumed in the crystallisation of subsequent assemblages there is likelihood of uncertainty in the interpretation of the early stages of the metamorphic history. However, the following features like

a) Detailed microprobe analyses and PT estimates

b) Pseudomorphs of sillimanite after kyanite in few cases

c) (i) staurolite inclusions in spinel;

(ii) spinel growth from a reaction involving staurolite;

(iii) removal of staurolite because of the absence of abundant kyanite (sillimanite) in garnet cores (Droop & Nurminen, 1984);

d) sporadic occurrence of sapphirine

led the author to infer that the rocks of the study area did witness medium to high pressure conditions but uplift due to obduction impeded their growth in prolific amounts. But the identical rocks in Sandmata area of Central Rajasthan, which form the NE extension of the study area show considerable development of staurolite, kyanite etc. (SinhaRoy et al, 1995, Guha, 1996, Sharma, 1996). The relevance of these aspects is discussed in the last chapter.

M1a . Perhaps the pressure-temperature conditions during progressive metamorphism shifted from kyanite-sillimanite to sillimanite field. Appearance of staurolite and/or spinel along with sillimanite in metapelites during prograde metamorphism, helps in assessing the pressure at which melting occurred. P_{Max} was approached earlier than T_{Max} (clockwise) during prograde M1 event. T max had exceeded beyond 810°C because there is excessive remelting in biotite bearing pelites. Moreover, relict olivine in pyroxene granulites suggests higher temperature.

Absence of staurolite/kyanite in the pelitic granulite other than as an included variety shows that conditions of metamorphism shifted from staurolite-spinel (hercynite) - almandine field to sillimanite - spinel - sapphirine -almandine field as indicated by sapphirine rim over spinel containing staurolite inclusion. It is not possible to know about the chemical composition of the staurolite but it could be high-Mg staurolite as such high-Mg staurolite in a sapphirine-garnet rock from the Limpopo Belt, S.A. has been described by Schreyer et al (1984).

Textures developed in the aluminous layers immediately adjacent to quartzo-feldspathic lenses are seen as reaction rims or grown layers and as intergrowths with finely crystalline neomorphic sillimanite. Overgrowths of spinel by sapphirine, overgrowth of sapphirine by garnet, overgrowth of spinel by hypersthene as also as garnet overgrowth on spinel suggest :

1. Spinel + quartz = sapphirine or

   spinel + quartz = hypersthene

2. Sapphirine + quartz = hypersthene + sillimanite (Caporuscio & Morse, 1978)

3. Sapphirine + quartz = garnet + sillimanite or

   spinel + quartz = garnet + sillimanite

4. sapphirine + quartz = cordierite + sillimanite.

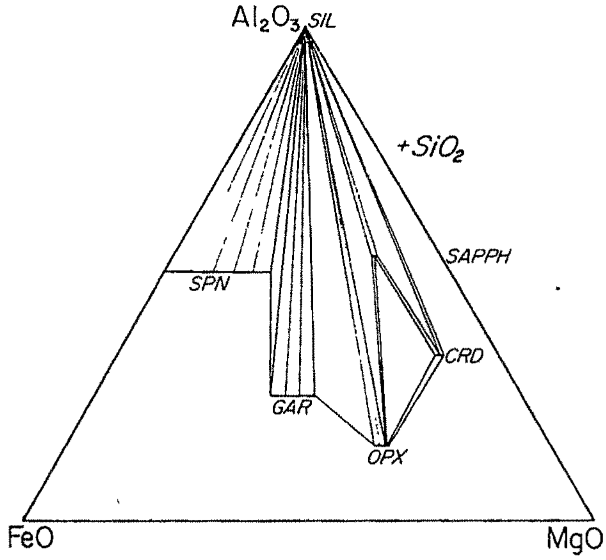
Fig.7.1 depicts the different minerals in the quaternary system MgO-FeO-Al2O3-SiO2 with SiO2 projection in it showing the generalised compositional ranges of minerals that are found to co-exist with quartz. Progressive order of magnesium enrichment is garnet-hypersthene-sapphirine-cordierite.

The textures suggest that magnesian spinels reacted with silica to produce variously, sapphirine, orthopyroxene, garnet or cordierite (plus sillimanite). Rimming and inclusions are compatible with the above reaction sequence.

The early breakdown of spinel plus quartz to sapphirine or hypersthene may be attributed to the relative ease with which these product minerals could nucleate. Garnet has less structural similarity with spinel and hence did not begin to form until late in the reaction sequence. Therefore garnet might have started crystallising after sufficient undercooling (during M1c event) below the equilibrium temperature required for nucleation of garnet as opposed to sapphirine or hypersthene as it has been experimentally shown that at temperatures above 1150°C, garnet cannot exist in pelites (Vielzeuf and Holloway, 1988). The textural observations (such as sapphirine rim around spinel) indicate that sapphirine and hypersthene developed at far higher temperatures, presence of perthitic K-feldspar and co-existence of sillimanite + orthopyroxene in sapphirine bearing assemblages point to high temperatures during sapphirine formation (Sivasubramanian et al, 1981 & Jayananda et al, 1995) and garnet overgrowths began to develop only after sufficient cooling . (Similar observations have been arrived at in Salt Hill and Emery Hill, Cortlandt Complex, New York (Tracy and McLellan, 1985).

Therefore the peak P-T conditions were attained when spinel-sapphirine developed i.e. M1b event. Porphyroblastic garnet certainly indicates a cooling event (**isobaric cooling - ?** (M1c). This may have been facilitated by the first stage of minor uplift of the peak metamorphic assemblage across the shallower isotherms.

The P-T conditions implied by the mineral assemblage data for the sapphirine bearing granulites in the study area are the highest yet reported in the granulite provinces of NW India (Rajasthan and N.Gujarat) by Desai & Patel (op cit). It is necessary to have precursor sediments with appropriate bulk composition to record such ultra high



Generalised compositional ranges of the minerals that are found to coexist with quartz - progressive order of magnesium enrichment in garnet - hyperathene - sapphirine - cordierite

Fig. 7.1 SiO_2 Projection within the quaternary system MgO - FeO - Al_2O_3 - SiO_2.

peak conditions to develop diagnostic mineral assemblages (Brown and Raith, 1996) In the study area the peak metamorphic conditions are recorded by Mg-rich pelite.

As alluded to earlier (Chapter-IV), the prograde reaction textures in the granulites indicate heating (dehydration with some degree of melting and transition from kyanite-sillimanite stability field to staurolite-sillimanite-hercynite stability field, in pelitic rocks) at pressures higher than 4 kbar - reaching initially upto 9 kb or even higher.

The first formation of staurolite and/or cordierite, in pelitic rocks of appropriate composition, defines the beginning of medium grade metamorphism. These minerals are present in high-grade metamorphism as well.

The P-T requirements of staurolite formation has narrow limits 545+20°C , 4-8 kb pressure for the reaction

Chloritoid + And/Ky = Staurolite +Qtz (Winkler, 1979).

At low pressures, as in the present case, staurolite, in the presence of quartz and muscovite, disappears before the upper limit of medium pressure is reached On the other hand at medium and high pressures, the stability of staurolite extends into high grade metamorphism (Winkler, 1979). As such P-T box 1 **(Fig. 7.2)** has been constrained within 510-560°C and 6-7 kb while reconstructing the prograde evolutionary path. The relictic staurolite in spinel supports this).

The conditions leading to the formation of granulites are very high temperatures, very low P_{H2O}, and high or very high P_s. The condition of $P_{H2O} << P_s$ can be realised in the deeper (though not necessarily deepest) parts of the crust where very little water had access to igneous rocks and to metamorphosed sediments which had lost most of their water either during exceptionally long period or during a previous period of high-grade metamorphism (Winkler, 1979).

The condition of $P_{H2O} << P_s$ could also be produced by a dilution of the fluid phase with CO_2. This process is suggested by the nature of fluid inclusions (Touret, 1981). According to Touret, the fluid inclusions in quartz from [almandine]-high grade rocks consisted essentially of water, whereas the same in rocks from [granulite]-high grade (i.e., from the hypersthene zone) is indicated by the prominant gas species of CO_2. This explains why P_{H2O} was very much smaller than P_{total} during granulite formation. In the present case, in the pelitic and calc-granulites of the study area, CO_2 inclusions are present in different forms and the work is in progress.

