CHAPTER - X

SUMMARY & CONCLUSIONS

INTRODUCTION

The crystalline rocks of Balaram area and its surroundings in Banaskantha District of North Gujarat comprise a complex assemblage of metamorphic and igneous rocks which were considered by most of the earlier workers to belong to the Delhi Supergroup intruded by basic and acid igneous rocks. Desai et al (1978) described them as granulites of charnockitic affinity belonging perhaps to either Pre-Delhi or even of older age. The study of various metamorphic events suggests that these high grade metamorphites belong to a sequence older than Aravallis (? Bhilwara Supergroup) of Archaean age. The area under discussion lies between Balaram in North Gujarat and Abu Road in South Rajasthan and comprises the granulitic rocks of charnockitic affinity from acid type to ultrabasic type that perhaps form the Pre-Aravalli basement.

Heron (1953) classified the Pre-Cambrian rocks of Rajasthan and Gujarat of northwestern India, into Banded Gneissic Complex (BGC) of Archaean age, Aravalli System and Delhi System. Subsequently Gupta et al (1992) revised the stratigraphy of Rajasthan into the oldest Bhilwara Supergroup, overlain by rocks of Aravalli and Delhi Supergroups. The parametamorphites of Bhilwara Supergroup essentially constitute psammitic, pelitic and calcareous rocks that have been profusely intruded by acidic and basic igneous rocks and have been subjected to polyphase deformation and metamorphism (Raja Rao et al, 1971; Sharma, 1988).

In Rajasthan, Aravalli-Delhi Tectonic Belt (ADTB) comprises BGC, Aravallis and Delhis. Granulites and charnockitic rocks form part of the BGC and occur southeast of Ajmer in Sandmata Complex (Sharma, 1988), Ramgarh (Khandelwal and Pandya, 1988). Granulites have also been reported in the western limb of Delhi Fold Belt (DFB), NNW of Ajmer (Fareeduddin et al, 1991). Granulite facies metamorphism is suggested to predate Aravallis (Fareeduddin, 1995b).

Coulson (1938) worked in Sirohi State and Heron and Ghosh (1938) worked in Palanpur, Danta and part of Idar states in Gujarat, but none of them have mentioned about the sillimanite/cordierite bearing rocks in these areas. Desai et al (1978) studied the area southeast of Balaram-Abu Road and identified granulite facies rocks - represented by basic-ultrabasic charnockitic rocks of igneous parentage and pelitic-, psammitic-, psammopelitic-, and calc-granulites. Assemblages such as garnet-cordierite-sillimanite-spinel-hypersthene-sapphirine were first reported by them (1978, 1992) and tentatively correlated them with the Bhilwara Supergroup of Archaean age.

AIMS AND OBJECTIVES

The main objectives of the present work are :

1. ***Geochemical studies*** of the charnockitic rocks (granulite facies rocks) to reveal the nature of their precursors which constituted the basement for the pelitic- and calc-granulites.
2. ***Petrological studies*** (including mineral chemistry) of the rocks of the study area to establish the metamorphic facies and P-T conditions and their comparison with those of the granulite facies rocks of Bhilwara Supergroup of Central Rajasthan.
3. The ***stratigraphic status*** of these polymetamorphites is very significant as it opens the scope for future workers to search for basemetals, precious metals and platinum group element (PGE) mineralization in this terrain. This is based on their analogy with the granulite facies terrains of Archaean age of South India which are known to host such deposits.
4. ***Application of geophysical data in conjunction with remote sensing studies*** in satisfactorily understanding Precambrian tectonic history to explain the upliftment and exhumation of this granulite facies terrain and its possible correlation with Sandmata Complex of Rajasthan.

For the first time geophysical data (Bouguer Gravity) has been used for correlation of the high grade polymetamorphites of the study area with the Sandmata Complex of Banded Gneissic Complex (BGC) of Central Rajasthan. This correlation has helped in assigning a Archaean age to the polymetamorphites of the study area (as the Sandmata Complex is generally considered to be of Archaean age). Gravity data of Northwestern India has been utilised to reconstruct the Late Proterozoic tectonic history of the region. This satisfactorily explains upliftment and exhumation of the granulite facies rocks of N.W.India as also the origin of Erinpura granites of the area and development of stresses responsible for the Delhi Orogeny. Tectonic upliftment also explains the reasons for retrogression of granulite facies assemblage to amphibolite facies.

