CHAPTER IV

D E L H I   S Y S T E M

STRATIGRAPHY

The rocks of the Delhi system in this part of North Gujarat exhibit the usual sequence of arenaceous, argillaceous and calcareous metasediments. Deformation and granite intrusion have considerably modified the nature of these rocks, but looking to the regional picture these ideally fit in with the typical Delhi succession. The author following Heron (1953) and Pascoe (1965,p.404, 409) has correlated these rocks with the neighbouring areas as under:-

Idar (study area)	Sirohi area	Udaipur area	
3. Calc-gneiss and crystalline limestone.	3. Calc-gneisses, calciphyre & amphibolitic rocks.	4. Calc-gneiss & crystalline limestone.	Ajabgarh
2. Biotite-gneiss	2. Mica-schists, phyllites with amphibolitic rocks.	3. Calc-schists	
		2. Biotite schists	
1. Quartzite	1. Quartzites	1. Basement quartzite	Alwar

The Delhi rocks of Idar-Vadali form the southernmost extremity of the Delhi synclinorium. The main syncline which is fairly narrow in the Mewar region, considerably opens up southward and in the Idar area, it forms a fairly wide structure. Being the hinge region, on account of the presence of a large number of minor folds, the various formations show varied and repetitious outcrops. The Idar-Vadali area lies on the eastern portion of the synclinorium hinge and the structure resembles a distorted Z shape, whose constituent folds show varied geometry. Extensive intrusions of granite have considerably obliterated the fold pattern. The basal quartzites are almost entirely displaced by the granite and the overlying biotite schists have been changed over to gneissic rocks. Thus, the fold pattern is visible only in the calc-gneisses in the northern part of the area.

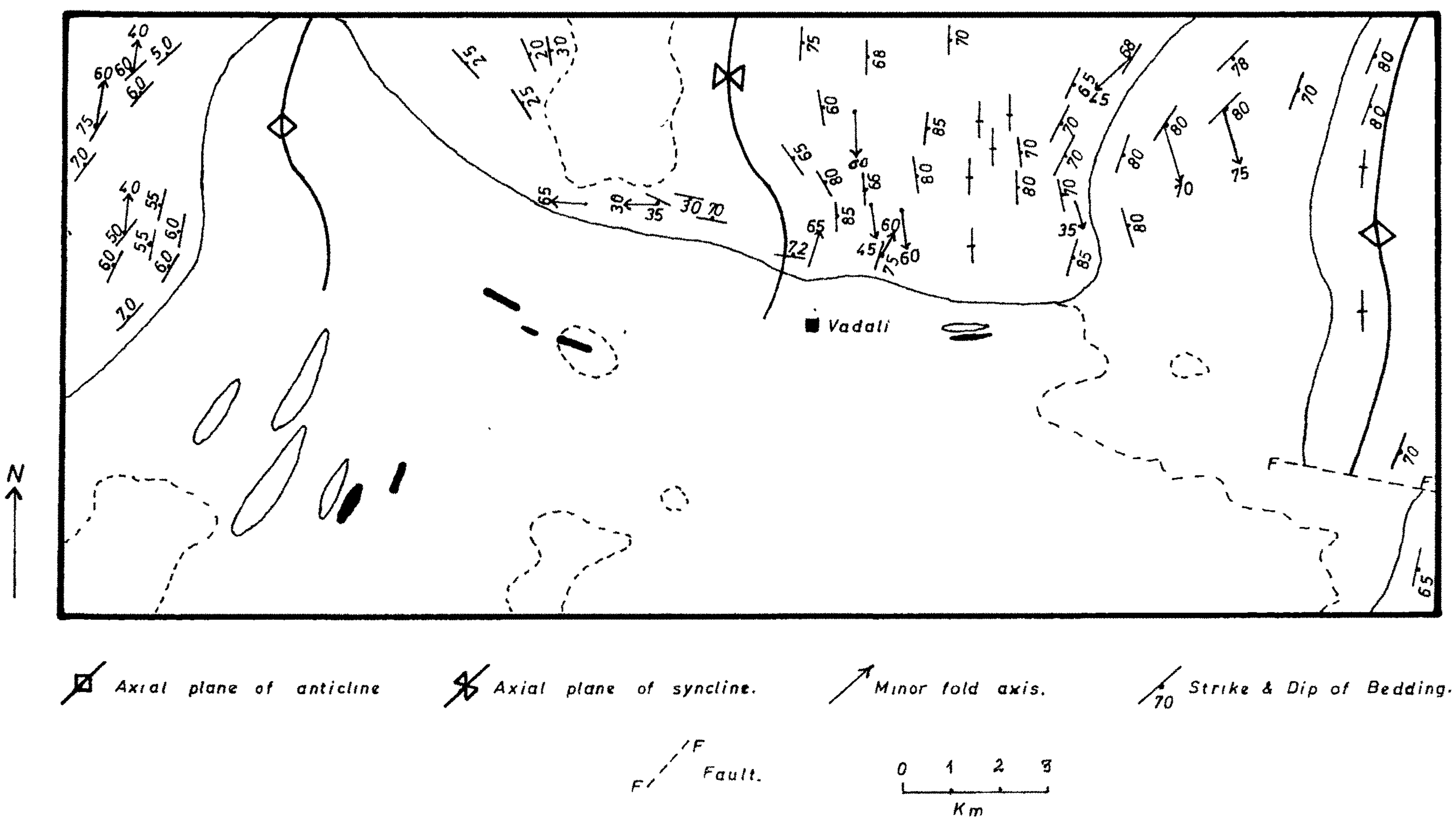
STRUCTURE

From E. to W. the structure constitutes a syncline and an anticline. The easternmost limb is almost vertical and strikes N.-S., while the other limb of the syncline is moderately dipping due N.E. The limb of the complimentary anticline in the W. strikes N.E.-S.W. and dips due N.W. Obviously the folds are plunging due N. There seems to be a progressive opening up of the folds from E. to W. The quartzite hill of Chorivad itself constitutes a very tight anticlinal structure and the calc-gneisses of Vadali show a large number of isoclinal minor folds related to the Chorivad anticline. Structurally, the exposures of these calc-gneisses showing a regional trend of N.N.E.-S.S.W. and steep dips (comprising the eastern limb of the syncline) are very interesting (Fig.-IV.1). A careful analysis of the structural elements of this portion reveals a succession of deformations to which the rocks were subjected.

Although the author did not carry out a detailed and systematic structural mapping, yet he collected adequate information so as to work out the structural history in a fair detail. In all 211 foliations (= bedding) and 108 lineations (= fold axis) readings from the different parts

Fig. — IV.1.

Sketch map showing the structure of the Delhis



of the calc-gneiss band were stereographically plotted and analysed. Taking into consideration the outcrop pattern, foliation trends and the behaviour of minor fold axes, the author could make out that the calc-gneisses have undergone two episodes of folding. The main Delhi folding comprises the early deformation with a N.N.E.-S.S.W. general trend. Over this is superimposed another fold whose axial plane strikes N.W.-S.E. Of course the late folding is only a local phenomenon and perhaps is related to the stresses generated during emplacement of Idar granites of Erinpura age. The effects of cross-folding are maximum in the easternmost portion of the calc-gneisses. In the exposures N. of Vadali, calc-gneisses abundantly show refolded folds and 'eyed-folds'.

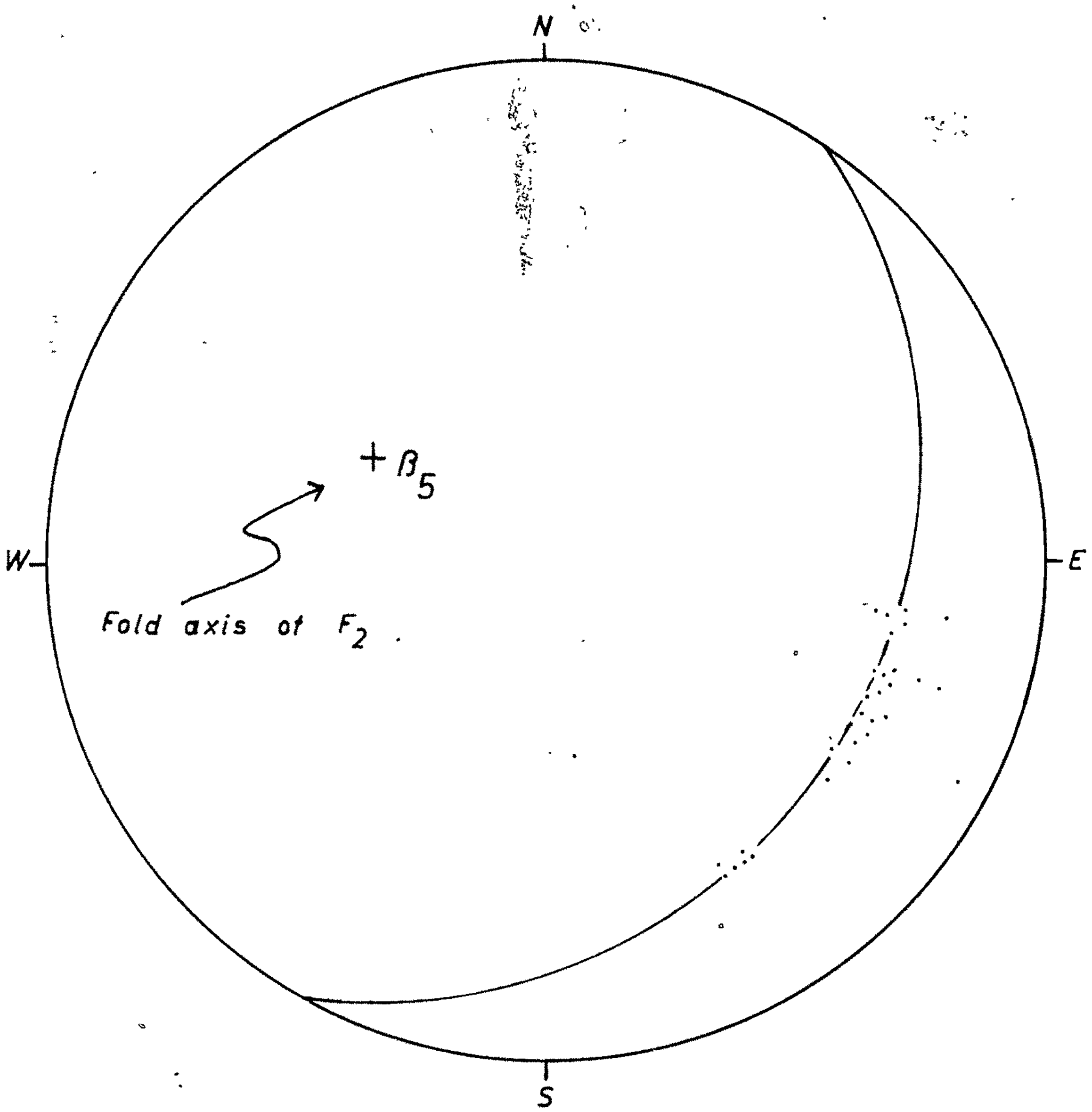
Structural Analysis

The diagrams of western, central and eastern exposures (Figs.-IV.2,3,4) clearly show that the later folding took place on two axial planes, N.E.-S.W. and N.W.-S.E. of which the latter is the most prominent. Both the axial planes dip steeply due N.W. and S.W. respectively. The superimposition of flexures on the above two axial planes on a pre-existing folded sequence has given rise to considerable structural complexity.