VII.1a ***The facies of early metamorphism*** M_1

The critical assemblage Cpx-Opx-Plg occurs in both rocks - basic igneous rocks and thought to be calc-magnesian metasediments The stability of this assemblage

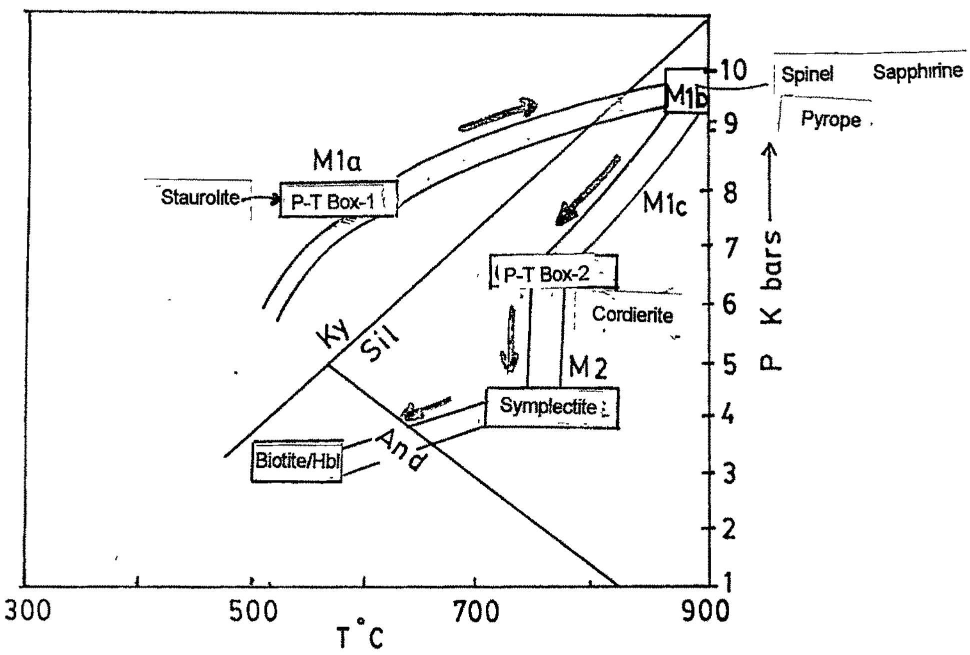


Fig. 7.2 P.T. Trajectory of the evolution of Granulites of the study area.

suggests that the early metamorphism took place in the "pyroxene-granulite subfacies" of Turner and Verhoogen (1960). As suggested by Cooray (1960) in Sri Lanka and by Sen (1959) in Bihar, India, it is possible that basic granulites form from both igneous and sedimentary rocks of appropriate composition by metamorphic convergence This view of the metamorphic facies is supported by the evidences such as :

i) The occurrence of hypersthene in rocks of a wide range of composition.

ii) The characteristic association diopside-scapolite in the calc-granulites.

iii) Presence of sillimanite and / or cordierite in the pelitic rocks

iv) Absence of sphene except in calcareous rocks.

v) The relative freshness of most minerals in all rock types.

The presence of distinctive mineral associations in rocks of calcareous and of pelitic composition suggests that the early metamorphism belonged to a low pressure facies series. **(Fig.73)**

VII.1b ***Reactions during early metamorphism***

In most of the rock types, the minerals formed before the peak of granulite facies metamorphism have been rarely preserved due to resetting of the assemblages due to differential upliftment (to lower P-T conditions). The only exception appears to be relicts of staurolite as inclusions within the spinel in Mg-rich pelites in the northern part of the study area and of kyanite in iron-rich pelites in the southern part of the study area.

Some basic rocks however retain remnants of primary igneous textures and minerals which have not been replaced by Opx-Cpx-plg assemblage. A faintly pleochroic hypersthene (bronzite), thought to be primary, is partly replaced by a more pleochroic hypersthene + diopside and marginal acidification of plagioclase may be associated with this reaction. Sen (op cit) has described a rather similar reaction in Bihar as under :

Bronzite+Plagioclase —>Hypersthene+Diopside +Plagioclase

$Fs18$ + $An72$ $Fs53$ $Di91$ $An64$ + SiO_2 + Al_2O_3

Some silica is set free in the reaction . The presence of interstitial silica in the basic charnockites of the study area may also be attributed to this reaction. Moreover, the presence of reaction rims or coronas similar to those occurring in basaltic rocks (Green and Ringwood, 1967, p.809) may also be a product of similar reaction during early metamorphism. In the study area, Desai (1974) first recorded such structures wherein hypersthene rims olivine and the vermicular pyroxene again rims in igneous looking norites. According to him, while hypersthene rimming olivine may be an example of igneous corona structure, the vermicular pyroxene might have formed during high grade

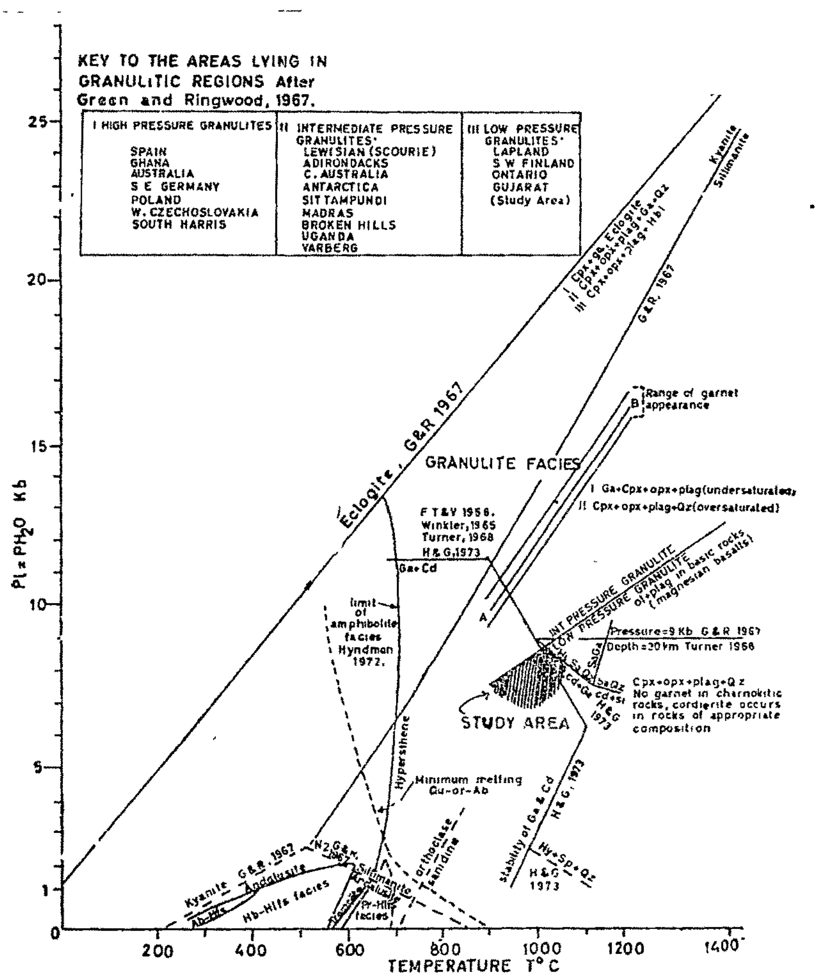


Fig. 7.3 P.T. Diagram indicating Granulite fields of rocks of the study area. (After Desai et al, 1978)

regional metamorphism (granulite facies) i.e. when the olivine bearing basic rocks were transformed into pyroxene granulites, although no such reaction structures have been noted in the pyroxene granulites of the study area Cooray (1960) has reported the occurence of vermicular pyroxene in the pyroxene granulites in the Highland Series of Sri Lanka. The occurrence of relict olivine in some of the basic charnockites could be considered as a satisfactory evidence that at least some of the basic charnockites might have been formed by the metamorphism of olivine bearing noritic rocks The change Cpx-Opx has been observed in charnockitic rocks suggesting some reaction during the period of granulite facies metamorphism.