This Ph.D. dissertation is an attempt to correlate the high grade granulite terrain of the study area with that of Bhim Karera and Sandmata Complex of Rajasthan based on petrography and geophysical studies suggesting a subsurface connection between these distantly placed geographic basement provinces. Upliftment of these rocks which must have originated under deep seated conditions is explained in terms of obduction at the convergent margin of Indian plate during the Precambrian times.

GEOLOGICAL SETTING

The charnockitic terrain occupies mostly the southern part of the study area and is characterised by subdued topography - mostly mounds and small hills. The best sections are in quarries. The dominant amongst these granulites is the 2-pyroxene granulite (basic type) which has much larger spatial distribution, most of it is concealed below the thin veneer of alluvium as is evidenced from the bore-well cores. The ultramafic variety which possesses distinct layering and banding has restricted occurrences around Kanpura - Dhanpur and Ajapur villages. The knotty appearance on the surface is due to large crystals of olivine surrounded by rim of pyroxene. The banding is sub vertical in Ajapur area whereas in Kanpura area these bands in general dip 30° due south. The morphological expression of the differential resistance of the bands is seen as ridges and grooves. There are a number of nodular features which are most conspicuous at the contact of the bands. Rhythmic banding of light coloured plagioclase rich and darker mafic rich portions is clearly seen in the freshly broken surfaces of individual bands. The intermediate and acid charnockite (i.e. hypersthene granite) varieties occur as patches within the above mentioned 2-pyroxene granulites. The junction between charnockites and pelitic & calc-granulites is often mylonitised, there is no evidence of a reacted contact between the two. Therefore the precursors of the charnockitic rocks are surmised to have constituted the basement over which pelitic and calcareous sediments were deposited and the whole sequence later subjected to granulite facies metamorphism.

The pelitic granulites are represented by garnetiferous granulite gneiss and marked by coarse light and dark metamorphic banding. The dark grey (bluish) bands are mostly of cordierite studded with reddish brown garnets. The leucocratic bands are rich in quartzo-feldspathic material. These are seen as mesoscopic tight, isoclinal reclined folds. Unlike the charnockitic rocks these are very hard to break and on account of their resistance to weathering they stand out as ridges.

The calc granulites are easily distinguished from the pelitic granulites due to their light colour - mostly dirty white to buff colour. Development of calc silicate minerals such as tremolite, actinolite, wollastonite etc. in this unit has resulted in many irregularities in foliation planes. Outcrops of the calc granulites are much less as compared to the pelitic granulites. They trend parallel to the adjacent pelitic granulites and are conformable with the latter. These rocks in turn are intruded by basic and acid igneous rocks of Post-Delhi age.

Four phases of deformation are recognised in the area, two of which are related to granulite facies metamorphism (Pre-Delhi) superimposed by two episodes of Delhi deformation. This wedge shaped granulite facies terrain is separated by two tectonic discontinuities viz. (i) the NE-SW trending Kui-Chitrasani fault in the west that separates the granulite facies terrain from the Erinpura granite in the NW and (ii) by approximately N-S trending Or-Surpagla tectonic junction that separates the polymetamorphites of the study area from the amphibolite facies rocks of the Delhi Supergroup occurring in the east and northeast.

The generalised stratigraphy of the area as worked out by the author is given in Table-I.

TABLE- I

Erinpura Granite	**Post-Delhi**
Calc-schists and calc-gneisses & associated metavolcanics and syngenetic basemetal mineralization	**DELHI SUPERGROUP** (Middle to Upper Proterozoic)
——— Tectonic junction ———	
Calc Granulites Pelitic Granulites Charnockitic rocks (with igneous precursors)	**BHILWARA SUPERGROUP** (Archaean ?)

PETROGRAPHY

On the basis of the petrographic studies following lithotypes of granulite facies rocks have been identified.