Fig. - IV. 2

Stereograms of we

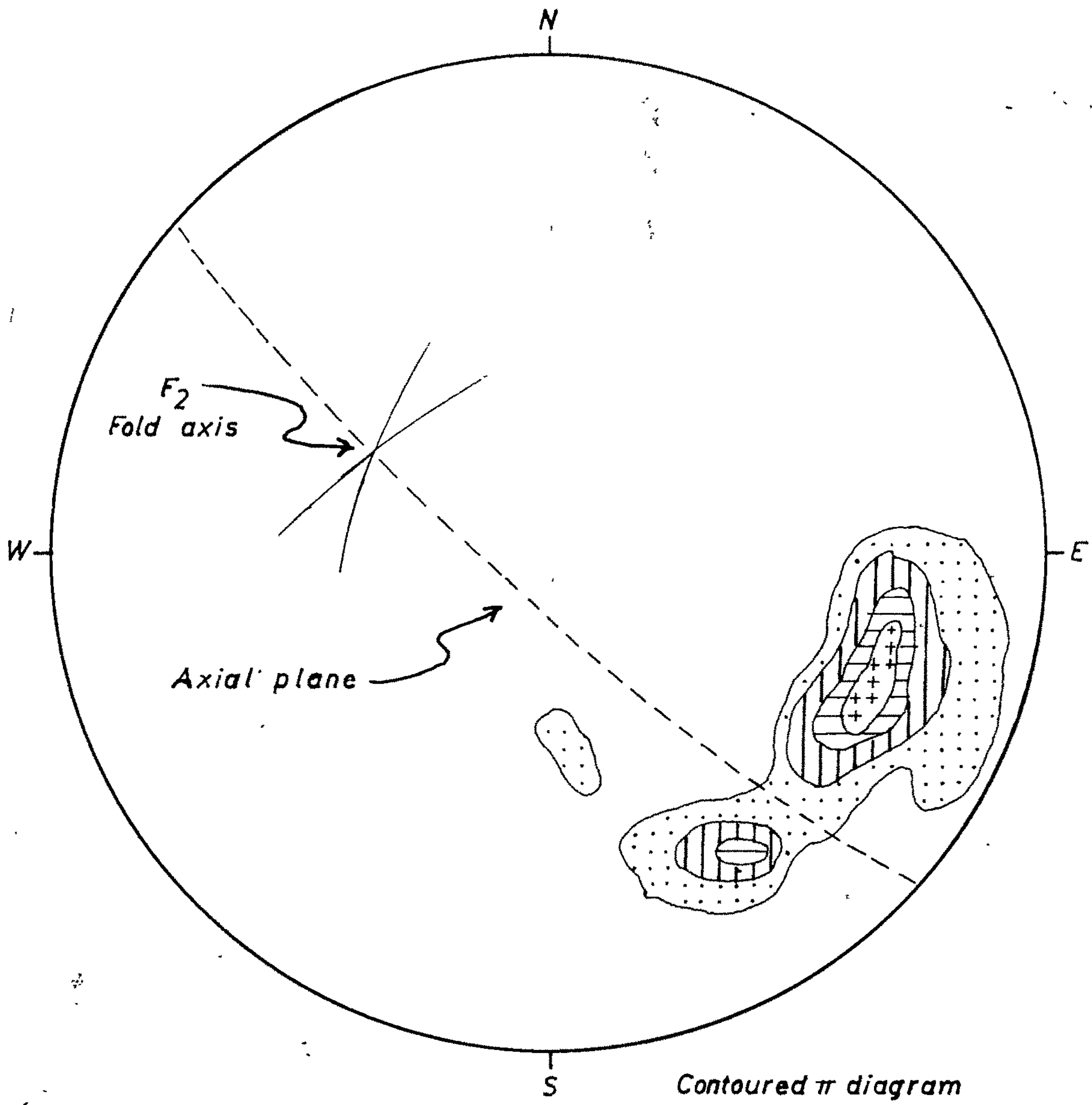
A



Foliation poles (30) ·

stern exposures of Delhis.

B

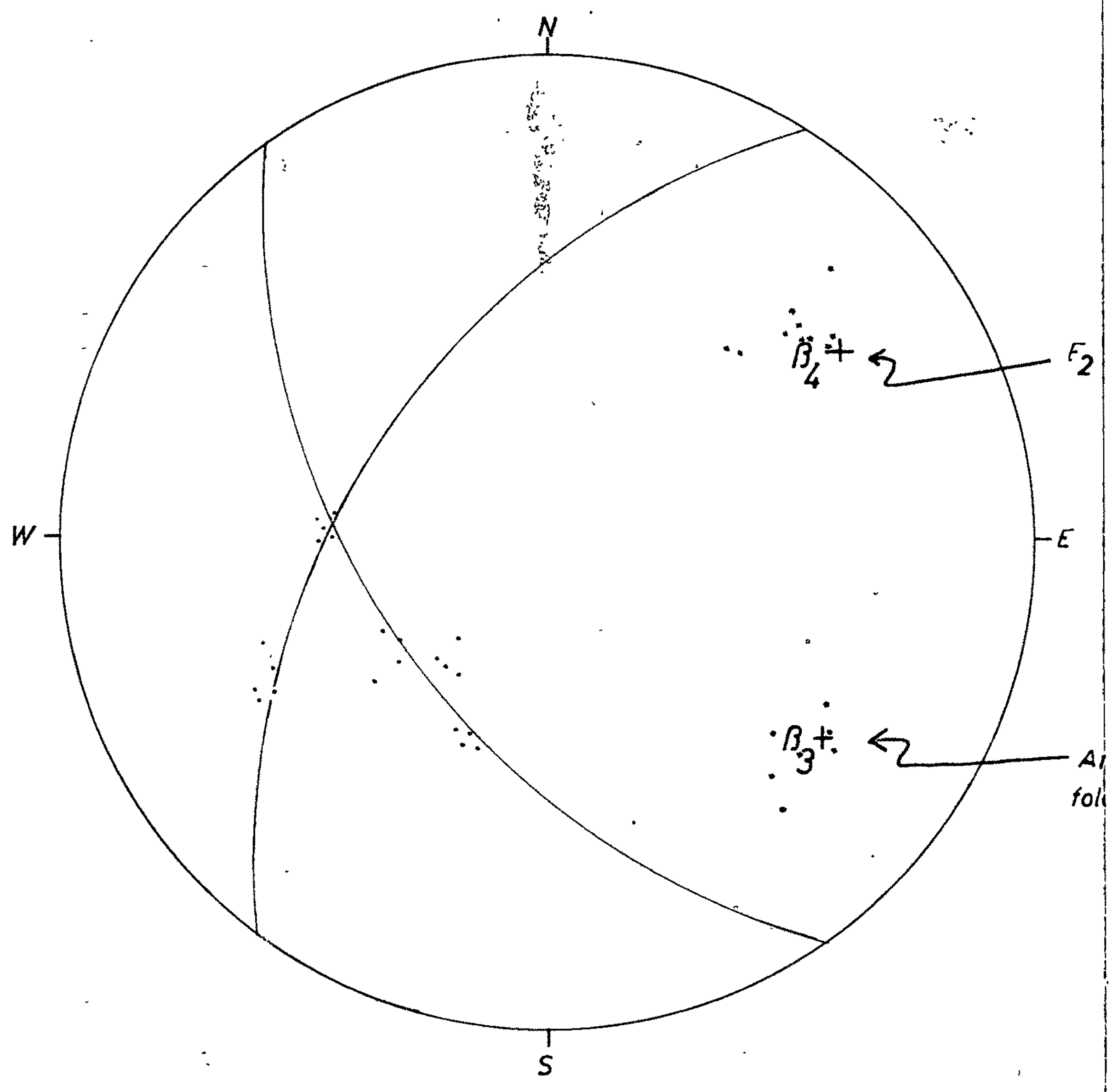


Contoured π diagram of foliations (30)

Fig.- IV. 3

Stereograms of central

A

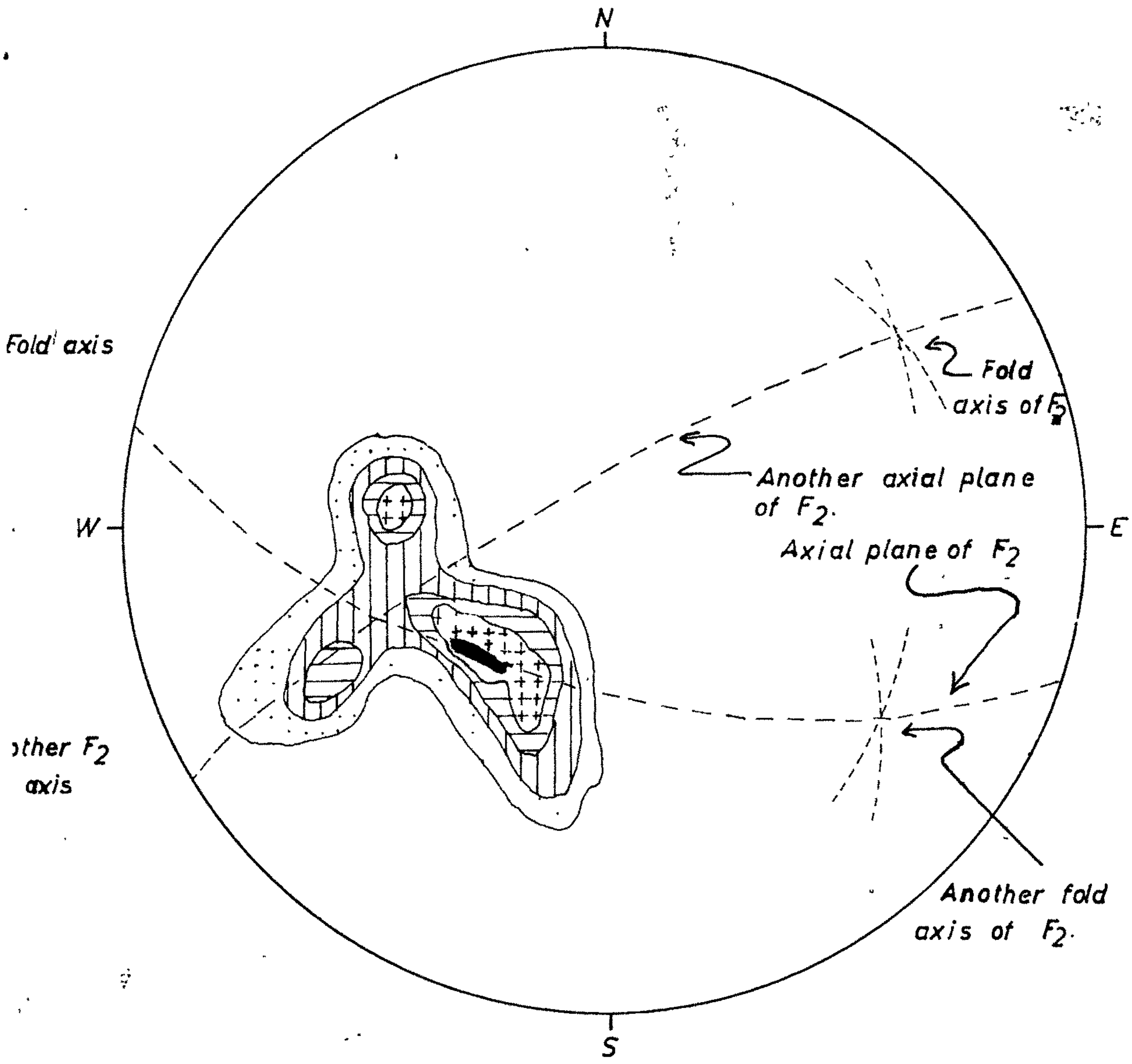


π- diagram showing foliation poles, and fold axes of F_2.

Foliation poles (24). - .
Minor fold axes related to F_2 (17) - •

exposures of Delhis.

B



Coutoured π diagram showing the two axial planes and the two fold axes of late folding F_2.