VII.1c *Lateral variations in early metamorphism*

In the study area, there is little regional variation in character of the early metamorphic assemblages, but some characters of the assemblages (e.g. presence of sphene, wollastonite & grossular) suggest conditions transitional to amphibolite facies.

However, presence of scapolite (meionite), diopside, plagioclase and andradite in calc-granulites indicates that they may have once belonged to granulite facies.

VII.1d *Relationships of acid-intermediate charnockites*

In acid and intermediate charnockites, the heterogenous nature, the mineralogical and textural characters similar to those observed in magmatic charnockites, could suggest that they are after all intrusives formed during metamorphic period. But considerable variation in charnockitic rocks and the presence of folds (as noticed in the area north of Balaram and near Khapa in NE) within a comparatively restricted area is contrary to what one would expect in a plutonic mass, and may indicate the effects of granitisation (Prider, 1945, p.168). Thus these rocks may represent products of migmatisation (Desai, 1974, Nurminen and Droop, 1983).

As pointed out earlier, the rocks have been at higher temperatures and pressures at some earlier stages during metamorphic evolution. This would imply conditions inside the P-T field for formation of granitic melt. Pelitic assemblages indicate anatexis during decompression (Harris, 1981) & migmatisation in sillimanite- garnet bearing assemblages have been reported in Usilampatti and Andipatti of Kodaikanal area by Sivasubramanian et al, (1991). Young et al (1988) have also invoked partial melting to form similar assemblages in McCullough Range, Nevada in Southern Cordillera. Partial melting is, in fact, indicated by

(a) Formation of acid and intermediate charnockites from basic charnockites by widespread migmatisation or granitisation (Desai et al, op cit, Nogueira et al , 1996)

(b) Development of widespread migmatitic textures in pelitic and semipelitic granulites, K-feldspar patches and veinlets in pelitic gneisses and the stable existence of Opx + Qz + Kfs + Sillimanite under H2O -rich conditions also requires temperatures clearly within the melting point of granite (Nurminen and Droop, 1983, Desai et al, op cit).

(c) Scapolitisation of plagioclase is also due to this migmatisation (Desai et al, op cit).

VII.1e *Minor reactions following formation of granulite facies assemblages : Near Isothermal Decompression M_{2a}*

Some of the important minor reactions that follow the cessation of granulite facies conditions are the intergrowth textures described in previous chapters. These intergrowth textures like (a) perthites and antiperthites (though rare in charnockitic rocks), (b) Perthites and symplectites (plumose) in pelitic and semipelitic granulites, (c) diopside, scapolite, quartz symplectites in calc granulites, (d) spinel with magnetite, biotite, feldpar and sapphirine-spinel symplectites in the pelitic rocks.

A marked effect of post-crystalline deformation in charnockitic rocks as well as in associated rocks is the presence of strained quartz and feldspar crystals. The K-feldspar sometimes show a vague and indefinite cross hatched twinning which is generally unevenly distributed over the crystals. Eskola (1952) has called this effect "microclinisation" of orthoclase, and it is a feature reported from charnockites of many parts of the world The plagioclase crystals show fewer signs of deformation and these consist mainly in the bending of twin lamellae (wedge shaped lamellae) and infrequent fracturing of the crystals.

VII.1f *Major changes associated with later metamorphism : M_3*

Conspicuous changes associated with the later metamorphic phase coeval with Delhi deformation are recorded in respect of the rock types, the mineral assemblages; the styles of folding and the amount of migmatisation. These changes are linked with introduction of hydroxyl radicle.

The rocks assume dominantly migmatitic and granitic appearance as granulitic rocks are gradually reworked into amphibolite facies rocks Microcline is the typical K-feldspar, hornblende and biotite are the dominant ferromagnesian minerals. Sphene, Wollastonite and dominance of grossularite are present in calcareous rocks - all these suggest that the rocks belong to amphibolite facies.

In charnockitic rocks , the development of amphibole and mica at the expense of pyroxenes is also associated with addition of OH. Sen (op cit) explains the formation of biotite and hornblende at the expense of diopside and hypersthene. According to him, hornblende (bluish green) is invariably after diopside and hypersthene and this amphibolitisation may have been aided by hydration; albitisation of feldspar suggests that this was followed by introduction of Na and release of Ca,Al which combined with pyroxenes to produce hornblende. With further addition of Na, hornblende takes a blue tinge. More characteristically, the mineral is transitional with pyroxenes persisting in varying proportions. With addition of potassium, biotite replaces hornblende. According to Watson (1949) transformation of hornblende to biotite (during later metamorphism) with or without epidote is probably not due to physical changes but to arrival of K which makes the the formation of biotite possible.

Microcline which is the main K feldspar shows distinct cross-hatch twinning extending uniformly over the crystals. this twinning is distinctly different form the vague and ill defined cross hatched twinning which occurs in parts of K-feldspars of the granulite facies rocks. Perthitic and myrmekitic inclusions together with rounded bodies of quartz are often seen in the microcline crystals. Myrmekite is present in most of the thin sections. In some sections myrmekitic biotite is also present.

The occurrence of myrmekite, presence of hypersthene inclusions in microcline etc. suggest that K, Na and silica bearing emanations have passed through these rocks. The presence of myrmekitic biotite supports this view, as far as migration of K is concerned.

Comparable mineralogical changes in the associated rock types are as follows :-

(a) Formation of biotite and chlorite after garnet in pelitic rocks.

(b) Alteration of cordierite to biotite and pinite in cordierite bearing rocks.

(c) The change over of plagioclase to epidote and of garnet and hornblende to chlorite

(d) Formation of tremolite after diopside in calcareous rocks.

The presence of microcline in calcareous and pelitic rocks is also interesting. In pelitic rocks, microcline shows parallel inclusions of biotite. Similar parallel inclusions of biotite are also noticed in cordierite. This cordierite with biotite inclusions may be of a later generation than cordierite with fibrolite needles. The biotite inclusions may suggest earlier biotite developed at the expense of pyroxene and a hornblende and garnet. The presence of myrmekitic intergrowths further suggests addition of quartzo feldspathic material in these rocks.

Further, the transformation of pyroxenes to hornblende (in basic and noritic rocks) and to biotite in all the three varieties (especially the acid) is an indication of retrogression, such that hornblende/biotite containing rocks might represent metamorphic conditions of almandine amphibolite facies. alteration of pyroxene to hornblende and biotite could be very well connected to this later phase of metamorphism (accompanied by granitisation). Similarly, the transformation of garnet and cordierite to biotite and of diopside to tremolite may be associated with this later metamorphism. Higher core T than the rim T in most of the most of mineral pairs confirms the retrograde path According to Eskola (1952) cordierite is stable under PT conditions of granulite facies but he considered that it belonged when associated with biotite, to a subfacies stable at next lower temperature. Also the presence of tremolite and sphene in the calcareous rocks suggests that these rocks belong to amphibolite facies (Cooray, 1960).

VII.1g ***Relationship of metamorphic changes with granite emplacement***

The metamorphic changes associated with granite formation are Superimposition of contact metamorphism over high grade rocks (cordierite granulites)

In the area to the west and southwest of Rabaran village, development of (i) hornfelsic rock and (ii) migmatitic rocks respectively represents a case of superimposition of contact metamorphism over the regional metamorphism (Desai et al, op cit). This has resulted in the development of andalusite. The mineral assemblages in both the cases are (i) quartz-andalusite-biotite-cordierite-muscovite-plagioclase belonging to hornblende-hornfels facies and (ii) quartz-cordierite-andalusite-garnet-biotite-sillimanite-microcline-plagioclase indicating "pyroxene-hornfels" facies of Turner (1968) and Miyashiro (1973).

Therefore it is logical to infer that there exists a retrogressive metamorphic series in granulites and in rocks of amphibolite facies and that represents polymetamorphism or reworking. Such dynamic reworking (Watson, 1973, Krupicka, 1973, Goscombe et al, 1992, Harley, 1989, Young et al, 1989) accelerates adaptation to new equilibrium conditions and promotes a general tendency to granitisation. The increase in amount of K-feldspar and the decrease in the An-content of plagioclase are especially pronounced in intensely reworked rocks. Thus in the present area too, the migmatitic rocks showing abundance of microcline may indicate that they are reworked high grade rocks.