CHARNOCKITIC ROCKS

These include the granulite facies rocks with igneous precursors. Among these 2-pyroxene granulites the following mineral assemblages have been identified.

a) ***Ultrabasic Type*** (Olivine - calcic-plagioclase - diopside - hypersthene - bronzite - phlogopite - calcite).

b) ***Basic Type*** (Calcic-plagioclase - hypersthene - Hornblende - biotite).

c) ***Olivine Norites*** (Calcic-plagioclase - olivine - diopside - hypersthene- bronzite).

d) ***Intermediate Type*** (Plagioclase - antiperthite - quartz - hypersthene - hornblende - biotite).

e) ***Acid Type (Charnockite sensu stricto)*** (Quartz - perthite - oligoclase - hypersthene - hornblende - biotite).

Textural features in ultrabasic 2-pyroxene granulites such as olivine with a rim of hypersthene, depletion in An content in plagioclase near olivine as also segregation of purplish dust of rutile within the plagioclase laths indicate charnockitisation of olivine bearing rocks (Cooray, 1960). This is also evident from the recrystallisation of olivine, bronzite, and diopside to hypersthene.

Distinct compositional layering of plagioclase rich bands alternating with olivine and pyroxene rich bands with nodular structures and granoblastic texture suggest that the parent igneous rock was a layered anorthosite - peridotite - troctolite. Tilted nature of the relict original layers indicates its involvement in deformation. The southerly dipping nature of the banding suggests its deformation along E-W axis and these bands possibly represent one limb of the fold. A feebly pleochroic hypersthene (bronzite) obviously a primary mineral is seen partly replaced by a more pleochroic hypersthene. This process is accompanied by (i) formation of diopside and (ii) marginal acidification of plagioclase. Sen (1959) has described a similar reaction from the charnockitic rocks of Singhbhum, Bihar as under :

$$\underset{Fs_{18}}{\text{Bronzite}} + \underset{An_{72}}{\text{Plagioclase}} \longrightarrow \underset{Fs_{53}}{\text{Hypersthene}} + \underset{Di_{91}}{\text{diopside}} + \underset{An_{64}}{\text{plagioclase}}$$

Some silica is set free in the above reaction, which would explain the presence of interstitial silica in the basic charnockites.

In the basic type coarse granoblastic texture with development of large feldspar nodules with a rim of vermicular orthopyroxene has obliterated the original igneous texture to appreciable extent.

Amphibole and or amphibole-quartz corona due to extensive replacement of orthopyroxene in an otherwise dry pristine assemblage of orthopyroxene - clinopyroxene - plagioclase - ilmenite - suggest amphibole and biotite formation in localized open hydrous conditions during retrogression.

In acid charnockites textural features suggest that amphibole and quartz are secondary minerals and formed through the following reaction,

$$\text{Orthopyroxene + plagioclase + ilmenite} + H_2O \longrightarrow \text{amphibole + quartz} \quad \text{(i).}$$

Coarse granoblastic texture with development of large feldspar augens completely obliterated its original igneous texture. Appearance of apparently intrusive nature of this rock is evident from its crosscutting the foliation in the associated basic and intermediate charnockitic rocks but on a closer inspection it reveals a fine persistent banding in them thereby suggesting a metamorphic character of these rocks.

GRANULITES

These include the granulite facies rocks with sedimentary parentage viz. pelitic granulites and calc granulites.

A. Pelitic Granulites

(Cordierite - garnet - hypersthene - sillimanite - biotite - potash feldspar - plagioclase - quartz - pinite - spinel - sapphirine).

Important textural relations of the constituent phases in pelitic granulites suggest following reactions :

Chloritoid ————> Fe-cordierite + hercynite + vapour (1)

Chloritoid ——> almandine + staurolite + hercynite + vapour (2)

Staurolite + almandine —> Fe-cordierite + hercynite + vapour (3)

Fe-cordierite ————> mullite/ sillimanite +liquid (4)

Spinel + quartz ———> sapphirine (5)

Spinel + quartz ———> orthopyroxene (6)

Biotite + aluminosilicate + quartz + plagioclase ——> garnet + K-feldspar + vapour/melt (7)

Bands/lenses of quartz and feldspar in pelitic granulites may indeed represent melt fraction as indicated in reaction (7)

Sillimanite needles as well as fibrolitic variety of sillimanite form (S_e) which warps against the garnet porphyroblast and delicate intergrowth of biotite and quartz and myrmekite develops in the rock are possible result of reversal of (7)

Garnet + K-feldspar + V ——> biotite + sillimanite + quartz (8)

Alternatively, reaction (8) could have resulted from melt-solid interaction on cooling.