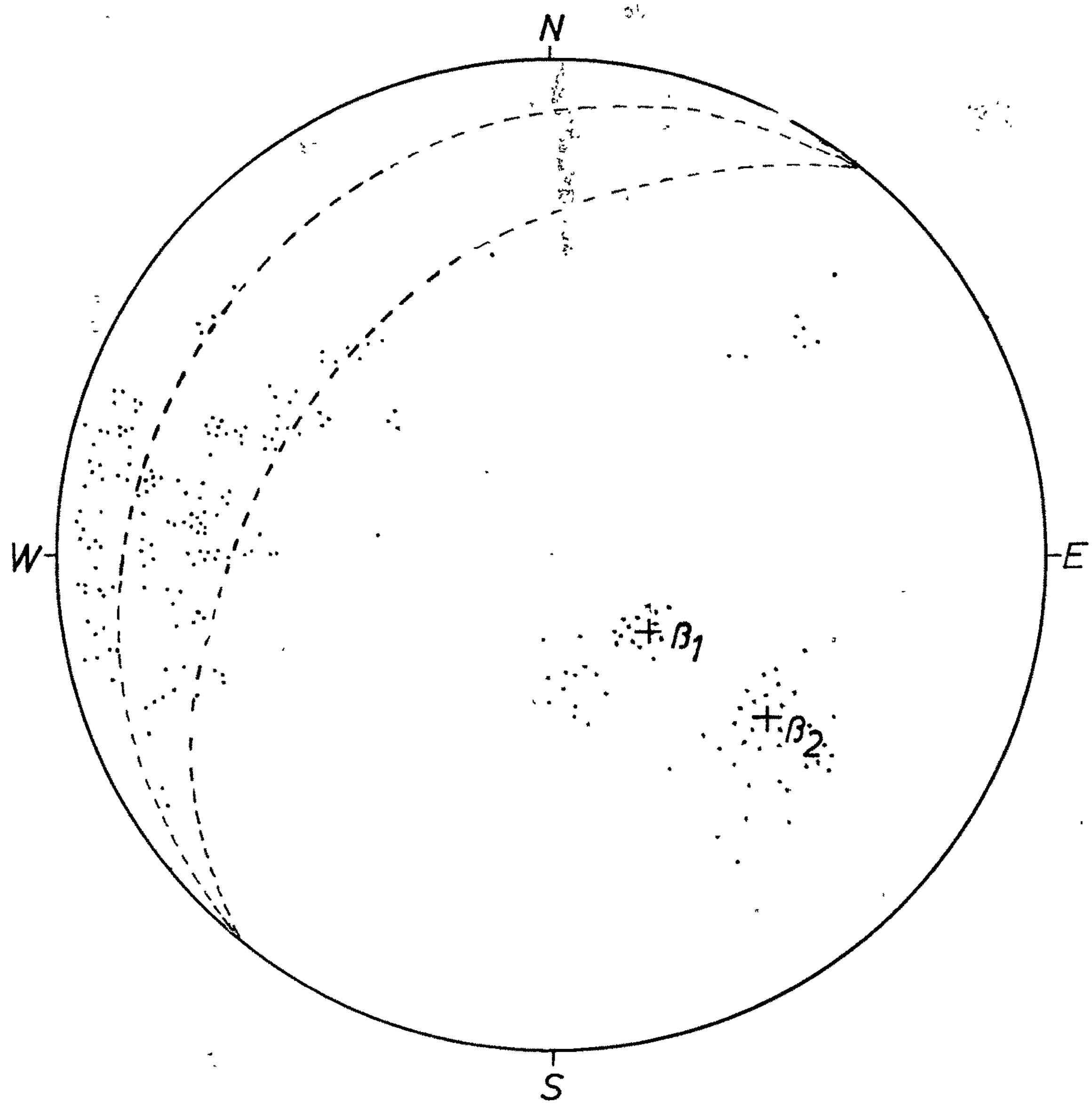
0-1 %	12-18 %
1-6 %	18-24 %
6-12 %	>24 %

Minor fold axis related to F_2.-

Fig.- IV.4

Stereograms of eastern

A

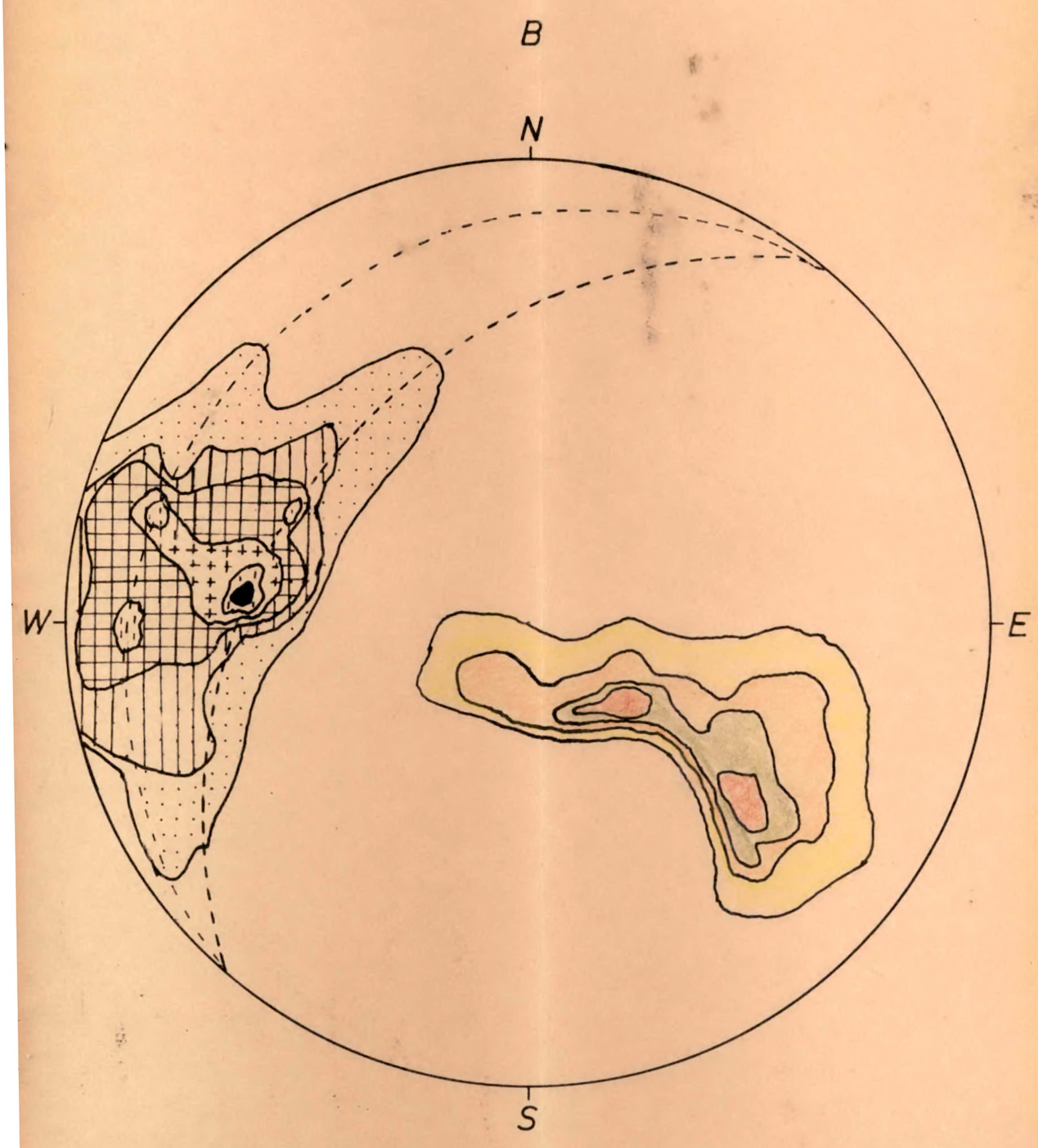


π-diagram of foliations showing the effects of F_2 folding on the two limbs of F_1

Foliation poles (153) - ·

Minor fold axes of F_2 (88) - •

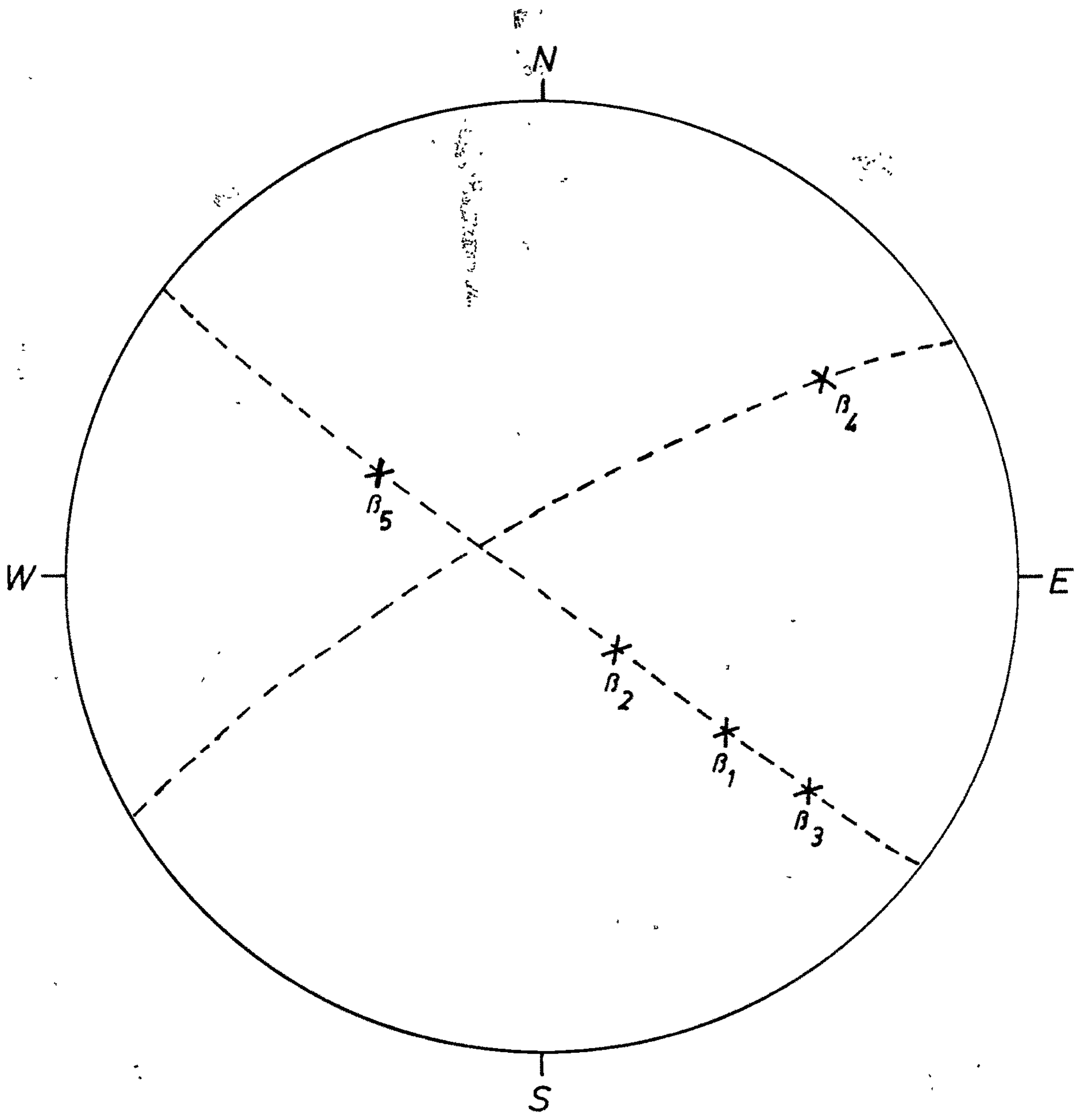
exposures of Delhis.