A parallel can be drawn with other areas e.g. (i) Scourie, Scotland (Sutton & Watson, 1951), (ii) Australia (Wilson, 1952), (iii) Tanzania (Sutton, Watson & James, 1954), (iv) Ceylon (Cooray, 1960), (v) East Manbhum, Bihar (Sen, 1959), (vi) W. Australia (Binns, 1964), (vii) Adirondacks, USA (Dewaard, 1964), (viii) West Greenland (Windley, 1972), Devon Island, (ix) Canadian Shield (Krupicka, 1973), (x) Westport map area, Canada (Wynne-Edwards, 1967), where similar metamorphic history has been envisaged.

VII.2 RELEVANCE OF METAMORPHIC HISTORY TO TECTONIC EVOLUTION OF GRANULITES

It is a well established fact that in most of the granulite provinces, mineralogical geothermobarometers usually fail to preserve the imprints of the peak P-T conditions of metamorphism owing to resetting of mineral compositions according to the reduced P-T conditions on account of their exhumation to higher crustal and/or near surface levels (Frost and Chacko, 1989; Spear, 1991). Nevertheless, they may provide discrete P-T points often on the retrograde trajectory of evolution of granulite complexes. In exceptionally rare cases, as in the present study area, relict assemblages of prograde metamorphism that are very useful in ascertaining peak metamorphic conditions, are preserved. In most of the granulitic terrains world over where the prograde metamorphic path is poorly understood, in the granulite provinces of Gujarat and Rajasthan are also not an exception. However the rare relics of staurolite within Mg-rich spinel-sapphirine assemblages and of kyanite in Fe-rich pelites have helped in understanding the prograde path to some extent in the study area

An understanding of the prograde path of metamorphism (clockwise or anticlockwise) is essential to determine the sense of movement of the crust prior to attainment of peak P-T conditions of metamorphism (Harley, 1989). The granulites of the study area do provide few indications about the prograde path.

The origin of granulites on anticlockwise P-T path is usually ascribed to enhanced heat budget due to magmatic under-/ intra-plating (Bohlen 1987, 1991, Janardhan et al, 1996), crustal extension (Sandiford & Powell, 1986) or lithospheric scale perturbation (Oxburgh, 1990). The P-T trajectory in granulites of the study area as worked out by the author is clearly a clockwise one which is linked to thickening of the crust due to collision (England and Thompson, 1984, Goscombe, 1992, Srinivasulu et al, 1996, Jayananda et al., 1995). In the study area one can rule out heat-input by advective fluids (Young et al, 1989, Newton 1993). Exposed magmatic rocks (mostly acid igneous suite of Erinpura granite) in the area under investigation, are clearly inadequate to supply significant amount of heat for thermal perturbation. Secondly on account of their being lighter, the acid igneous suite of Erinpura granite could have never underplated. Magnetic data (Geophysical studies, Chapter-VIII) too does not indicate any major mafic body underneath the study area which could cause any significant amount of magmatic underplating. Definite evidences from geophysical (gravity, magnetic and extrapolation of seismic) data suggest a collisional tectonic regime (Chapter-VIII), in the study area and its extension in the granulite provinces of Rajasthan, as probable cause for granulite facies metamorphism (Srikarni et al, op cit, Tewari et al, 1995, 1997). Thus, the available evidence argues for a subduction related compressional tectonic regime (Archaean oceanic plate subduction) to be responsible for granulite facies metamorphism of rocks of the study area.

Petrographic studies shows evidences of post-peak steep decompression in the form of development of various types of symplectites (Chapter-IV), which normally occur in an overthickened crust formed due to collisional tectonics (England and Thompson, 1984; Harley, 1989). These evidences supported by geothermobarometry data are in conformity with the upliftment and decompressional histories of other granulite provinces of the world (Limpopo Belt, South Africa (Schreyer et al, op cit); Rauer Group, E. Antarctica (Harley et al, 1988, 1992, 1994).

The recorded P-T during the M1a event (development of staurolite presumably from chloritoid in the metapelites) c.a. 5 kbars and 400°C followed by P-T max in the study area is c.a 9-10 Kbar, 900°C for the M1b event (development of spinel and overgrowth of sapphirine) which must have been close to peak conditions. Sapphirine-quartz assemblage requires a minimum T of 800°C (Newton et al, 1974, Janardhan & Sivasubramanian, 1996) and Tmax of 1000°C. This must have been followed by a slight cooling event (isobaric cooling- ?) when garnet overgrowth over spinel and/or sapphirine was facilitated as the nucleation temperature of garnet is about 875°C (Veilzuef and Holdaway, 1988) while the lower temperature limit is constrained at 730°C (Grew, 1982b). The staurolite inclusions within spinel in pelitic granulites of the study area are probably a relic of high pressure metamorphic stage of this mobile belt, which survived subsequent metamorphism as in Limpopo area (Schreyer et al, op cit).

Similarly in the case of calc-granulites, the nucleation temperature for the grossular-andradite (grandite) garnet is ~810°C. The development of garnet in calcgranulites at the expense of scapolite and clinopyroxene suggests lowering of temperature during M1c event (to 735°C). Garnet-cordierite thermometry has been useful in constraining this temperature around 760-800°C

Development of symplectites (Osumilite breakdown to cordierite, quartz-cordierite symplectites, garnet breakdown symplectites in metapelites and various symplectites in calc-granulites) suggest rapid uplift (the second stage of uplift) and near isothermal-decompression (M2 event). The pressure fell to nearly 4 kb. followed by slower cooling to nearly 400-500°C. According to Janardhan and Sivasubramanian, (1996), all these features point to high temperature breakdown products, suggesting a steep decompression path.

The author would tend to suggest a two-stage upliftment of the rocks The first stage upliftment may account for the M1c event (leading to sufficient cooling for garnet nucleation) and second stage of rather rapid uplift as an isostatic response to overthickened crust (Goscombe. 1992) and decompression marking the M2 event as evidenced by various symplectites (including garnet breakdown).

There is no evidence yet to suggest open-system chemical behaviour within the small reaction domains in the M1 and M2 events, therefore, the metamorphic reactions during these episodes are considered to be broadly isochemical However, the retrogression suggest hydration e.g. biotitisation of garnet and pinitisation of cordierite.

Preservation of symplectitic intergrowths suggest rapid decompression preventing annealing and destruction of the earlier textures (Windley, 1984). Hence uplift path of the pelitic granulites is inferred to be near-isothermal (Santosh, 1987).

On the basis of petrographic (symplectites), mineralogical criteria (Chapters-IV & V) suggesting decompression preceding cooling, and geochemical (Chapter-VI) criteria viz. presence of I-type Y and HREE depleted synmetamorphic granitoids (Desai & Patel, 1989), as outlined by Harley (1989), the author would prefer to argue that the overall P-T trajectory for the N. Gujarat granulites is in fact clockwise (**Fig. 7.2**).

VII.3 TECTONOMETAMORPHIC EVOLUTION OF GRANULITES OF STUDY AREA

The results of the thermobarometry are summarised in Table-8.1. for some of the samples separately. The data permit the selection of a reasonably well defined PT range for the last supposed chemical equilibration at 3-4 kb and 550-650°C.

Sapphirine-orthopyroxene granulites in the northern part display evidence for a rather complex metamorphic history and yield peak metamorphic conditions of 8-10 kb and 825-900°C. These conditions appear excessively high compared to the estimated regional metamorphic environment.

It may be suggested that the Fe-rich metapelites reequilibrated along the retrograde portion of the regional PT-path and lost their memory with respect to earlier stages whereas the magnesian metapelites did not (assuming that these different rock types indeed had the same PT-path in common). The reason for the apparently different memory may be related to the fact that above staurolite 'out' isograd in Fe-rich metapelites, the assemblage biotite + aluminosilicate + garnet + K-feldspar persisted upto granulite facies conditions. In Mg-rich metapelites, variety of additional phases may appear in the assemblages such as spinel, orthopyroxene sapphirine, osumilite etc. These mineral assemblages and their variants record the high grade metamorphic history more sensitively than the Gt + Als + Bi + Kfs assemblage in Fe-rich metapelites (Bucher-Nurminen and Giles Droop, 1983).