Sporadic presence of staurolite 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.

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

6 Gt + 4 Kfs + 4 H_2O ——> 3 Qz + 3 Cord + 4 Bi (9)

(in Qz saturated domains) and

9 Gt + 5Kfs + 3 Sill + 5 H_2O ———> 6 Cord + 5 Bi (10)

(in Qz poor domains)

In some of the samples 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 H_2O —> 1 Sill + 1 Bi + 2 Qz (11)

Such 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 11. However the spinel inclusions in garnet which frequently occur together with sllimanite 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 H_2O (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 H_2O (14)

B. Calc Granulites

(Diopside - plagioclase - scapolite - calcite - sphene - wollastonite- tremolite - grossularite - apatite).

Textural relationships of the phases in both the associations suggest early stabilization of the assemblage clinopyroxene- plagioclase - calcite - quartz - scapolite -titanite.

Textural features such as aggregate of scapolite grains embaying large porphyroblast of plagioclase and calcite and scapolite replacing plagioclase along the grain boundary suggest the formation of scapolite by the following reaction

Plagioclase + Calcite ——> scapolite (i)
(Anorthite) (meionite)

Calcite + anorthite + quartz ——> grossular + CO_2 (ii)

Slight compositional variation within garnet suggests participation of clinopyroxene (hedenbergite component) in reactions (ii) & (iii).

Hedenbergite + calcite + anorthite + quartz ——> $garnet_{ss}$ + CO_2 (iii)

Formation of coronal garnet over scapolite, calcite, anorthite and clinopyroxene as well as the variation in composition of the garnets from rim to core suggests the reaction :

Hedenbergite + calcite + scapolite + quartz ——> $garnet_{ss}$ + CO_2 (iv)

and

Anorthite + calcite + quartz + hedenbergite ——> $garnet_{ss}$ + CO_2 (v)

Petrographic studies reveal that an early assemblage of clinopyroxene - quartz - calcite - titanite - plagioclase was stabilized in these calc granulites. Scapolite appeared later at the expense of plagioclase. Subsequent mineral reactions stabilized coronal garnet.

Meionite originated exclusively from the primary bulk of the rocks. The mineral assemblage quartz - calcite - K-feldspar -meionite - diopside indicates calc-magnesian sediments as their precursors and represents conditions corresponding to pyroxene granulite sub-facies.

The probable mineral reactions are :

1) Anorthite + calcite = scapolite [quartz, grossular,vapour]
2) Anorthite + calcite + quartz = grossular + vapour [scapolite]
3) Scapolite + quartz + calcite = grossular + vapour [anorthite]
4) Scapolite + quartz = grossular + anorthite + vapour [Calcite]

Formation of scapolite from calcite and plagioclase denotes increase in temperature and this reaction, occurred during the prograde metamorphism. Both the deduced garnet - forming reactions can occur in response to either increase in T or increase in X_{H2O} or both.

The origin of scapolite from plagioclase as suggested by the textural relationships between the two could be due to the metasomatic processes involving such fugitive constituents as CO_2, Cl. SO_3 etc. released during the regional metamorphism. The fugitives necessary for scapolitisation of plagioclase might have been liberated from "within" during metamorphism itself, the CO_2 having been freed during reactions between carbonate rocks (while SO_3 and Cl were possibly contributed by the granitic melt formed from the metamorphism of pelitic rocks).

It may be noted that the hedenbergite-involving reactions produce garnets with grossular : almandine ratio 5:1. The studied garnet compositions are not that almandine-rich. Therefore, it is envisaged that these reactions were accompanied partially by the solid-solid reaction,

Hedenbergite + anorthite = grossular + almandine + quartz. (vi)

The reactions

Scapolite + hedenbergite + calcite + quartz = garnet + CO_2

and

Scapolite + calcite + hedenbergite = garnet + CO_2

both produce grossular-rich garnet (84-89 mole%) according to the stoichiometry of the reactions. Hence, to produce more almandine-rich garnet operation of another reaction viz.