Contoured π - diagram of foliations (153) and fold axis lineations (58)

Fig.— IV. 5

Synoptic stereogram showing the F_2 fold axes in different exposures of the Delhi's



All ß axes lie along NW-SE axial plane

$ß_1$ & $ß_2$ Fold axes in eastern exposures

$ß_3$ & $ß_4$ Fold axes in central exposures

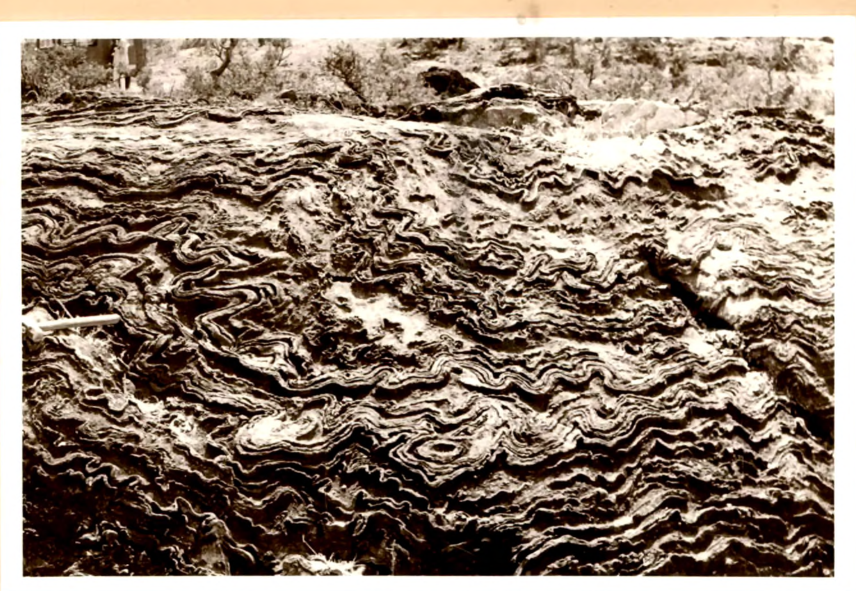
$ß_5$ Fold axes in western exposures

The axes of the minor folds related to the late folding (F_2) show a variety of orientation (Plate-IV.1).

As the F_2 folds were superimposed on the various limbs of F_1 folds, depending on the orientation of those limbs, the fold axes of F_2 show different orientations and plunge. The plots of the F_2 axes in the three sub-areas (parts), though showing different orientations, all lie on the axial plane of F_2 (Fig.-IV.5). The F_2 fold on S.W.-N.E. axial plane are not very common, but they are numerous enough to be noted. These two facts fully explain the wide variation noticed in the F_2 fold axes.

A careful scrutiny of the calc-gneisses shows double folding and also indicates that the orientations of the axial planes of early fold (F_1) have controlled the development of 'eyed-folds' and refolded folds. It is commonly observed that the axial planes of the minor folds of F_1 in the eastern exposures of calc-gneisses are either vertical or steeply inclined due E. or W. Whenever F_2 minor folds are superimposed over the 'upright' F_1 folds, 'eyed-folds' have developed, while the superimposition of F_2 on 'inclined' F_1 folds have

PLATE-IV.1



Calc-gneiss showing superimposition of N.E.-S.W. and N.W.-S.E. late folds (Loc: Patera dam) given rise to refolded fold pattern with F_2 axes plunging due E. or W. The orientations of the F_2 fold axes in turn, have been dependent on the (i) axial plane of F_2 and (ii) the original attitude of the folded surface (Fig.-IV.6).

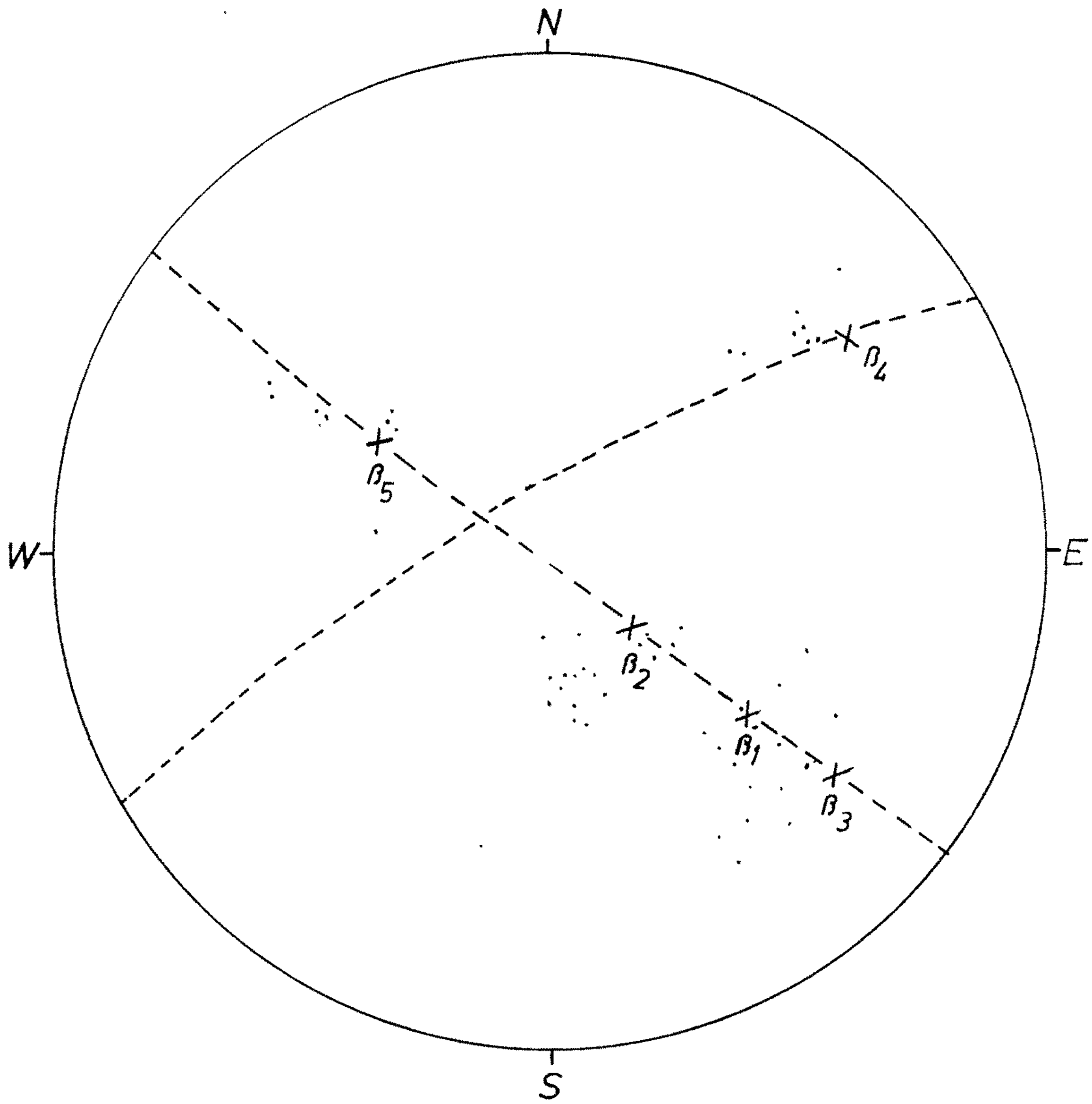
The overall effect of the F_2 folding on the F_1 fold axes is not very clear, but in a broad manner the F_2 fold being of the nature of a conjugate anticline, the originally north plunging fold axes are now showing a southward plunge (Fig.-IV.7).

Discussion

As stated earlier the F_1 folding is the dominant structure related to the Delhi orogeny. The various folds tight as well as open, comprise a portion of the Delhi synclinorium. It is however, not clear as to how and when the F_2 folding was superimposed. The cross-folding is a local phenomenon and the author from this limited study is not in position to throw light on the regional extent of the late folding. He however believes that in the present case, the doming up was due to a lateral push from the S. during the intrusion of granite (Erinpura age) which was responsible for the development of a conjugate set of F_2 folds in the calc-gneisses.

Fig.- IV. 6.

Stereogram showing the position of F_2 fold axes.



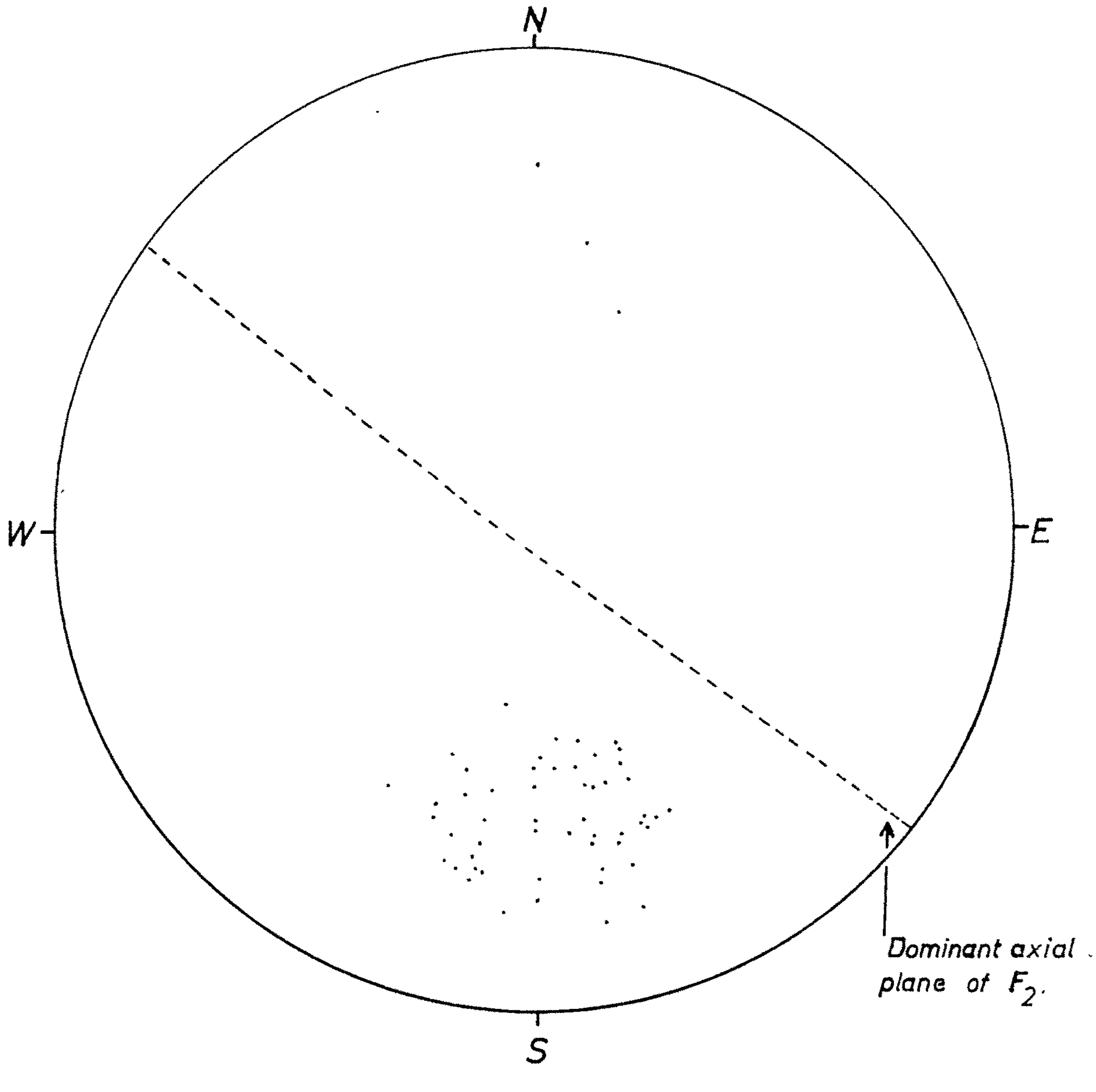
The variation in the minor fold axes due to the original attitude of folded surface and axial plane of F_2.