Reactions 9 to 14 are already shown in Chapter-IV in pelitic granulites. But as they have relevance in metamorphism they have been repeated in this chapter for ready reference for the reader

Simultaneous growth of biotite and cordierite observed in some samples (6D3) may be explained by hydration reactions of the type :

6 Gt + 4 Kfs + 4 H2O ——> 3 Qz + 3 Cord + 4 Bi 9

(in Qz saturated domains) and

9 Gt + 5 Kfs + 3 Sill + 5 H2O ——> 6 Cord + 5 Bi 10

(in Qz poor domains)

Gt-Bio and Gt-Cord thermometry in this sample gives 750°C (c) - 650°C (r) and 840°C (c) - 810°C (r) respectively.

The textural relations involving cordierite suggest that it does not represent a cogenetic prograde mineral with garnet, but rather indicate cordierite production relatively late in the metamorphic history of the rocks. It may coincide with sillimanite-biotite formation from garnet according to reaction ..11

1Gt + 1 Kfs + 1 H2O —> 1 Sill + 1 Bi + 2 Qz 11

As concluded from reaction 11 cordierite formation may have resulted from decompression. This conclusion is further supported by spinel + cordierite features which are possibly the consequence of the reaction :

5 Qz + 2 Sp ——> 1 Cord 12

Spinel inclusions in cordierite have been interpreted as the minerals of the reaction 14. However the spinel inclusions in garnet which frequently occur together with sillimanite probably represent a prograde feature and may be related to breakdown of staurolite, once present, by the reaction (in Qz-deficient rocks) :

10 stau + 3 Gt = 11 Sp + 31 Sill + 5 H2O 13

Relictic (metastable ?) staurolite is imperceptibly present within spinel. In very magnesian metapelites, quartz + spinel was converted into sapphirine prior to cordierite formation. The supposed quartz + spinel assemblage may have formed from a prograde reaction :

1 Bi + 3 Sill ——> 3 Sp + 1 Kfs + 3 Qz + 1 H2O 14

After reaching its maximum prograde P-T conditions at about 10kb and 900°C, the whole chunk experienced a dramatic period of uplift, which ceased in the vicinity of 4kb. From this point it shared the further metamorphic history with the surrounding units. The field setting imply that the uplift was greatest in the south and decreased towards north i.e. a sort of tilting. This may explain the occurrence of charnockitic basement towards south and almost at the same level as the pelitic and calc-granulites. The retrogression in the charnockitic rocks, must have been more than that in the pelitic and calc-granulites. This is clearly evident from the P-T distribution summarised in Table-VII.2.

The recognisable geological events are numbered from oldest (1) to youngest (8).

1. Deposition of a sedimentary sequence of pelitic and calcareous strata over an igneous basement during Pre-Delhi (Upper Archaean ?) times. The pelitic sediments were Mg-rich in the northern part and Fe-rich in the southern part.

2. Burial of the sedimentary sequence along with the igneous basement due to subduction.

3. Subduction caused in increase in metamorphic conditions. Initially there was increase in P faster than T. This differential increase in P and T was due to dragging down of geoisotherms by the subducting plate. Thus the dP/dT slope had a steep gradient (**Fig.7.2** Segment-I of P-T trajectory. [The descending plate (slab of the igneous basement along with the overlying sedimentaries) being comparatively cooler than the middle and lower crustal levels initially for a while dragged down the successive isotherms. It therefore resulted in very high pressure -low temperature conditions (steep dP/dT). Gradual smoothening of the isotherms led to increase in temperature (very shallow dP/dT slope) when the staurolite was converted to spinel and overgrowth of sapphirine over spinel took place i.e. peak metamorphic conditions were attained.

4. This subduction resulted in the first prograde transformation of Fe-rich pelites through biotite/chloritoid to staurolite under medium - high pressure - moderate temperature metamorphic conditions (M1a).

5. After sufficient subduction and time,the isotherms regained their original configuration due to homogenisation. The source of heat for the increase in temperature could be the homogenisation or material derived from mantle. Thus while the pressure increased slowly, the temperature rose faster continuously. The dP/dT slope therefore was +ve but rather shallow (**Fig.7.2**, Segment-II of P-T trajectory). It was under such high temperatures when development of spinel and sapphirine (in the Mg-rich metapelites) overgrowth took place. It was also at this stage, the peak metamorphic conditions of ~10kb and ~825-900°C temperatures might have been attained by these rocks (P-T box-2).

   Development of scapolite may have taken place during this event (M1b).

6. This was followed by the first stage of minor uplift when the temperature fell to a level below the garnet nucleation temperature (~810°C). This facilitated the overgrowth of garnet over spinel and sapphirine (P-T Box-3). Development of coronary garnet in calc-granulites may have developed during this stage (M1c). This may have been a isobaric cooling (IBC) event.

7. It was the second stage of uplift event which had a major and rapid uplift when the various symplectitic textures were developed. The uplift resulted in nearly isothermal decompression bringing down the pressure to ~3.5-4 kb range (**Fig.7.2**, Segment-III of P-T trajectory). Preservation of quartz-cordierite-symplectites due to osumilite and garnet breakdown bear a testimony to this. This major uplift leading to partial retrogression (P-T Box-4) and caused by obduction of the granulite facies rocks as tectonic slivers or slices synchronised with M2 event. Such two stage uplift has been shown in Gruf Complex, Eastern Pennine Alps by Bucher-Nurminen & Giles Droops (1983). This uplift was in isostatic response to the crustal thickening.

8. The above sequence of events of collision which culminated in the obduction of granulites to near surface levels resulted in a positive relief. As basin could not exist, no deposition of sediments (Aravallis) could take place until rift related opening of Delhi basin came into existence. The sedimentation in the newly opened Delhi basin commenced with bimodal volcanism evidences of which are seen as volcanic structures (Coulson, 1933; Golani et al, 1990; Deb et al, op cit etc.) at the base of the Delhis in the Deri-Ambaji area (northeast of the study area).

   The whole region experienced compression from west and east (closure of the Delhi basin) during Delhi orogeny when the preexisting granulite facies rocks and the Delhi sedimentaries were subjected to a rather vehement deformation and amphibolite facies conditions of metamorphism. It was M3 event.

   The presence of garnets containing inclusions of cordierite, sillimanite etc. are occasionally present in metapelites. The author would to prefer to correlate such garnets to the metamorphism during Delhi deformation.

   Some of the prograde conditions (Grt-Bt and Grt-Crd thermometry estimates) could possibly represent the peak of these conditions (core 736°C rim 762°C Grt-Bt; core 708°C rim 714°C Grt-crd).

   Development of second generation of biotite in the pelitic granulites and hornblende in charnockitic rocks probably occurred during this event.

9. The intrusion of Erinpura granite, another thermal event which occurred around 735-850 Ma led to development of various hornfelses. The peak temperature during this episode which overprinted the earlier ones suggests a temperature of ~500-690°C (450-540°C by Pl-Kfs thermometry) resulted in development of cordierite and andalusite near Balaram.

Coexisting k-feldspar and plagioclase in sample sm96/3 (Siyawa granitoid) reveals a solvus temperature of 550-600°C at 6-7 kb. Garnet-biotite thermometer for the same sample range 760°C (c), 700°C (c) and 660°C (r) suggesting a cooling event.

The upliftment of the granulite terrain was differential in the sense that the southern part, mostly comprising the charnockitic basement rocks was uplifted relatively more than the northern part.

One intriguing part of the present mineral assemblages is the absence of garnet in charnockitic rocks, which is ubiquitous in the pelitic and not uncommon in calc-granulites. It is difficult to say whether garnet did or did not develop in these charnockitic rocks during M1 event. However, large uplift culminating into drop in pressure, might have caused breakdown of garnet to Orthopyroxene + Quartz in these charnockites. It is now represented by a corona (crescent shaped) of orthopyroxene and quartz. This is merely a conjecture as relicts of garnet have not been noticed so far. Alternatively, low magnesium-iron ratio (Green & Ringwood, op cit) precluded the development of garnet in these rocks. A point may be mentioned here that the pyroxene granulites (charnockites) formed under low pressure facies Series e.g. Lapland (Eskola, 1952), SW Finland (Parras, 1958), Dangin, W.Australia (Prider, 1945), Ontario, Canada (Wynne Edwards & Hays, 1963); South Savana Complex, British Guiyana (Singh, 1964), are all devoid of garnet.