Hedenbergite + plagioclase = grossular + almandine + quartz

is necessary. As the garnet in the present study is having 26 mole % almandine, this reaction also must have taken place concomitantly.

Andradite is suggested to have been derived from originally impure calcareous sediments by the following reaction :

$$3CaCO_3 + Fe_2O_3 + SiO_2 \longrightarrow Ca_3Fe_2Si_3O_{12} + 3CO_2$$

Introduction of FeO leads to formation of hedenbergite and insufficient silica leads to development of magnetite (spinel) :

$$4CaCO_3 + 2Fe_2O_3 + 2FeO + 5SiO_2 \longrightarrow Ca_3Fe_2Si_3O_{12} + CaFeSi_2O_6 + Fe_3O_4 + 4CO_2$$

Coexisting calcite (white recrystallised marble) along with wollastonite suggests that the parent sediments had insufficient quartz for transformation of all $CaCO_3$ to wollastonite by the following reaction :

$$CaCO_3 + SiO_2 \Longleftrightarrow CaSiO_3 + CO_2$$

Development of wollastonite may have depleted all silica which facilitated spinel formation along with hedenbergite.

The above mineral assemblages of the various charnockitic and granulitic rocks and geothermobarometry based on mineral chemistry suggests high metamorphic grade forming a typical granulite province indicating P-T conditions of 6-9 kb pressure and 650-900°C temperature which may approximately correspond to the M1 event (Guha and Bhattacharya, 1995) of Sandmata complex.

The symplectitc textures, clearly indicating breakdown of high pressure minerals, suggest decompression and thus confirm the upliftment of this deep crustal segment to shallow level. This upliftment and the resultant decompression may have lead to retrogression of granulite facies assemblages to amphibolite facies. The upliftment must have been a rapid phenomenon. Geothermobarometry supports near isothermal decompression experienced by these rocks.

Besides these the mylonitic rocks occur in close association with granulites and are characterised by gneissic foliation and dark green groundmass with ovoid patches of feldspar drawn out parallel to foliation. The mylonitic rocks typically occur at the contact of granulites and charnockites and might have formed due to extreme shearing along the weaker zone in granulitic terrain during deformation.

GEOCHEMISTRY

The nature of the precursors of the pyroxene granulites (charnockites) in the study area has been worked out assuming broadly isochemical metamorphism. The major elements of representative charnockitic rocks viz. ultramafic, mafic, intermediate and acid, from the study area were determined and their normative mineral composition was calculated. These values are used in the various diagrams. Most of the samples occupy the tholeiitic field and suggest that the precursors of the pyroxene granulites (charnockites) of the study area possess mostly tholeiitic affinity for the igneous basement. Though metasomatism on a restricted scale should not be ruled out. From the chemical behaviour of all types of charnockites, it is suggested that their protoliths were all igneous rocks (tonalite / adamellite / quartz-monzonite / granodiorite - tholeiites), with the development of minerals exhibiting metamorphic transformations.

Major element, trace element and REE chemistry of the granulites of the study area suggest their Archaean affinity.

Metamorphic History

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).

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

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.

The mechanism responsible for the upliftment was obduction of the granulites as tectonic slices or slivers.

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.

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).

GEOLOGICAL EVENTS

The successive metamorphic episodes vis-a-vis Pre-Delhi deformation under deep seated P-T conditions transformed these rocks to granulites. Both the basement and the overlying granulites experienced the Delhi deformation resulting in their present spatial disposition. The sequence of various geological events can be summarised as given below :

1. Deposition of sequence of pelitic, psammitic, psammopelitic and carbonate sediments over a basic-ultrabasic crystalline basement (olivine, bronzite, hypersthene and calcic plagioclase bearing suite).

2. Deep burial and intense deformation due to subduction during ? Archaean brought about the development of sillimanite-garnet-cordierite-spinel-hypersthene bearing granulites representing psammo-pelitic suite of rocks, together with quartz dominant garnet-sillimanite bearing psammites and diopside- scapolite calc granulites as also the development of charnockitic rocks from the igneous basement - all indicating metamorphism under pyroxene granulite subfacies.