Minor F_2 fold axes (52) - ·

Fold axis of F_2 - β

Fig.- IV.7.

Stereogram showing fold axes related to early F_1 folding



The F_1 fold axes mostly seen plunging due S due to F_2.

Fold axes (55) - ·

ROCK TYPES

Quartzites

These quartzites comprise the base of the Delhi system and are exposed all throughout the eastern border of the study area. The distribution and field characters of these arenaceous metasediments have already been described in the previous chapter. Here the author proposes to elaborate on their megascopic and microscopic characters.

The quartzites from this formation belong to the following two main types:-

1. Massive and entirely quartzose (with only a very subordinate mica content).
2. Somewhat flaggy and with an appreciable mica content.

Massive quartzite: It consists entirely of quartz grains which show a considerable range in grainsize . Generally these are grey or buff coloured rocks devoid of any foliation. Under the microscope, the thin sections show an interlocking mosaic of sutured quartz grains. No other mineral except a few tiny specs of white mica (muscovite, sericite) are present. Larger quartz crystals perhaps represent the original detrital grains while the finer aggregates might be the recrystallised siliceous cement (Plate-IV.2). Such texture has been referred to by Read (1931, p.46-48) as 'granulated type'.

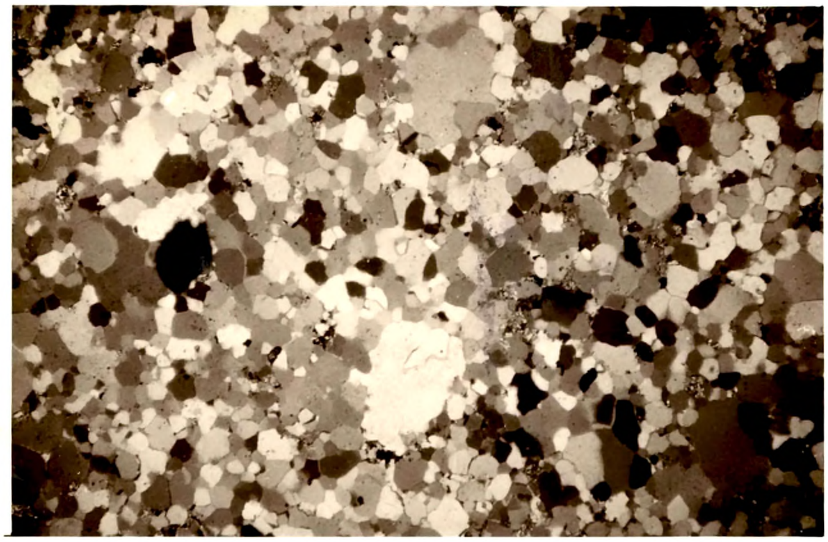
Flaggy quartzite: This variety is less massive and shows a tendency for flagginess. Medium-grained and somewhat greyish, these quartzites are seen to contain a small but significant proportion of micas and a little feldspar. In thin section, the quartz grains are essentially 'tesselate' (Macgregor, 1951, p.56) and show sharp and straight mutual contacts (Plate-IV.3). Micas- both muscovite and biotite, form tiny flakes and occur as discrete individuals uniformly scattered, or form thin and discontinuous streaks. The feldspar - an orthoclase, is only occasionally recorded.

The above mentioned two quartzitic types occur in intimate association and it is not possible to delineate them in the field. Obviously, the texture and mineralogy of these two, reflect the nature of the original sediment, the micas and feldspar suggesting argillaceous impurities.

Biotite-Gneisses

These gneisses overlying the quartzites are evidently a migmatised pelitic formation. From their field characters and petrographic study these amply reveal their metasomatic

PLATE-IV.2



Photomicrograph (X30) of Delhi quartzite showing granulated type of texture.

PLATE-IV.3

Photomicrograph (X30) of Delhi quartzite showing tesselate type of texture.

origin. The author has found them to have derived from the pelitic schists by a progressive contact migmatisation brought about during the granite emplacement. In the field itself, this fact is clearly established. From the geological map of the area it is seen that the most of the granite, after breaking through basal quartzitic formation transformed the biotite schists into gneissic granite. On tracing the nature of these gneisses towards the granite massifs of Idar it is evident that the grain size, texture and feldspar content progressively increase, and the biotite gneisses merge into gneissic granite. Based on the increasing migmatisation the gneisses have been classified into following four varieties:-

1. Feldspathised schist
2. Fermeation gneiss
3. Sub-augen gneiss
4. Augen gneiss

Of course it should be understood that one variety merges into the other without any clearcut boundary.

<u>Feldspathised schist</u>: This is the transitional rock which with decrease of feldspar content would grade into the mica schist while with the increase of the same

mineral the rock grades into permeation gneiss. This rock shows an initial stage of feldspathisation.

It is a dark coloured almost schistose rock, highly micaceous and containing small feldspar grains (Plate-IV.4).

Texturally, these rocks are fairly coarse grained. The foliation is characterised by parallel or sub-parallel flakes of mica, the intervening spaces filled with aggregates of quartz and little feldspars.

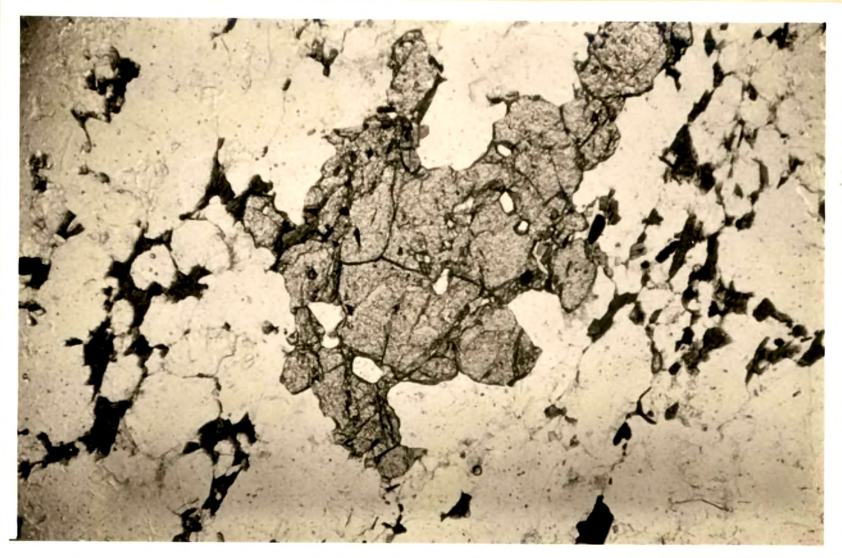
Quartz is the dominant mineral and most of it appears to be the original constituent of the schist. However, some quartz grains, interwoven with plagioclase might have been introduced by the later granitic emanations.

Feldspars are both plagioclase and microcline, the former dominates. Plagioclase (An_{34-36}) forms small grains which are seen occuring scattered in the foliated mass suggesting its introduction in the original schistose matrix. The plagioclase is quite fresh, unaltered except for some bigger grains which show alteration to sericite. It contains tiny inclusions of quartz and mica, and the mineral is recognised by its characteristic polysynthetic twinning, and refractive index higher than the canada balsam. Microcline is only occasionally present and when

PLATE-IV.4

Feldspathised garnet-mica-schist with some veins and pods of more feldspathic material (Loc: Damavas).

PLATE-IV.5



Photomicrograph (X30) showing skeletal garnet in feldspathised schist.

present it is in small quantity only, and confined to the groundmass.

Biotite is dominant and occurs as small flakes marking the schistosity. It is strongly pleochroic with

X = yellow

Y = Z = dark greenishbrown

$X < Y = Z$

The bigger flakes (about 3 mm.) are riddled with tiny quartz inclusions.

Muscovite forms slender flakes and occurs in association with biotite. Some of the muscovite appears to have derived from biotite.

Garnet is seen forming irregular skeletal isotropic grains of variable size (Plate-IV.5).

Accessory minerals comprise stray needles of apatite, grains of magnetite and zircon.

Permeation gneiss: This variety represents one further stage of migmatisation, and is more feldspathic than the previous variety. It shows development of thin feldspathic streaks parallel to foliation in addition to the scattering

PLATE-IV.6

Permeation gneiss showing stripped appearance
(Loc: Medh)

of feldspar grains in the groundmass. The rock has a striped appearance (Plate-IV.6).

Under the microscope, the quartz and feldspar are seen to form a granoblastic streaky aggregate with alternating less feldspathic micaceous layers. Parallel flakes of mica characterise foliation.

Quartz occurs as fairly big grains with semisutured contacts. Occasionally they show a flattened habit parallel to the foliation. Most of the quartz that occurs in association with micas appears to be the original constituent of the schists, while those quartz grains which show bigger size, are sutured and interlocked with feldspar seem to have been added later on.

Feldspars are represented by plagioclase and microcline and the total feldspar content is almost equal to that of quartz. Plagioclase (An_{30-32}) however is more than microline, and occurs as equant grains showing inter-growth with quartz. It shows characteristic polysynthetic twinning. Microcline content is subordinate to plagioclase and is mostly confined as interstitial grains in the groundmass.

Biotite occurs as clusters of thin and slender flakes oriented in the direction of the foliation. It is also found as small scattered flakes in the rock. It is pleochroic from yellow to greenish brown

X = yellow

Y = Z = greenish brown

$X < Y = Z$.

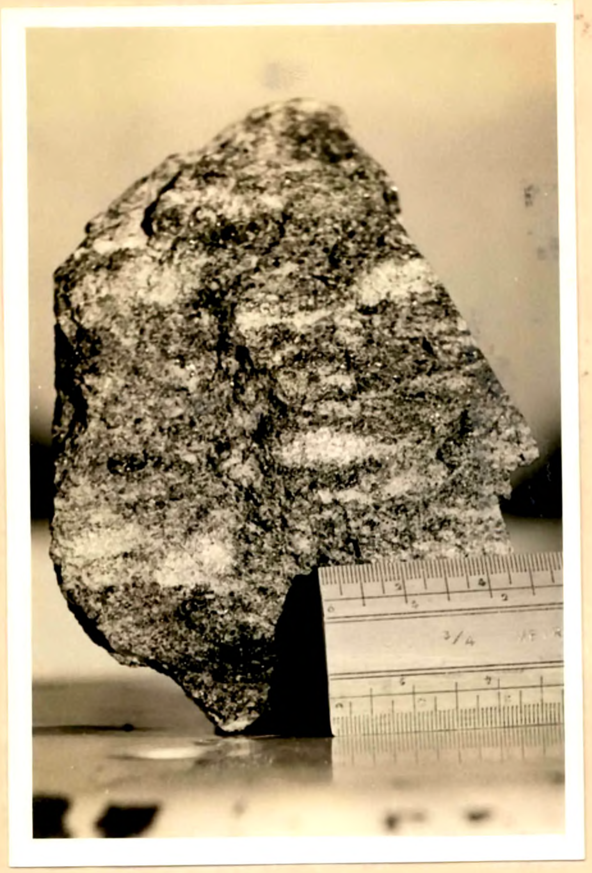
Muscovite is much less as compared to biotite and occurs as long flakes in association with biotite.

Accessory minerals are apatite and magnetite.