A pervasive decompression through 4-5 kb in the northern part and 5-6 kb in the southern part occurred at temperatures excess of 650°C. This P-T evolution, which indicates a uniform unroofing of some 6-11 km while quite high mid to lower crustal temperatures only decreased by50-100°C,is consistent with the later stages of prolonged collision related thermal evolution. Similar inference has been drawn about Rauer Group, East Antarctica granulites by

Harley (1988), Ellis, (1988) and Goscombe (1992).

Thus the prograde metamorphic evolution of pelitic rocks suggests the following :

In the northern part of study area :

Mg-rich pelites—> Chloritoid ? ——> staurolite + kyanite ? —> spinel (hercynite) + sillimanite —> Sapphirine + Opx

Retrograde path has :

spinel + sapphirine —> Pyrope + cordierite —> Biotite

In the southern part :

Prograde evolutionary path had

Fe-rich pelite —> Biotite —> sillimanite —> spinel

Retrograde path had the following minerals :

Spinel (green)—>Almandine —> cordierite —> Bt/Hbl and various symplectites

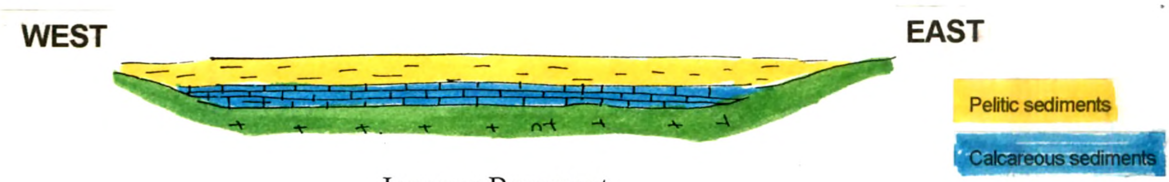
In the calcareous rocks prograde path is shown by

carbonate—> scapolite + Cpx + Wo

Retrogression is indicated by :

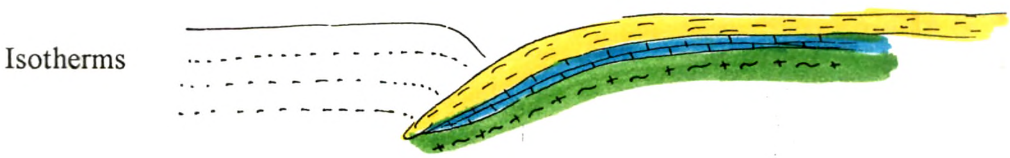
scapolite + Cpx + Pl —> Andradite/Grossular and tremolite

VII.4 Schematic representation of tectono-metamorphic evolution of Granulites of N. Gujarat

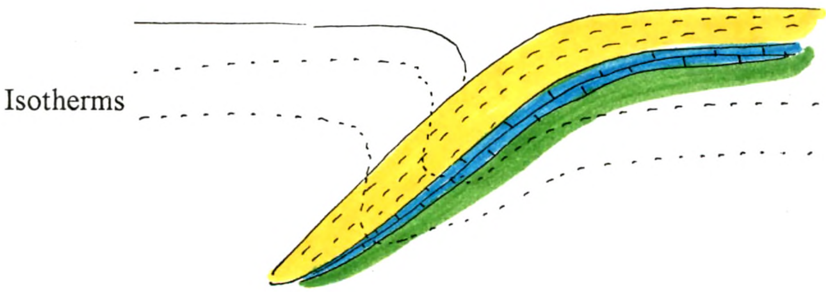


Igneous Basement

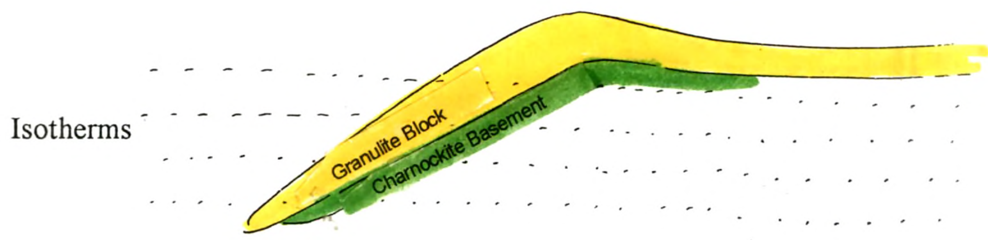
1. Deposition of calcareous, pelitic and semipelite sediments on a igneous (?) basement during Upper Archaean (?)



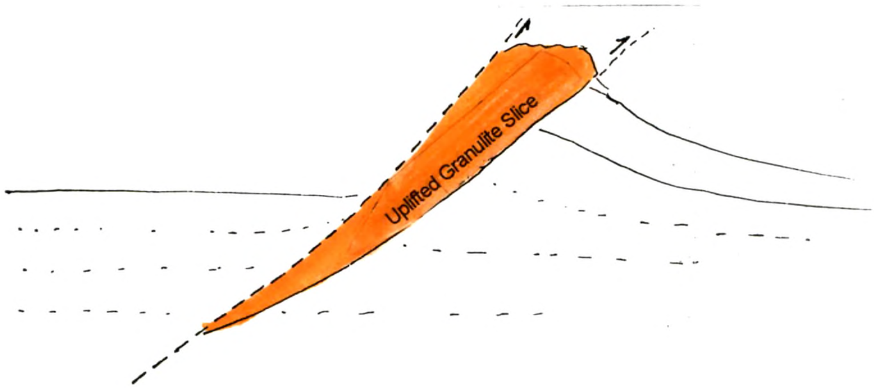
2. Beginning of westward subduction of the basement alongwith the sedimentaries (Upper Archaean ?). M1a event : Medium pressure moderate temperature (development of staurolite in metapelites) P = ~4 kb, T = ~550°C



3. Later stage of subduction. High P, High T conditions transgression of deeper isotherms by the subducting slab; Peak metamorphic conditions of granulite facies were attained. P ~8-10 kb, T ~825-900°C. M1b event. Development of Spinel (Hercynite) - sapphirine in Mg rich metapelites; scapolite (meionite) in calcareous rocks. Regional hypersthene grade.



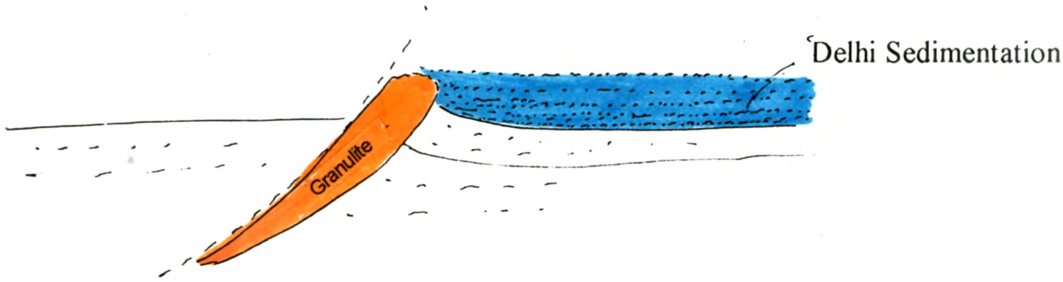
4. First stage of minor uplift : decrease in temperature; development of almandine garnet (pyrope in the northern part); development of coronal garnet andradite-grossular in calcareous rocks. T fell to ~700°C. M1c event.



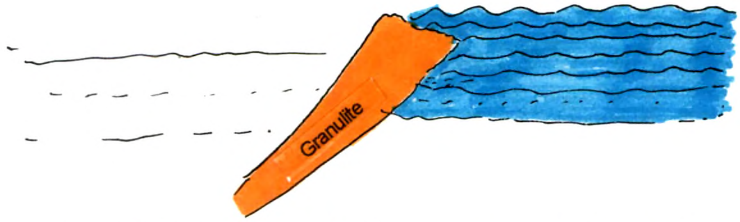
5. Rapid uplift of the metamorphosed rocks as tectonic slices or slivers by obduction. Development of symplectites. Near isothermal decompression. P dropped from 8 kb to ~4 kb. T remained ~700°C. M2a event.

