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Structural studies and their bearing on the Early Precambrian history of the Dharwar tectonic province, southern India

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Abstract. In the Dharwar tectonic province, the Peninsular Gneiss was considered to mark an event separating the deposition of the older supracrustal Sargur Group and the younger supracrustal Dharwar Supergroup. Compelling evidence for the evolution of the Peninsular Gneiss, a polyphase migmatite, spanning over almost a billion years from 3500 Ma to 2500 Ma negates a stratigraphic status for this complex, so that the decisive argument for separating the older and younger supracrustal groups loses its basis. Correlatable sequence of superposed folding in all the supracrustal rocks, the Peninsular Gneiss and the banded granulites, indicate that the gneiss 'basement' deformed in a ductile manner along with the cover rocks. An angular unconformity between the Sargur Group and the Dharwar Supergroup, suggested from some areas in recent years, has been shown to be untenable on the basis of detailed studies, A number of small enclaves distributed throughout the gneissic terrane, with an earlier deformational, metamorphic and migmatitic history, provide the only clue to the oldest component which has now been extensively reworked.

Keywords. Dharwar Supergroup; Early Precambrian; India; Peninsular Gneiss; structural history.

1. Introduction

Two problems which have recurred in the geology of the Dharwar tectonic province for more than a century are: **(a)** the relationship between the gneissic complex and the supracrustal belts, and **(b)** the presence or absence of more than one supracrustal rock group.

Foote (1886) coined the term Dharwar system (now termed Supergroup) to include the metavolcanic and metasedimentary rocks which occur in five large linear and many smaller belts within the gneissic complex which covers a major part of the Precambrian terrane. This gneissic complex, named by him as the Fundamental Gneiss in the belief that it forms the basement, was thought to have been exposed in the anticlinal cores, the narrow synclinal portions having been occupied by the supracrustal rocks of the Dharwar Supergroup. A corollary to this interpretation is that the supracrustal rocks throughout this terrane belong to the same stratigraphic group.

Detailed geological mapping in subsequent years led Smeeth (1915) to an interpretation completely at variance with that of Foote. He took the view that the Dharwar Supergroup is older than the gneissic complex; therefore, he changed the name of the

Fundamental Gneiss to the Peninsular Gneiss. He classified the Dharwar Supergroup into a lower Hornblendic Division and an upper Chloritic Division. It may be mentioned here that in later years he (Smeeth 1926) seemed to have doubts as to whether his Chloritic and Hornblendic Divisions do indeed belong to one stratigraphic unit.

Differing both from Foote and Smeeth, Rama Rao (1940) contended that the relationship between the supracrustal rocks and the Peninsular Gneiss is much more complex than formerly presumed. According to him, the metaigneous and metasedimentary rocks of the Dharwar Supergroup were laid down on a gneissic basement. However, repeated anatexis of the basement gneisses and their invasion into the supracrustal rocks ultimately led to a situation such that in its present state the Peninsular Gneiss for a major part is later than the rocks of the Dharwar Supergroup. A careful scrutiny of Smeeth's (1915) view shows that he also was aware of the reworking of the gneissic basement. Another important point that Rama Rao underscored is that the Hornblendic and the Chloritic Divisions are metamorphic groupings that have nothing to do with stratigraphy. Indeed, in one of his earlier papers he (Rama Rao 1924) showed that in the Holenarasipur area rocks belonging to the supposed Hornblendic Division are actually younger than those of the Chloritic Division.