Sub-augen gneiss: With further advancement in granitisation, the permeation gneiss changes to sub-augen gneiss. The streaks of feldspathic material of the permeation gneiss swell to form incipient augens and give rise to this type, which represents an intermediate stage between augen-gneiss and permeation gneiss.

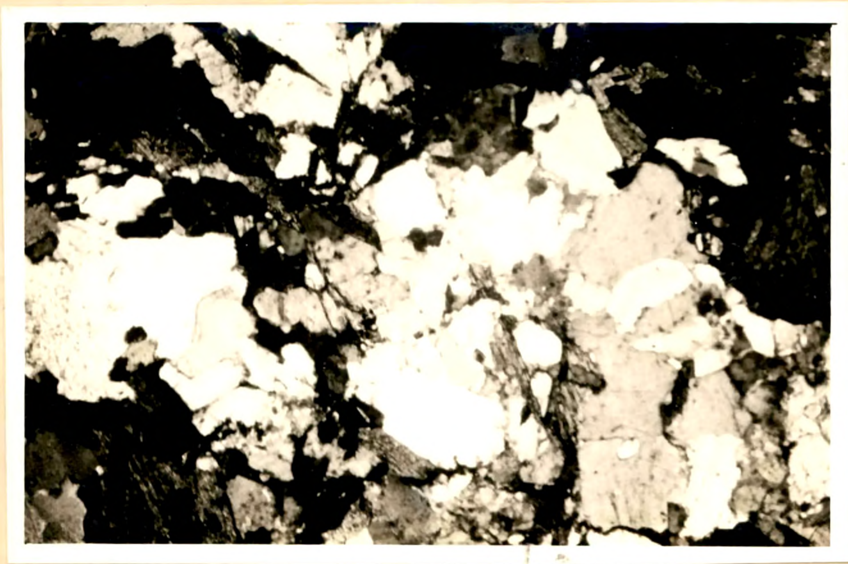
It is a medium-to coarse-grained greyish rock containing ill-developed augen shaped feldspar aggregates. The gneissic structure is characterised by the parallel arrangement of augens and streaks of feldspars and quartz grains within micaceous foliae (Plate-IV.7).

PLATE-IV.7



Sub-augen gneiss showing incipient growth of feldspar augens (Loc: N. of Badol).

PLATE-IV.8



Photomicrograph (X40) of sub-augen gneiss showing development of quartz and feldspar aggregates in the form of augens.

Quartz shows a variety of modes of occurrence. Its size varies considerably from fine grain in groundmass to rather coarse porphyroblasts. It is seen to form elongate aggregates of polygonal grains with smooth outlines. Some quartz grains also show a dimentional orientation. Quartz also occurs as inclusions in feldspars.

Plagioclase (An_{28-30}) occurs both in the groundmass and also as augen-shaped porphyroblastic aggregates. In the groundmass, it occurs in association with quartz and micas, and is recognised by its characteristic lamellar twinning. In composition it is mostly an Oligoclase. The augens seem to have grown along foliation and mica flakes therefore wrap round them (Plate-IV.8). The mineral grains are fresh and contain quartz inclusions.

Biotite is seen to occur as small scattered flakes as well as bigger laths arranged in the form of elongated tufts. Individual flakes within such tufts show parallelism with the elongation of such clusters which mark the general foliation. The orientation of the flakes is considerably disturbed due to the growth of plagioclase porphyroblasts. It shows pleochroism from yellow to greenish brown

X = yellow

$Y = Z$ = greenish brown

$X < Y = Z$.

Apatite is the only accessory mineral.

Augen gneiss: Due to increasing granitisation the sub-augen gneiss changes over to augen gneiss. These are quite coarse gneissic rock with numerous eye shaped feldspar augens developed along the foliation. These augens grow quite often into discrete euhedral to subhedral porphyroblasts. With increased content of such porphyroblasts, the rock merges into gneissic granite.

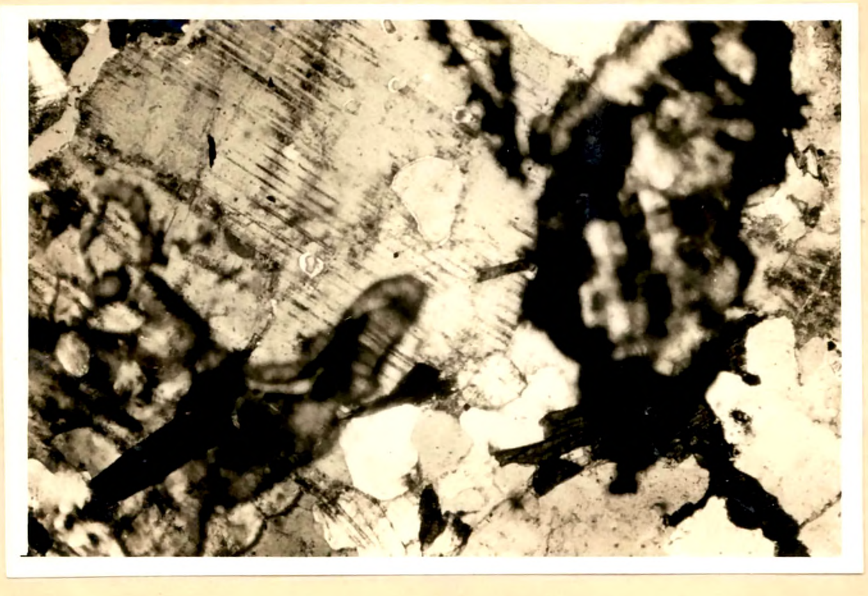
This gneiss represents an advanced stage of transformation of biotite schists to feldspathic rocks.

The study of the rock has revealed that the texture is porphyroblastic with large crystals of plagioclase, embedded in the coarse gneissic groundmass. The feldspar augens are developed fully in this rock and form 'eye' shaped grains which lie in the plane of foliation(Plate-IV.9). With the increase in quartzo-feldspathic content, the size of the 'eye' shaped augens increases and they

PLATE-IV.9

Augen gneiss showing eye-shaped porphyroblast (Loc: Hathoj).

PLATE-IV.10



Photomicrograph (X30) of augen gneiss showing porphyroblast of plagioclase with some microcline.

progressively show random orientation as a result of which gneisses gradually lose foliation and become massive. Biotite forms small clusters throughout the rock instead of bands or lenses. Ultimately, the rock is so much enriched in quartzo-feldspathic material that the gneiss gradually passes into gneissic granite.

Quartz is found in all sizes from small grains forming mosaic in the groundmass to big grains. The larger grains occur as elongated aggregates. It also occurs as inclusions in feldspar augens.

Plagioclase (An_{24-28}) is one of the most abundant constituents of the rock and almost equals the quartz in amount. The plagioclase in composition, is an Oligoclase. It occurs in groundmass as well as in the form of big porphyroblasts (Plate-IV.10). In groundmass, it occurs in association with quartz, microcline and mica. It is recognised by its characteristic lamellar twinning. The augens are generally seen to grow along foliation and only occasionally found cutting across it. It contains inclusions of quartz.

Microcline occurs in subordinate quantity, occupying interestitial spaces in the groundmass. It can easily be identified by the presence of cross-hatching.

Mica is mainly represented by biotite, with a few flakes of muscovite. Biotite occurs in the form of clusters or tufts with stray intergrown muscovite flakes. Each of the clusters show a crude orientation parallel to the foliation while individual flakes of biotite within the clusters quite often display a 'decussate' arrangement. The mineral is pleochroic with

X = brownish yellow

Y = Z = dark greenish brown

$X < Y = Z$.

Accessory minerals are apatite and magnetite, which occur as tiny grains.

Quartz-diopside rock: The biotite gneisses contain thin lenses of calc-silicate rocks. These represent originally impure calcareous sandy layers in pelites and now in their metamorphosed and granitised state show an interesting mineralogy.

In hand specimen, they seem to be a coarse to medium-grained pink rock, quite compact and massive. Under the microscope, rock shows a granular aggregate of quartz, diopside, plagioclase, microcline, biotite and zircon.

TABLE-IV.1

CHEMICAL ANALYSES OF BIOTITE-GNEISSES

Wt. %	Feldspathised garnet mica schist 682 & 683	Permeation gneiss 56/69 & 666	Sub-augen gneiss 627	Augen gneiss 601
SiO_2	66.31	68.10	69.00	70.01
TiO_2	00.92	00.78	00.67	00.60
Al_2O_3	15.20	16.03	16.02	16.50
Fe_2O_3	03.00	02.04	01.85	01.05
FeO	05.09	04.32	03.20	01.39
MgO	02.40	01.83	01.10	00.99
MnO	01.30	00.77	00.57	00.45
CaO	02.00	02.25	02.41	02.55
Na_2O	01.33	01.95	03.01	03.49
K_2O	03.10	02.90	02.75	02.99
P_2O_5	00.03	00.05	00.05	00.04
TOTAL	100.68	101.02	100.63	100.06

Analyst: Paresh Raval

<u>Chemical characters of gneissic rocks:</u> Table IV.1 gives the chemical analyses of typical representatives of the various gneissic types.

<u>Calc-Gneisses</u>

Calc-gneisses that overlie the migmatised schists (biotite-gneisses) are the most striking and interesting formation. Originally they were a group of well stratified calcareous rocks containing sandy and argillaceous impurities, and now in their metamorphosed state, show a characteristic banded and gneissic rock, the different bands showing variation in shade, mineralogy and texture. The calc-gneisses are seen invariably intruded by aplitic veins. These quartzo-feldspathic veins with varying thickness have invaded the rock along the foliation and follow the same trend.

The field characters of the calc-gneisses have already been briefly alluded to earlier in Chapter III. The structural geology of these rocks as already discussed is very interesting, and these rocks led the author to work out quite precisely the deformational history of the area. Petrographically too, these metamorphosed calcareous rocks are very interesting. The original lithological variation from layer to layer is reflected in the present mineralogical assemblages. Allowing some minor addition of quartz and microcline during the granite emplacement, the mineralogy of these rocks suggests following types to which the various layers can be assigned.

Type (1) Dominantly siliceous layers: almost exclusively of quartz with subordinate calc-silicates and calcite.

Type (2) Dominantly calcareous layers: almost exclusively of calcite with subordinate calc-silicates and quartz.

Type (3) Impure calcareous layers: containing quartz, calcite and various calc-silicates in different proportion.

The mineralogy of these rocks, when considered keeping in mind their geological setting, reveal effects of:

(1) Regional metamorphism, and

(2) Superimposition of contact metamorphism over regionally metamorphosed rocks.

Whenever the effects of contact metamorphism are predominant the rocks have developed a spotted appearance and development of cinnamon coloured corundum and wollastonite is noted.

The sandy layers comprise a pink coloured hard, compact and coarse-grained rock, with stray buff coloured specks of weathered feldspar grains. The calcareous layers on the other hand, give rise to a grey-coloured homogeneous saccharoidal rock almost entirely composed of coarse calcite grains. It can best be termed a crystalline limestone, characterised by a typical elephant-skin weathering. Thefresh surfaces however show, pale-bluish grey and pale-greenish grey colours. Its hand specimen typically shows scattered grains of quartz and weathered feldspars, with green and pale bluish-green calc-silicate minerals, imparting a 'pepper and salt' appearance (Moorhouse 1964, p. 457).