6. Cooling resulted in partial retrogression of granulite. T dropped to ~500°C. M2b event.

7. Tectonic quiescence, +ve relief prevented any sedimentation.

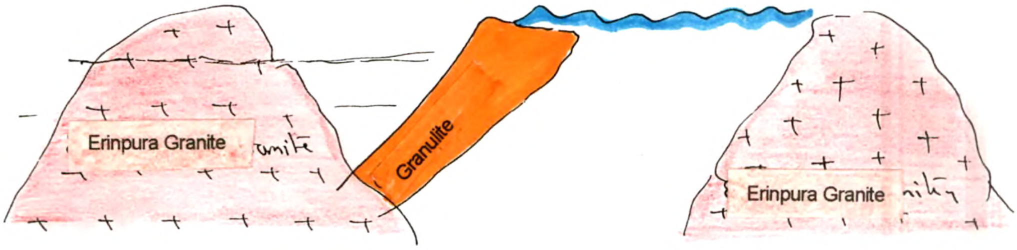


8. Rifting and opening of the Delhi basin. Sedimentation began with bimodal volcanism (in the adjacent area)Ca 1010Ma.



Closing of the Delhi basin along NNE-SSW axis regional folding. (DF1)

9. Closing of the Delhi basin along NNE-SSW axis. Compression due to Delhi orogeny. Superimposition of Amphibolite facies on the reworked granulites. M3 event.



10. Emplacement of Erinpura granite (735 ma). A. Thermal metamorphism, B. Metasomatism, C. Hydration. Development of biotite and hornblende bearing rocks. Andalusite bearing hornfelses in the retrograded granulites.

Thermobarometry estimates for the study area

Sample SH-12/1 Grt-Biot

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)			535	541
Holdaway & Lee (1987)			523	526
Ferry & Spear (1977)			504	507
Lavernt'Eva & Perchuk (1982)			522	514
Hodges & Spear (1982)			507	511
Pigage & Greenwood (1982)			523	526
Fonarev (1991)			523	526
Perchuk (1989)			532	535

Sample SH-12/2 Grt-Biot

			RIM	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)			447	453
Holdaway & Lee (1987)			445	448
Ferry & Spear (1977)			405	409
Lavernt'Eva & Perchuk (1982)			453	446
Hodges & Spear (1982)			402	405
Pigage & Greenwood (1982)			416	419
Fonarev (1991)			-	-
Perchuk (1989)			467	469

Sample SH/D/1 Grt-Biot sk14

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)			644	651
Holdaway & Lee (1987)			617	621
Ferry & Spear (1977)			633	637
Lavernt'Eva & Perchuk (1982)			601	592
Hodges & Spear (1982)			644	648
Pigage & Greenwood (1982)			668	672
Fonarev (1991)			612	615
Perchuk (1989)			606	608

Sample SH/D/2 Grt-Biot

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	639	647	659	668
Holdaway & Lee (1987)	614	617	631	634
Ferry & Spear (1977)	628	632	653	656
Lavernt'Eva & Perchuk (1982)	599	590	614	604
Hodges & Spear (1982)	639	642	665	669
Pigage & Greenwood (1982)	662	666	689	693
Fonarev (1991)	609	612	624	627
Perchuk (1989)	604	607	618	620

Sample ID3/1 Grt-Biot

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	497	503	599	606
Holdaway & Lee (1987)	489	492	579	582
Ferry & Spear (1977)	460	463	580	583
Lavernt'Eva & Perchuk (1982)	491	483	569	560
Hodges & Spear (1982)	463	467	588	591
Pigage & Greenwood (1982)	484	487	612	616
Fonarev (1991)	482	475	577	580
Perchuk (1989)	503	505	576	578

Sample ID3/2 Grt-Biot

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	473	580	605	613
Holdaway & Lee (1987)	556	560	584	588
Ferry & Spear (1977)	549	552	587	590
Lavernt'Eva & Perchuk (1982)	550	541	573	564
Hodges & Spear (1982)	557	561	595	599
Pigage & Greenwood (1982)	591	585	620	624
Fonarev (1991)	557	560	582	585
Perchuk (1989)	558	561	589	582

Sample 6D3/2 Grt-Biot

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	641	649	705	713
Holdaway & Lee (1987)	615	619	669	673
Ferry & Spear (1977)	630	634	709	713
Lavernt'Eva & Perchuk (1982)	601	592	646	636
Hodges & Spear (1982)	632	636	729	734
Pigage & Greenwood (1982)	649	653	756	760
Fonarev (1991)	611	614	659	662
Perchuk (1989)	606	609	648	651

Sample SM96/3/1 Grt-Biot

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	712	720	842	851
Holdaway & Lee (1987)	675	679	783	787
Ferry & Spear (1977)	718	822	888	893
Lavernt'Eva & Perchuk (1982)	648	639	735	724
Hodges & Spear (1982)	740	744	926	931
Pigage & Greenwood (1982)	772	776	964	969
Fonarev (1991)	663	666	756	760
Perchuk (1989)	650	653	729	732

Sample SM96/3/2 Grt-Biot

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	712	720	762	771
Holdaway & Lee (1987)	675	679	718	712
Ferry & Spear (1977)	718	822	783	787
Lavernt'Eva & Perchuk (1982)	648	639	684	674
Hodges & Spear (1982)	740	744	809	814
Pigage & Greenwood (1982)	772	776	843	847
Fonarev (1991)	663	666	700	704
Perchuk (1989)	650	653	682	684

Sample Ssm98 Grt-Biot

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	762	777	736	752
Holdaway & Lee (1987)	717	725	695	703
Ferry & Spear (1977)	783	791	749	757
Lavernt'Eva & Perchuk (1982)	682	662	664	644
Hodges & Spear (1982)	810	819	773	782
Pigage & Greenwood (1982)	837	847	799	808
Fonarev (1991)	699	705	680	686
Perchuk (1989)	681	687	664	670

SH12/1 Grt-Crd

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	850	857	879	886
Holdaway & Le (1977)	802	807	824	829
Wells (1979)	795	789	821	804
Lavrent'Eva & Perchuk (1981)	788	805	820	826
Bhattacharya et al. (1988)	797	803	809	815
Fonarev (1991)	820	825	845	849

SH12/2 Grt-Crd

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	806	812	873	879
Holdaway & Le (1977)	765	770	819	825
Wells (1979)	751	746	815	809
Lavrent'Eva & Perchuk (1981)	762 768	8	14	820
Bhattacharya et al. (1988)	770	776	807	813
Fonarev (1991)	780	784	839	844

SH/D/1 Grt-Crd

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	714	719	708	713
Holdaway & Le (1977)	689	693	684	688
Wells (1979)	665	660	659	654
Lavrent'Eva & Perchuk (1981)	694	690	679	685
Bhattacharya et al. (1988)	704	709	700	705
Fonarev (1991)	697	701	691	695

6D3/1 Grt-Crd

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	796	802	828	834
Holdaway & Le (1977)	757	762	783	788
Wells (1979)	742	737	773	767
Lavrent'Eva & Perchuk (1981)	752	758	778	784
Bhattacharya et al. (1988)	714	719	758	764
Fonarev (1991)	771	775	799	803
Perchuk (1989)	805	811	834	840

1D3/1c1 Grt-Crd

	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Thompson (1976)	734	639	710	715
Holdaway & Le (1977)	705	710	685	690
Wells (1979)	684	679	662	656
Lavrent'Eva & Perchuk (1981)	697	702	676	681
Bhattacharya et al. (1988)	708	714	699	704
Fonarev (1991)	714	707	692	696
Perchuk (1989)			721	727

OO/C3 Hbl-Pl

Geothermometry (°C)	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Spear (1981)	501	487	480	445
Geobarometry Hbl (kbars)				
Hammarstrom & Zen (1986)	3.082		3.879	
Hollister et al. (1987)	3.172		4.068	
Johnson & Rutherford (1989)	2.428		3.089	
Blundy & Holland (1990)	3.486 @ 750°C		-	
Schmidt (1991)	3.616		4.205	