The question of the gneiss-supracrustal rock relation has been resurrected in the sixties and the seventies by a number of workers. Radhakrishna (1967) went back to Foote's original suggestion that the Peninsular Gneiss is indeed the basement for the Dharwar Supergroup. Taking a cue from Glikson's older and younger greenstone belts Radhakrishna (1976), Viswanatha and Ramakrishnan (1976), and Radhakrishna and Vasudev (1977) took the view that there are two supracrustal groups (greenstone belts), one younger and the other older than the Peninsular Gneiss. For the former they retained the term Dharwar Supergroup, whereas the latter was given a new name, the Sargur Group. The decisive criterion for this division is, therefore, the relationship of the supracrustal rocks with the Peninsular Gneiss. The supporting arguments for this division are the difference in lithology, metamorphism and structural history, and the presence or absence of minerals like fuchsite and baryte (Swami Nath and Ramakrishnan 1981). As pointed out by Pichamuthu (1980), this classification goes against the Code of Stratigraphic Nomenclature (Hedberg 1976) because, for a part of the original Dharwar Supergroup, the name Dharwar Supergroup has been retained; for the other part, the new name Sargur Group has been given. The Sargur-Dharwar classification has also been questioned by Naha *et al* (1986), Srinivasan (1988) and Srinivasan and Naha (1996). It has been shown that: **(a)** shorn of metamorphic impress there is no difference in lithology of the two groups; **(b)** there is no sharp break in metamorphic grade as one passes from the Dharwar to the Sargur group of rocks; **(c)** both the groups of rocks have been affected by the Peninsular Gneiss; **(d)** the rocks of the Dharwar Supergroup show as complex a structural history as those of the Sargur Group and the Peninsular Gneiss; and **(e)** the presence or absence of a particular mineral like fuchsite or baryte cannot serve as a basis for stratigraphic division. Indeed, in the light of new work by various workers, some of the proponents of this division now consider that the Peninsular Gneiss is of different generations (Ramakrishnan 1994; Chadwick *et al* 1996). Yet a large number of workers in India and abroad take the Sargur-Dharwar division as an established fact. The main purpose of this paper is to present the results of detailed structural studies carried out by us during the last fifteen years, with a note on their bearing on the Sargur-Dharwar-Peninsular Gneiss relation.