3. Upliftment of the granulite terrain as tectonic slivers/slices due to obduction during pre-Delhi period resulted in the retrogression of the granulite facies rocks to amphibolite facies.
4. Superimposition of a dominantly NNE-SSW and a feeble NW-SE Delhi folding.
5. Emplacement of Post-Delhi basic and acid igneous intrusions resulted in contact metamorphism.

GEOPHYSICAL STUDIES

On account of the presence of minerals such as garnet, pyroxene and olivine etc. these rocks have higher densities and seismic velocities appropriate of lower crust. As such the granulite facies rocks of the study area are clearly reflected in the Bouguer Gravity map of Rajasthan and N.Gujarat and constitute prominent gravity highs. In the gravity map these are clearly distinguished from the amphibolite facies terrain of Delhi Supergroup and the Erinpura granites.

The study area is located in the southernmost domain of the three prominent gravity high domains of Rajasthan and Gujarat. The petrographic studies clearly suggest that the various charnockitic rocks are responsible for positive gravity contours in Balaram - Rabaran- Kanpura area. In contrast to these granulitic rocks of Pre-Delhi age, the calc schists and calc gneisses of Delhis and also the Erinpura granites in general are deficient in high density minerals and hence are identically reflected in gravity map. The Erinpura granite is intrusive into the metasedimentaries and is massive in nature.

Similar domains of positive gravity values of Bhim Karera and Ajmer-Sambhar areas of Rajasthan could be the northeastward extension of Palanpur-Kansara domain of North Gujarat where the high grade rocks of identical associations are expected. The classic study on high grade charnockitic and granulitic terrains of Rajasthan by different workers, in Bhim Karera area in Bhim- Kankroli- Gulabpura domain and in Sandmata area of Ajmer - Sambhar Domain support the contention of the present author.

The highest gravity values of +30 m.gals are represented by the 2-pyroxene granulite (basic - ultrabasic type) suite. Superimposition of the Bouguer gravity map on the geological map of the study area broadly shows that : (1) The highest values of +35 m.gals contour near Palanpur probably suggest the presence of 2-pyroxene granulites below the alluvium. (2) Associated granulitic rocks of sedimentary parentage fall within the contours of lower gravity. (3) Zero gravity contour approximately marks the boundary between the pyroxene granulites (charnockitic rocks) and granulitic rocks.

(4) The closely spaced gravity contours (0 to -30 m.gals) trending NNE-SSW approximately mark an important lineament (Kui-Chitrasani fault) where the pyroxene granulites and pelitic/calc granulitic rocks of relatively high density come in juxtaposition with low density Erinpura granites.

This gravity high domain is the southwesterly extension of the regional gravity high domain extending from Central Rajasthan and represented by Sandmata Complex of Bhilwara Supergroup of Archaean age. The Kui-Chitrasani fault of the study area is the southwestern extension of Phulad lineament which further supports the continuity of the BGC terrain of Rajasthan into the study area.

TECTONIC EVOLUTION

The granulitic and charnockitic terrain of the study area is bounded 1) in the west by NNE-SSW trending northwesterly dipping Kui-Chitrasani fault where it is seen to abut against the Erinpura granites 2) by approximately N-S trending Or-Surpagla tectonic junction to its east. A sharp structural and metamorphic discordance separates this terrain from the Delhi Supergroup of rocks whereas the intrusive Erinpura granites lying to the south do not exhibit any deformation.

The wedge or triangular shaped granulite-charnockite terrain having contrasting grade of metamorphism and lying between 1) rocks of Delhi Supergroup and 2). Erinpura granite suggests that it is an allochthonous or dismembered body.

The present high grade granulite-charnockite terrain of the study area therefore represents an obducted slice of the Pre-Aravalli basement similar to the Phulad ophiolite obduction. Ductile shearing and obduction of the dismembered basement is responsible for the occurrence of a wedge of the granulite-charnockite rocks in the study area. The NW steep dipping Kui-Chitrasani fault as a matter of fact represents a counter tectonic thrust plane. This model satisfactorily explains the occurrence of undeformed Erinpura Granite to the west of granulite terrain and low grade Delhis to its north and east.