OO [illegible] Hbl-Pl

Geothermometry (°C)	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Spear (1981)	473	469		
Geobarometry Hbl (kbars)				
Hammarstrom & Zen (1986)	3.730			
Hollister et al. (1987)	3.843			
Johnson & Rutherford (1989)	2.965			
Blundy & Holland (1990)	4.094 @ 750°C			
Schmidt (1991)	4.220			

B-2 Hbl-Pl

Geothermometry (°C)	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Spear (1981)	502	484		
Geobarometry Hbl (kbars)				
Hammarstrom & Zen (1986)	4.233		4.265	
Hollister et al. (1987)	4.359		4.528	
Johnson & Rutherford (1989)	4.258		3.424	
[illegible]	[illegible]			
Schmidt (1991)	4.610		4.476	

OOA (C1) Hbl-Pl

Geothermometry (°C)	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Spear (1981)	473	469	399	396

OOA (c1)

Geobarometry Hbl (kbars)		
Hammarstrom & Zen (1986)	3.720	3.199
Hollister et al. (1987)	3.843	3.301
Johnson & Rutherford (1989)	2.965	2.527
Blundy & Holland (1990)	4.094 @ 750°C	3.596
Schmidt (1991)	4.052	3.650

OO / Pl-Kfs

Geothermometry (°C)	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Geobarometry Hbl (kbars)				
Stormer (1975)	484	495		
Whitney & Stormer (1977)	532	543		
Powell & Powell (1987)	483	493		
Haselton et al (1973)	470	482		

SM96/3 Pl-Kfs

Geothermometry (°C)	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Stormer (1975)	485	495	553	565
Whitney & Stormer (1977)	532	542	608	618
Powell & Powell (1987)	483	493	550	561
Haselton et al (1973)	470	482	560	573

OO /c Cpx-Opx

Geothermometry (°C)	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Wood & Banno (1973)	905	838		
Henry & Madaris (1976)	1004	847		
Wells (1977)	1008	904		
Kretz (1982)	808	703		
Kretz (1982B)	904	1046		
Fonarev & Graphchikov (1983)	807	@ 6 kb	780 @ 6 kb	
Slavinsky (1983)	680	773		
Fonarev et al (1991)	870	@ 6 kb	826	@ 6 kb

Geobarometer (kbar)		
Mercier (1983)	10.10	10.92
Mecier (1984)	5.99	6.65

14Q Cpx-Opx

Geothermometry (°C)	RIM		CORE	
	@ 6 kb	@ 7 kb	@ 6 kb	@ 7 kb
Wood & Banno (1973)	910	923		
Henry & Madaris (1976)	960	981		
Wells (1977)	980	993		
Kretz (1982)	1073	1028		
Kretz (1982B)	851	932		
Fonarev & Graphchikov (1983)	765	@ 6 kb	789	@ 7 kb
Slavinsky (1983)	690	755		
Fonarev et al (1991)	761	@ 6 kb	803	@ 7 kb
Fonarev et al (1991) Cpx	920	@ 6 kb	926	@ 7 kb

Geobarometer (kbar)		
Mercier (1983)	15.46	13.90
Mecier (1984)	13.69	12.60

SM97/1 Bt-Opx

Sapphirine bearing pelitic granulites	@ 6 kb	@ 8 kb	@ 10 kb
Aranovich et al. (1988)	893	901	910
Sengupta et al (1990)	765	773	782
Grt-Opx			
Sen & Bhattacharya (1984)	912	930	948
Harley (1984)	815	827	840
Lee & Ganguly (1988)	916	930	943
Lee & Ganguly (1988)	895	911	928
Perchuk & Lavrent'eva (1989)	796	812	829
Grt-Opx			
Fonarev (1991)	824	841	858
Grt-Bt			
Fonarev (1991)	699	706	713
Bt-Grt			
Perchuk (1989)	681	687	693

GEOBAROMETERS (kbar)

Grt-Opx

	@ 600°C	@ 800°C	@ 1000°C
Harley & Green (1985)	-	3.52	9.84
Harley (1984)	5.33	6 23	7 62

GEOTHERMOBAROMETERS

Grt-Opx

Aranovich, Podlesskii (1989)	731°C	4.87 kb

CALC GRANULITES

Grt-Cpx (2D3)

Slavinsky, V.V. (1983)	Core 715-722°C	@ 6-7 kb
Rim	622-629°C	@ 6-7 kb

Cpx-Opx (180)

Slavinsky V.V. (1983B)	Rim	826-827°C	@ 6-7 kb
	Core	825-826°C	@ 6-7 kb

Summary

Pelitic granulites :

Northern part :	Bt-Opx	900-910°C at 8-10kb		
	Grt-Opx	6.2-9.8 kb at 800-1000°C		
	Grt-Bt	Rim	700-847°C	@ 6-7 kb
		Core	680-800°C	@ 6-7 kb
Central part :				
(central part of	Grt-Bt	Rim	600-650°C	@ 6-7 kb
Diwani hill)		Core	700-760°C	@ 6-7 kb
South-central part :				
(southern part	Grt-Bt	Rim	550-580°C	@ 6-7 kb
of Diwani hill)		Core	580-620°C	@ 6-7 kb
	Grt-Bt	Rim	480-500°C	@ 6-7 kb
		Core	570-615°C	@ 6-7 kb
Northern part of	Grt-Bt	Rim	600-660°C	@ 6-7 kb
Sarjan hill		Core	615-690°C	@ 6-7 kb
Central part of	Grt-Bt			
Sarjan hill		Core	600-660°C	@ 6-7 kb
Southern part of	Grt-Bt	Rim	440-470°C	@ 6-7 kb
Sarjan hill		Core	605-670°C	@ 6-7 kb

Garnet-Cordierite Geothermometry

Northern part :	Bt-Opx	900-910°C at 8-10kb		
	Grt-Opx	6.2-9.8 kb at 800-1000°C		
Central part :				
(central part of	Grt-Crd	Rim	715-810°C	@ 6-7 kb
Diwani hill)		Core	760-840°C	@ 6-7 kb

South-central part :				
(southern part	Grt-Crd	Rim	680-735°C	@ 6-7 kb
of Diwani hill)		Core	660-715°C	@ 6-7 kb
Northern part of	Grt-Crd	Rim	665-715°C	@ 6-7 kb
Sarjan hill		Core	660-710°C	@ 6-7 kb
Central part of	Grt-Crd	Rim	750-810°C	@ 6-7 kb
Sarjan hill		Core	810-880°C	@ 6-7 kb

Geobarometry .

(Hercynite-sapphirine pelites)	@ 600°C	@ 800°C	@ 1000°C
Harley & Green (1985)	-	3.52	9.84
Harley (1984)	5.33	6.23	7.62
Nickel & Green (1985)	-	3.99	10.67

Calc-granulites

	Grt-Cpx (2D3)	Rim	715-722°C	@ 6-7 kb
calc-granulites associated with Diwani Hill		Core	622-629°C	@ 6-7 kb
	Cpx-Opx (180)	Rim	826-827°C	@ 6-7 kb
North of Virampur		Core	825-826°C	@ 6-7 kb

Charnockites

Hbl-Pl

OO/c3	Rim	487-501°C	@ 6-7 kb
	Core	445-480°C	@ 6-7 kb
OO	Rim	473-469°C	@ 6-7 kb
	Core		@ 6-7 kb
B-2	Rim		
	Core	484-502°C	@ 6-7 kb
OOA/C1	Rim	469-473°C	@ 6-7 kb
	Core	396-399°C	@ 6-7 kb

Pl-Kfs

00	Rim	470-543°C	@ 6-7 kb
	Core	°C	@ 6-7 kb

SM96/3	Rim	470-542°C	@ 6-7 kb
	Core	550-618°C	@ 6-7 kb
Cpx-Opx			
OO/c	Rim	807-870°C	@ 6-7 kb
	Core	780-826°C	@ 6-7 kb
14Q	Rim	765-851°C	@ 6-7 kb
	Core	803-932°C	@ 6-7 kb
Geobarometer			
	Hbl	3.2-4.6 kb	
OO/c	Cpx-Opx	6-10 kb	
14Q	Cpx-Opx	13.7-15.4 kb	

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