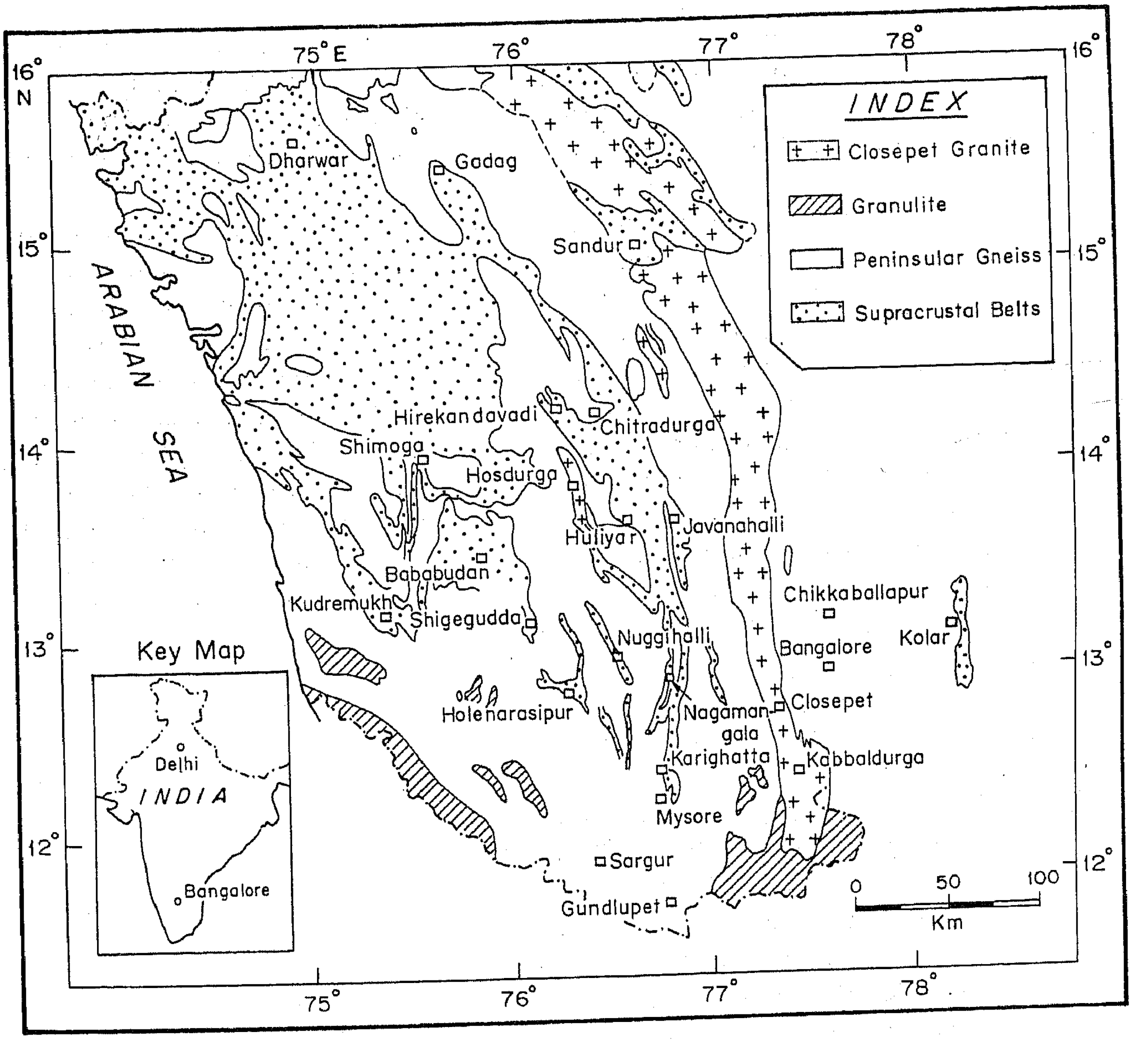

Figure 1. Map of the Early Precambrian rock formations in the Dharwar tectonic province of Karnataka.

2. Mesoscopic structures

2.1 *Structures in the supracrustal rocks*

The regional map of the Dharwar tectonic province brings out clearly one characteristic feature common to a majority of the supracrustal belts. This feature is that practically all the major supracrustal belts trend in a nearly NNW-SSE direction (figure 1). Indeed, this dominant feature led Holmes (1949) to take the NNW-SSE direction as the Dharwar 'trend'. The Bababudan belt seems to be the only one differing significantly from this trend. This apparently simple pattern, however, conceals structures of much greater complexity. As will be shown in the following section, folds of multiple generations abound from microscopic through mesoscopic to macroscopic scales. This NNW 'trend' represents the strike of the axial planes of a fold system of one particular generation (Mukhopadhyay 1986; Naha *et al* 1986).

The metasedimentary rocks occurring in the supracrustal belts are conglomerates, quartzites, chlorite-biotite schists, garnet-staurolite-kyanite-sillimanite schists, hypersthene-cordierite-sillimanite schists/gneisses, banded ferruginous (manganiferous) quartzites containing magnetite, cummingtonite-grunerite, riebeckite, hypersthene and garnet, marbles and calc-silicate rocks containing talc, tremolite, phlogopite, diopside, garnet, wollastonite and scapolite. Barring the dominantly micaceous rocks stratification laminae of varying thickness are discernible in all metasedimentary rocks of different metamorphic grades by colour and compositional banding. This is also true of some metamorphosed tuffs associated with metavolcanic rocks. That these layerings do represent stratification planes is proved by their association with foreset laminae in quartzose rocks, and by their parallelism with formational boundaries.

Stratification planes have been involved in isoclinal folding (DhF_1) throughout the Dharwar province in all supracrustal rock types. The shapes of the isoclinal folds – round hinged, sharp hinged, chevron – have been guided by viscosity contrast in the multilayers involved. Isoclinal folds in alternating quartzite-mica schist, dolomitic marble-mica schist and dolomitic marble-quartzite layers have resulted in rodding structures in the hinge zones and boudinage and pinch-and-swell structures in the limbs in quarzites and marbles, because of the large contrast in viscosity. Alternate