The various layers of intermediate composition, vary in the shades of grey and green, and exhibit a well banded nature. Variegated mineral assemblages of silicate rich and carbonate rich layers generally form alternate dark and pale coloured bands. Differential weathering of these has resulted in a characteristic ribbed appearance, and ideally reveal the intricate folds preserved in them (Plates-III.3, 5). Such a rock in hand specimen is seen to contain coarse grains of calcite, quartz, feldspars with various calc-silicate minerals. The entire aggregate of calcite, diopside and quartz with feldspar and other granular minerals, shows gneissose structure, and the rocks are best described as calc-gneisses (Plate-IV.11). These rocks in the immediate contact of the granite have developed various contact minerals. This skarn rock is hard, massive and compact with a mottled appearance due to brown, pink or cinnamon coloured corundum porphyroblasts which beautify the greyish green coloured groundmass of coarse grained wollastonite bearing calc-silicate assemblage (Plate-IV.12).

The different layers of these calc-gneisses show one or the other of the following mineral assemblages:-

(i) Quartz-microcline-calcite,

(ii) Calcite-diopside-quartz-microcline,

(iii) Calcite-(dolomite)-plagioclase-sphene-diopside-scapolite-quartz-microcline-plagioclase-zoisite,

(iv) Corundum-diopside-wollastonite-tremolite-calcite-apatite-sphene-microcline-plagioclase.

Petrography

Under the microscope the rock shows a granoblastic texture (Plate-IV.13). The arenaceous layers contain quartz grains and show an interlocking mosaic texture.

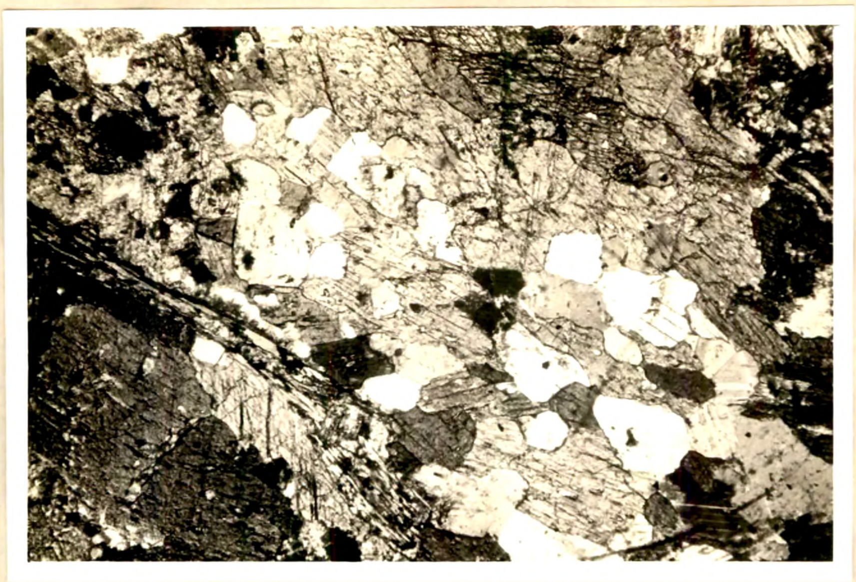
PLATE-IV.11

Calc-gneiss showing bands of different mineral composition (Loc: Vadali)

PLATE-IV.12

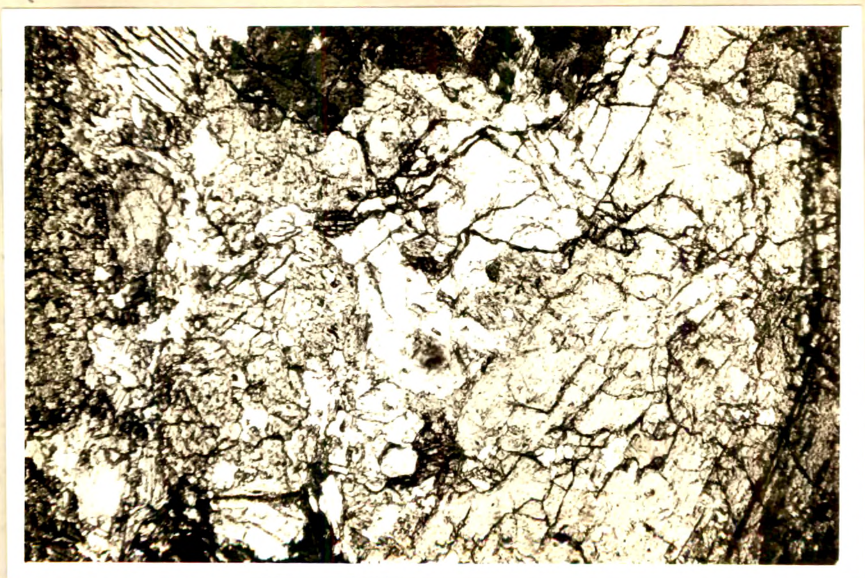
Skarn rock showing corundum porphyroblasts (Loc: Dharol).

PLATE-IV.13



Photomicrograph (X30) of calc-gneiss showing nematoblastic texture.

PLATE-IV.14



Photomicrograph (X50) of skarn rock showing development of corundum.

Crystalline limestones show crystalloblastic texture and contain granular aggregates of coarse, subhedral grains of calcite. Impure layers rich in calc-silicates show a peculiar arrangement of platy calc-silicate minerals giving rise to 'nematoblastic' texture (William, Turner and Gilbert 1965, p.170). The spotted calc-gneiss (having mottled appearance due to development of corundum) shows a hornfelsic texture. The development of corundum porphyroblasts, has given rise to a combination of 'porphyroblastic' and 'granoblastic' texture (Plate-IV.14).

Quartz though almost universally present, shows a considerable variation in its content. At one end it may comprise the entire bulk, being derived originally from siliceous layers in limestones. It forms fairly sutured and interlocking grains of medium size. A greater portion of the quartz is the original detrital constituent, and shows strained and flattened grains. Some bigger and patchy aggregates in association with feldspars possibly suggest their later addition from the granites. Varieties with smaller quartz content generally show this mineral as inclusions in diopside, calcite and tremolite.

Calcite also occurs in variable proportions, from constituting almost entire calcite layers at one end to those at the other with only a few grains in layers rich in calc-silicates or quartz. This mineral always forms well developed subhedral crystals (4 mm.) with usual twinning. When diopside is present, calcite grains show poikiloblastic inclusions of the latter. In less calcareous varieties, it forms small interstitial grains. 'Alizarin red-S' staining method confirms the presence of calcite grains by red stains (Evamy 1969, p. 787-792). While the calcite forms the major constituent of the calcareous rocks, the dolomites and ferron dolomites have stray occurrence and only few grains are recorded.

Diopside occurs in most varieties in varying proportions and sizes. It is scanty or absent in pure sandy or pure calc layers but occurs in a large proportion in the impure calcareous layers. Its grain size varies from small tiny rounded grains (0.4 mm.) to well developed coarse subhedral or euhedral grains (3 mm.). It also occurs as small inclusions in other minerals. In all the rock types they are seen as colourless non-pleochroic grains with high relief and having typical two sets of pyroxene cleavages. Extinction angle is high and varies from 30° to 40°. It shows biaxial positive interference figure and its 2V varies from 58° to 60°. Sometimes diopside is seen changing to hornblende.

Sphene like quartz and diopside, shows a wide range in proportion, and is present in almost all the varieties. Generally it forms small lozenge-shaped euhedral crystals with occasional large subhedral grains. The mineral has high relief and is pleochroic from light brown to dark brown

X = Y = light brown

Z = dark brown

$X = Y < Z$.

Actinolite is only occasionally present and is seen in some bands only as large plates containing inclusions of quartz, and showing pleochroism in the shades of light green

X = colourless

Y = pale yellowish green

Z = pale bluish green

$X < Y < Z$

The mineral shows length slow orientation and extinction angle of 18° with (110) cleavage. It gives biaxial negative intereference figure.

Scapolite occurs occasionally as small colourless anhedral grains occupying interstitial spaces. The mineral has a low relief, straight extinction and shows uniaxial figure with negative sign.

Plagioclase (An_{42-45}) occurs in small quantity only, yet is ubiquitous and occurs in the rocks of all the different bands of the calcarous horizon. It forms subhedral grains and laths of varying dimensions (0.5 mm to 2 mm.). Twinning on albite law is commonly present.

Zoisite is developed in small amount and occurs as tiny colourless granules. It shows low relief, n balsam, and perfect one set of cleavage. Twinning is occasionally seen and the mineral shows anomalous deep blue interference colour.

Corundum is profusely developed as porphyroblasts in the calc-gneiss near the granite contact. The porphyroblasts are seggregated in patches. Under microscope this shows pale yellowish coloured grains, varying in size from 2 to 3 cms. It has a high relief, R.I. —— $n_o = 1.768$ to $n_e = 1.760$ and shows basal partings. The mineral contains many inclusions of other mineral grains (mainly diopside). Birefringence is as low as that of quartz. It gives uniaxial negative figure.

Wollastonite occurs as plates and blades in calc-gneisses showing effects of granite intrusion. The mineral is recognised by its low order polarisation colours, perfect cleavages, parallel extinction and biaxial figure with negative 2V measured is 39°. Some transverse sections show perfect development of three sets of cleavages. It is occasionally seen altering to calcite.

Idocrase is occasionally present in contact aureole and forms subhedral, medium sized colourless grains with high relief and blue interference colour. The mineral is uniaxial and shows negative interference figure. This mineral has developed at some places only in the calc-gneisses suggesting thermal effects of later granite.

Accessory minerals comprise tiny needles of apatite in calcite rich layers. Generally it occurs in small amount, but sometimes it is seen in appreciable quantity. Stray flakes of biotite are also recorded in these rocks. Microcline is the introduced mineral and is quite often present in these rocks.

Chemical Characters

Chemical analysis of 3 typical samples representing various bands in calc-gneisses are given in the Table-IV.2.

TABLE-IV.2

CHEMICAL ANALYSES OF CALC-GNEISSES

Wt. %	552	29/40	54/66
SiO_2	24.50	28.14	38.82
TiO_2	00.89	01.31	01.70
Al_2O_3	07.91	06.78	08.88
Fe_2O_3	01.20	01.01	00.96
FeO	04.59	04.92	03.62
MgO	02.71	02.53	02.50
MnO	00.02	00.05	00.04
CaO	38.13	36.37	27.81
Na_2O	01.56	01.60	02.01
K_2O	01.80	02.00	02.50
P_2O_5	00.09	00.10	00.09
CO_2	17.60	15.19	11.06
TOTAL	101.00	100.00	100.01
A	11.21	08.73	13.57
C	74.50	75.75	70.82
F	14.27	15.52	15.59

Analyst: Paresh Raval

METAMORPHISM

The rocks of the Delhi system have preserved within them an interesting sequence of metamorphic changes, and the study area ideally reveals a superimposition of contact metamorphism over the regionally metamorphosed sediments. While the regional metamorphism is related to the Delhi orogeny, the contact metamorphic changes were brought about by the emplacement of the granite. The various rock types furnish adequate data to reveal a complete metamorphic history of the area. The field characters as well as the petrography and chemistry of these Delhi rocks, have enabled the author to work out the following succession of metamorphic events:-

(1) Regional (Dynamothermal) metamorphism of Delhi sediments, synchronous with the main folding changing the argillaceous and calcareous sediments to biotite-schists and calc-gneisses respectively.

(2) Migmatisation of the folded and metamorphosed rocks, during the early synkinematic phase of the granite activity converting the biotite schists into biotite gneisses.

(3) Contact (Thermal) metamorphism of the calcareous metasediments during the late post-kinematic intrusion of granite masses, bringing about the

development of corundum and wollastonite, and imparting a spotted appearance to the calc-gneisses.

Metamorphic Event I - Regional Metamorphism

The regional metamorphism is essentially related to the Delhi orogeny, and is quite obvious that the metamorphism was synchronous with the main folding. The schistosity that developed during the metamorphism is a product of the deforming stresses that accompanied the mineralogical changes.