DISCUSSION

The regional lineament extending from west of Ajmer to Palanpur coincides with the gravity lineament. This perhaps suggests the subsurface continuity of a regional tectonic feature - in this case an obducted slab of the basement (granulite fadcies) from Balaram (north of Palanpur) to Sandmata Complex of probably Pre-Aravalli (? Archaean). This is supported by a sharp increase gravity in magnetic profile northeast of Balaram suggesting the basic- ultrabasic basement.

Thus the Balaram-Abu Road area represents a tectonic slice of Pre-Aravalli basement, uplifted by obduction at the collision margin of a northwesterly moving Indian plate against the old crustal block at the convergent margin of the Kui-Chitrasani tectonic lineament.

TECTONOMETAMORPHIC EVOLUTION

On the basis of geophysical data, it has been postulated by Srikarni et al (op cit) that there is a possibility of sub-surface continuity of a regional tectonic feature - in this case - an obducted slab of the basement from Balaram (North of Palanpur) to Sandmata complex through Bhim-Karera-Bandanwara of probably pre-Aravalli (? Archaean).

If the surmise that Balaram - Abu Road area represents subsurface continuity of Sandmata area is logical, then the granulite facies rocks of Sandmata & Balaram Abu Road area through Bhinai-Bandanwara (Bhim-Karera) define a polymetamorphic terrain that shows two contrasting but overlapping PT paths. Sandmata-Bhinai-Bandanwara (SinhaRoy op cit, Sharma, op cit, Gyani et al, op cit, Dasgupta et al, op cit) indicate that the first metamorphism had an "anticlockwise PT path" with time and was terminated by isobaric cooling to a stable crustal geotherm. In contrast the metamorphic episodes (M1-M2) in Balaram-Abu Road area define a "reworking" (Goscombe et al op cit) and followed a "clockwise P-T path" (i.e. decreasing P-T with time) terminated by Isothermal decompression and cooling (6-7 kb) on a stable crustal geotherm.

Balaram Abu Road area being a low pressure granulite province (Desai et al, op cit) is bound to show decompression (clockwise PT path) during minimal cooling (Young et al op cit); and in their subsurface continuity, the higher pressure granulite of Sandmata-Bhinai of central Rajasthan is bound to exhibit evidences for isobaric cooling paths. (anticlockwise PT trajectory, Bohlen, op cit, Young et al, op cit).

Thus the granulite facies metamorphic terrain is correlatable with that of Sandmata area & is thus pre-Delhi. Although the reworking of granulite facies rocks has also to be related to (i) Pre-Delhi collisional tectonics (ii) a temporally & tectonically unrelated tectono-thermal cycle attributable to Delhi orogeny.

With the help of geophysical (gravity) data Srikarni et al (1996) had shown that the present granulite province is the southwestern continuity of Sandmata complex, Bhinai, Bhim-Karera areas of Rajasthan (Chapter-VIII)

The age of the Sandmata granulites, has been debated by different workers. These are stratigraphically positioned in the Banded Gneissic Complex (Bhilwara Supergroup) (Gupta et al, 1992, Sinha-Roy et al, 1998). These have been considered to be

Proterozoic (Roy, 1996). The upper age limit is constrained by the enderbite plutons intrusive into the granulites in Sandmata Complex at 1730 Ma (Sarkar et al, 1989). So all the granulites are certainly older than 1730 Ma. As the geophysical studies suggest that the study area is the southern continuation of Sandmata Complex, these granulites too, can be safely considered to be even much older than 1730 Ma.

Another mute question in the area is the relationship between the granulite facies complex (pre-Delhi ?) and adjoining amphibolite facies terrain (Delhi). There is a sharp difference in the PT conditions of metamorphism and also in the tectonic styles in the two terrains. This boundary is marked by the development of a ductile shear zone

Thus the amphibolite-granulite facies contact in the study area (similar to one in Sandmata area) does not indicate a zone of progressive or retrogressive metamorphism. Instead, one is looking at two crustal sections juxtaposed against each other probably due to differential uplift **(Fig. 10.1)**.