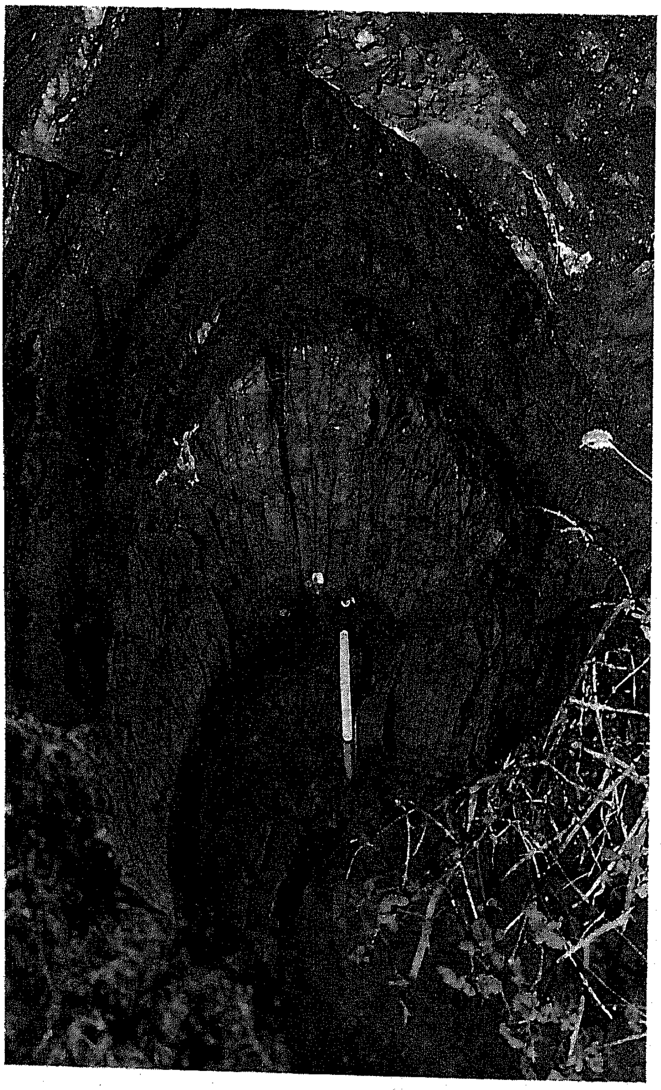

Figure 2. Hinge zone of a DhF_1 fold on stratification in BIF with axial planar cleavage showing convergence towards the core in the siliceous layer. Chitradurga Group, Kereyaganahalli, south of Chitradurga.

layers with less contrast in viscosity show flattened parallel folds with thickened hinges and thinned limbs (class 1C of Ramsay 1967). As a rule, stratification is effectively parallel to the axial planes of the isoclinal folds over a large area because of extremely narrow hinge zones. Thicker bands showing folding of large wave length, disharmony, fold shapes dependent on the viscosity contrast with very viscous materials such as quartzites and quartz veins showing class 1B geometry (parallel folding), point to a buckling origin of these folds. That homogeneous strain (flattening) played a significant role in shaping the folds is indicated by thickening at the hinges and thinning at the limbs, ultimately leading to boudins in limb zones. A cleavage parallel to the axial planes of these isoclinal folds is the dominant diastrophic structure which is observable in all the rocks, except in massive quartzites, some BIFs and marbles. This cleavage (S_1) is defined by platy minerals like chlorite, muscovite and biotite, bands of amphibole, and inequant grains of quartz. Depending on the competency contrast in multilayers involved in folding, the cleavage is strictly parallel to the axial planes of folds or may show convergence and divergence (figure 2). This axial planar cleavage shows a wide

Figure 3. Type 3 interference pattern traced by metapelites in calcitic marble, coin and lens cap near the DhF_1 fold hinges, scale parallel to DhF_2 axial plane. Chitradurga Group, Yelenadu near Huliyar.

variation in orientation ranging from subhorizontal to vertical. Quartz and pegmatite veins, flexurally folded where they are at high angles to cleavage and boudinaged where subparallel to it, provide evidence for compressive strain normal to the cleavage. Strain markers like pebbles and lapilli corroborate this observation. Demonstrable slip along these planes implies that after its formation, this cleavage served as a plane of movement. Intersection of cleavage with the bedding planes gives rise to a striping lineation which is parallel to the DhF_1 fold axis.

Coaxial refolding by DhF_{1a} has produced variation in the attitude of S_1 cleavage and axial planes of DhF_1 folds in mesoscopic scale, with constant orientation of the fold axis. These coaxial DhF_{1a} folds are generally open and upright. In some instances, the axes of the DhF_{1a} open folds are slightly oblique to DhF_1 lineations, so that the latter curve around the hinges of the DhF_{1a} folds. We consider these two sets of folds to belong to different phases of a progressive deformation. This coaxial folding has resulted in the DhF_1 folds varying from recumbent/reclined through inclined to upright attitude. Type 3 interference patterns have resulted from the overprinting of DhF_{1a} on DhF_1 folds (figure 3). In general no axial planar fabric has developed during this phase of folding.