However, from the point of view of this early metamorphism, the Delhi rocks are somewhat disappointing, and reveal very little. Subsequent feldspathisation and contact metamorphism, have further obliterated the original metamorphic impress and as a result only very general and rather vague conclusions have been obtained by the author. On account of the addition of the Quartzo-feldspathic material during migmatisation, the bulk chemical composition of the various calcareous and argillaceous has been considerably changed, but the existing mineral assemblages, to provide adequate clues to the original nature of the metasediments. The author has in the following lines, attempted to describe in brief the possible mineralogical changes that took place during the regional metamorphism.

Calcareous rocks: The various mineral assemblages, occurring in layers, indicate original variation in the composition of the constituent rock. At one end are dominantly calcitic layers while at the other are quartzitic layers. Almost invariable presence of diopside in varying proportions is the most noteworthy feature. Minerals other than calcite, quartz, and diopside, are sphene, scapolite, zoisite, tremolite and plagioclase. These all point to an initially impure limestone comprising of thin layers containing arenaceous and argillaceous impurities in different proportions. The existing diversity in the content of quartz, diopside and calcite, thus reflect the original differences from layer to layer.

Argillaceous rocks: The metamorphic rock which by migmatisation, gave rise to the biotite-gneisses, was a garnet-mica schist, and the original metamorphic mineral assemblages might have been quartz-biotite-muscovite-garnet. It is not clear if some feldspars (plagioclase, microcline) were also originally present. But in all probability, the unmigmatised biotite-schists did contain some plagioclase and microcline. In order to get this information, the author studied the samples of the biotite-schists and 'schistose-quartz porphyries' of Ambaji and Danta area

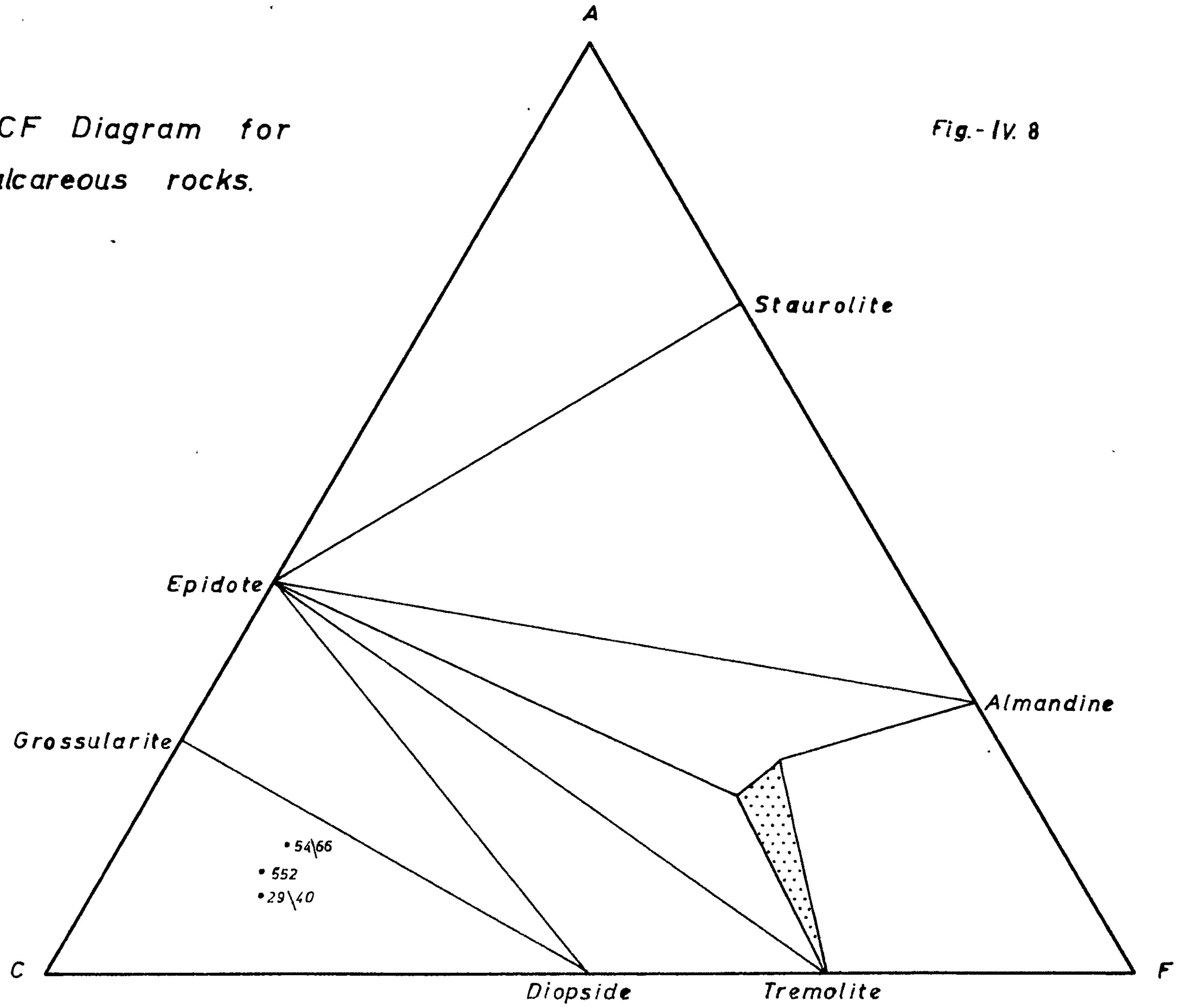
(Sharma, 1931; Heron and Ghosh, 1938), which belong to the same horizon. He found these dominantly argillaceous rocks to contain pebbly subgraywackes and arkoses. It is not unlikely that the biotite - schists of Idar area too were derived from similar sediments.

The textures and mineral assemblage of the calcareous and argillaceous derivatives, clearly suggest a medium-grade of metamorphism. The calc-gneisses show an assemblage typically representing a metamorphism, equivalent to that of the Barrowian Almandine zone. The ACF diagram (Fig.-IV.8) of these metamorphosed calcareous rocks clearly assigns them to the Amphibolite facies (Almandine zone) of Turner (1968, p.308). The presence of garnet in biotite-gneisses is also indicative of similar metamorphic conditions.

According to Turner and Verhoogen, regional metamorphism is typically associated in space and time, with intense deformation leading to formation of folded mountain ranges and regional metamorphism typically involves rock deformation (Turner and Verhoogen, 1960, p.660-668). The metamorphism in the present area was impressed upon the sediments during the folding at the time of Delhi orogeny. Due to the large scale crustal deformation in this region of active orogeny, the geosynclinal sediments were subjected

ACF Diagram for Calcareous rocks.

Fig.- IV. 8



to extreme differential non-hydrostatic stresses. The oriented growth of flaky and platy minerals producing schistose foliae indicate their recrystallisation under directed pressure. It is therefore reasonable to conclude that directed stresses acting on the sediments of Delhi geosyncline at deeper levels folded them, and the metamorphism that accompanied the deformation gave rise to mineral assemblages which characterise moderately high pressure aided by stresses.

The mineral assemblages characterising 'Zone of Almandine' of 'Amphibolite facies' point to a temperature range of 550° - 750° C. Source for this heat to raise the temperature so high could be partly due to deep burial, but in the present case, the intruding granite magma appears to be responsible for the rise in temperature.

Metamorphic Event II - Contact Migmatisation

Regional metamorphism was followed by a period of metasomatic changes during which considerable quartz and feldspar were added to the argillaceous metasediments, as a result of which the biotite-schists were transformed into biotite-gneisses. This metasomatic change was a direct result of the migmatisation brought about by the rising granite. The quartzo-feldspathic emanations given out during the syntectonic stage of granite activity, invaded the nearby biotite-schists most, and changed them considerably - almost imparting them a granodioritic composition. The effect of migmatisation is much restricted in the calcareous rocks, and is seen only as occasional addition of plagioclase and microcline, and in clac-gneisses, the effect of the granite is confined to the frequent development of quartzo-feldspathic veins and strings. The quartzites have resisted the migmatisation and show little mineralogical change.

The biotite-gneisses ideally show a progressive increase of feldspar content when traced towards the granite contact. It has also been observed that the process of migmatisation comprised a gradual increasing addition of soda, followed by potash. The author has concluded that while the sodic phase was synkinematic, the onset of potash was related to the late potash rich intrusions.

The migmatisation generally takes place in the same environments as that of high grade regional metamorphism. Many migmatites are formed under conditions of 'Amphibolite' facies. Stresses may play an indirect part in facilitating the passage of migmatising emanations by providing tectonic planes. The details of the migmatisation shown by the biotite-gneisses are discussed at length in the Chapter VI.

Metamorphic Event III - Contact Metamorphism

The intrusive granties, mark the post-tectonic acid igneous phase. Wherever they have intruded the calc-gneiss, they have given rise to typical contact metamorphic phenomena. On the whole, the biotite-gneisses show little contact effect, though it is in the immediate neighbourhood of the main massifs of late granite. On the other hand, intrusions which have come in contact with the calc-gneisses, have resulted into the development of coarse hornfelsic rocks with porphyroblasts of corundum. The texture and mineral assemblage (Corundum-wollastonite-diopside-idocrease-calcite etc.) indicate the superimposition of contact metamorphism over a mineral assemblage of regional metamorphism. Wherever the granites cut the calc-gneisses, the latter's banded appearance has been somewhat obliterated, and instead the rock has developed a spotted look. The spotting is due to the large porphyroblasts of corundum. The presence of corundum in association with wollastonite typically illustrates contact metamorphism. Generally, the former occurs in skarn rocks together with spinel, grossularite and zoisite. The unusual association of corundum with wollastonite in the absence of the above other alumino-silicates in the study area appears to be due to the instability of the latter in the contact aureole. According to Ramberg (1958, p.286) the highly charged Al^{3+} ions have affinity for doubly charged oxygen in oxides, rather than singly charged oxygen of silicates and other oxysalts. Hence relatively unstable aluminosilicate will give rise to stable aluminium oxide (Al_2O_3) i.e. corundum. This shows that whatever little aluminium was present in the impure rock developed corundum which was stable at that temperature. Liberated silica from the silicates went into the formation of wollastonite,

$$Al_4(SiO_4)_3 \longrightarrow \underset{\text{(Corundum)}}{2\ Al_2O_3} + 3\ SiO_2$$

$$CaCO_3 + SiO_2 \rightleftharpoons \underset{\text{(Wollastonite)}}{CaSiO_3} + CO_2$$

The temperature at which these contact metamorphic changes took place must be fairly high, being almost that of the intrusive granitic melt. Most frequent depth of solidification of granitic intrusions from earth's surface has been estimated by Schneiderhöhn (1961) to be 3-8 km. corresponding to load pressure of 800-2100 bars, the temperature of the magma forming granitic intrusion would be generally 700-800°C (Winkler, 1962). It has been concluded by Winkler (1967, p.81) that at the immediate contact, the temperature of the country rock is somewhat greater than 60% of intrusion temperature + T_c, where T_c = temperature of country rock prior the intrusion.

Thus presuming the depth of the granitic intrusion to be 5-6 km. where temperature prior to intrusion might however be 150°C, maximum temperature attained by country rock would be 610°-660°C, at presssure of 1500 bars (Winkler, 1967, p.82). This temperature and pressure range characterises 'Hornblende-hornfels facies' of contact metamorphism.

From the above account, it becomes obvious that the entire metamorphism of the Delhi rocks, comprising the three events, were closely controlled by the granite activity. The author is inclined to believe that though depth might have contributed to the temperature rise, the main source of heat responsible for regional metamorphism, migmatisation and contact metamorphism, was directly related to the rising granite-magma. The depth and the deformational stresses generated during the Delhi folding, however aided the metamorphism and also facilitated the ascent of the granite bodies.