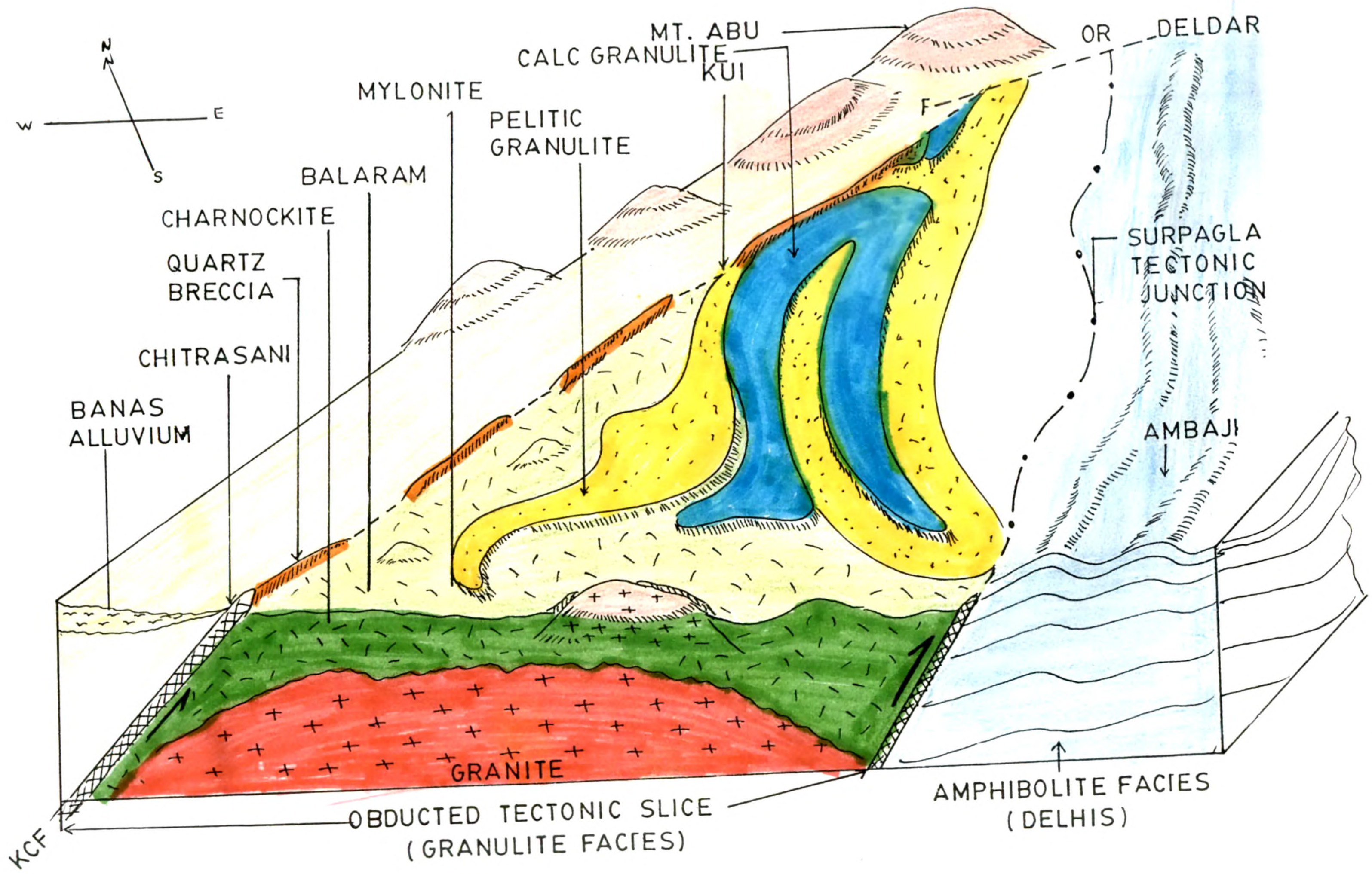

FIG. 10.1 SCHEMATIC BLOCK DIAGRAM SHOWING THE RELATIONSHIP BETWEEN GRANULITES AND AMPHIBOLITE FACIES ROCKS IN THE REGION