Both the sets of folds described above have been involved in upright folding with the axial plane striking nearly N-S to NNE-SSW (DhF_2). These later folds vary in tightness from open to isoclinal style. DhF_2 folds have variable orientation of axes being nearly parallel to DhF_1 in some domains of strong deformation and at high angles to the latter in other domains. Superposition of DhF_2 on the earlier folds has resulted in interference patterns of different types (figures 4 and 5).

The effect of DhF_2 folding is brought out in a striking manner in the hinge zones by the folding of boudinaged layers. Thus the boudins of more viscous material such as

Figure 4. An impure marble showing refolding of DhF_1 isoclinal fold due to superimposition of later open folding. Chitradurga Group, Yelenadu near Huliyar.

Figure 5. Dome-and-basin interference pattern traced by siliceous layers in calcitic marble due to interference of DhF_2 on DhF_{1a} folds. Chitradurga Group, Yelenadu near Huliyar.

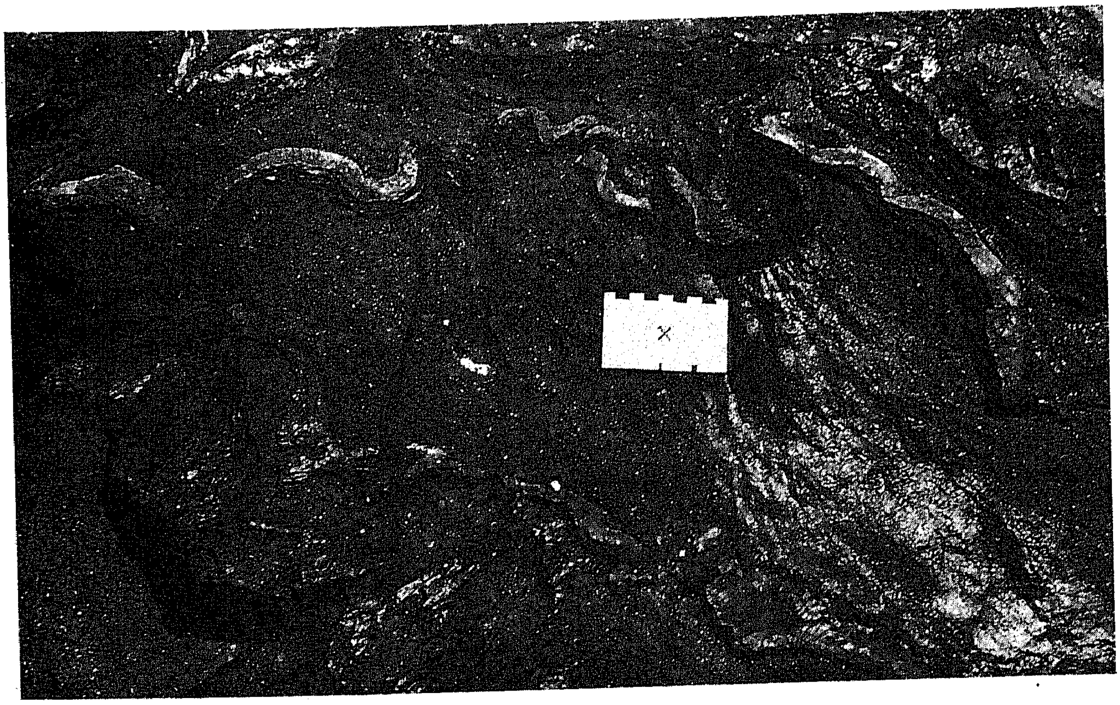

Figure 6. Quartzite boudins of first generation involved in DhF_2 folding, scale divisions in cm. Chitradurga Group, Yelenadu near Huliyar.

quartzite in calcitic marble involved in DhF_2 folding have resulted in folding of individual boudins (figure 6). DhF_1 fold hinges and lineations bent by DhF_2 folds are the other obvious evidences of superposed folding (figures 7 and 8).

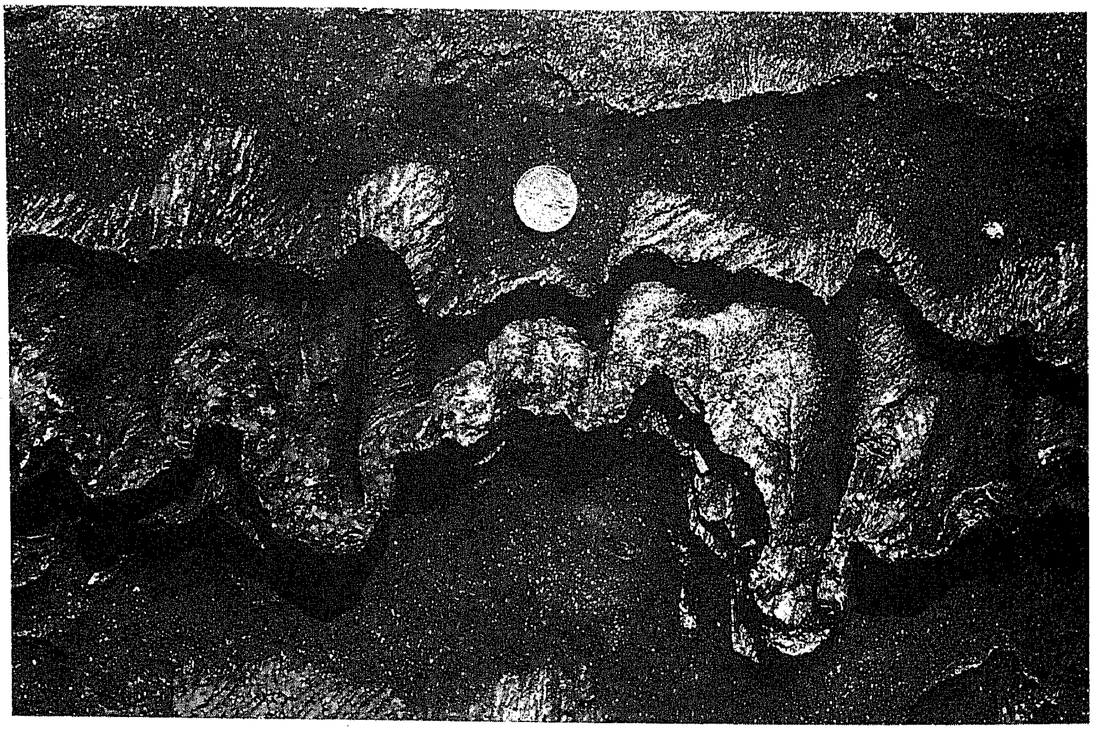

Figure 7. Bending of early (DhF_1, DhF_{1a}) lineations by later (DhF_2) folding in thin metapelite layers in calcitic marble. Chitradurga Group, Yelenadu near Huliyar.

Figure 8. Bent fold hinges in metapelites within marble because of superimposition of DhF_1, DhF_{1a}, DhF_2 generations. Chitradurga Group, Yelenadu near Huliyar.

Interference patterns of all the three types are brought out in a spectacular manner in some outcrops of impure calcitic marble interlayered with thin quartzite and mica schist near Huliyar. These interference patterns range in scale from centimetres to

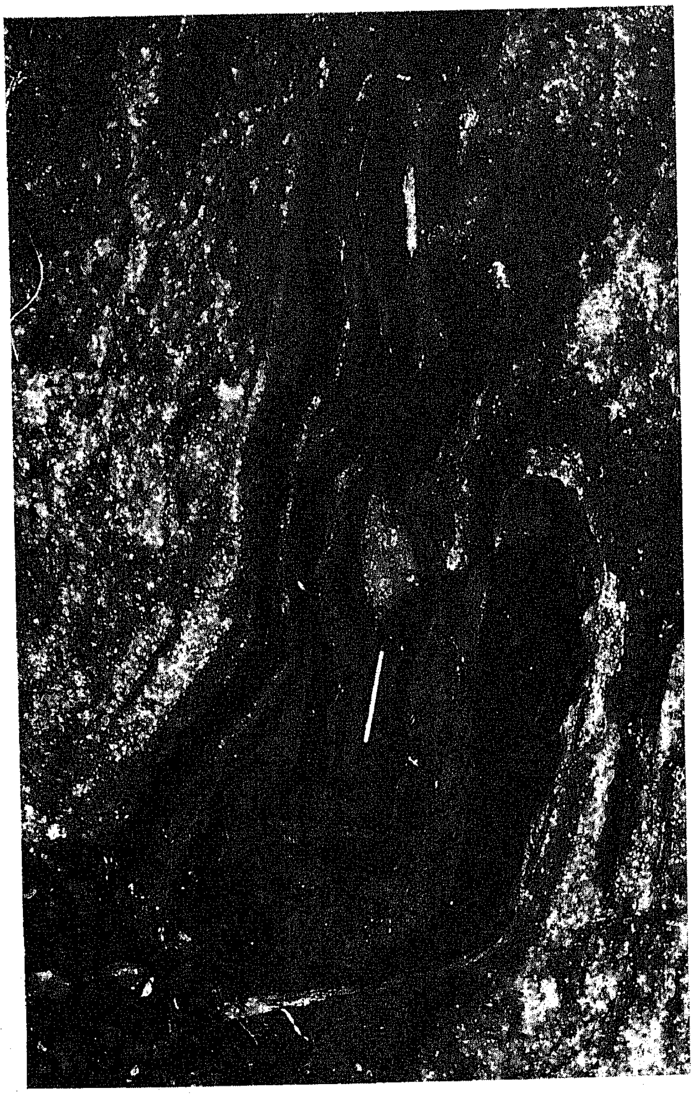

Figure 9. Type 2 interference pattern in impure marble traced by calc-silicate bands in the Sargur Group; pencil parallel to DhF_2 axial trace. Bettadabeedu, south of Mysore.

several metres. DhF_1 isoclinal folds, traced by more viscous mica schist layers within calcitic marble, have been affected by DhF_{1a} coaxial refolding. This has resulted in axial plane folding which is observable on flat ground because of moderate axial plunge (figure 4). In a smaller scale convergent-divergent type interference pattern (type 3) are seen (figure 3). Type 2 and type 1 interference patterns occur side by side because of the effect of DhF_2 on DhF_1 and DhF_{1a} folds respectively. Significantly, the dome-and-basin structures are on cleavage surfaces which are parallel to the axial planes of the DhF_1 isoclinal folds.

Interference patterns of different types are also well displayed by the calc-silicate rocks belonging to the supposed Sargur Group in Bettadabeedu near Mysore (figure 9).

A crenulation cleavage parallel to the axial planes of the DhF_2 folds has developed in different rock types over wide areas. At some places they look like discrete fractures, whereas at other places mica and chlorite have developed along these cleavage planes, giving rise to zonal crenulation cleavage. Instances of DhF_2 axial plane schistosity have been observed in some places with strong folding. The axes of DhF_2 folds are paralleled by puckers on the S_1 cleavage.

By using the same criteria as in DhF_1 folds, the DhF_2 folds have also been taken to have formed by buckling, accompanied in some instances by homogeneous strain. Warps on nearly EW-striking axial planes (DhF_3) are seen at some places in mesoscopic scale, causing a variation in the amount of plunge of the early folds.

2.2 *Structures in the Peninsular Gneiss*

The Peninsular Gneiss in a major part of the area is migmatitic with quartzofeldspathic layers of varying thickness alternating with muscovite/biotite-rich or hornblende-rich layers. In many instances discrete amphibolite bands alternate with quartzofeldspathic bands, the border between the two being rich in biotite with some epidote. Partial transformation of amphibolite to biotite-epidote rock at some places suggests that the amphibolites are the palaeosomes in the migmatites. Similarly, metapelite palaeosomes have at their contact muscovite-biotite rich gneisses. Where quartzite and marble are the palaeosomes, they have remained unaffected by migmatization. One of the most startling features discernible in numerous outcrops in the Peninsular Gneiss terrane is the similarity in the structural sequence of the gneisses and the Dharwar supracrustal rocks (Naha *et al* 1990, 1991). This suggests ductile deformation in the 'Peninsular Gneiss basement' and the cover rocks, which is contrary to the view of Chadwick (1994 p. 88).

These banded gneisses register the effect of all the three deformational episodes that the supracrustal rocks have undergone. In numerous instances gneissic layering has been involved in isoclinal folding (DhF_1, figure 10) with the development of an axial planar fabric. These isoclinal folds have divergent shapes depending on the viscosity contrast between the alternate layers. Flattening has resulted in the formation of

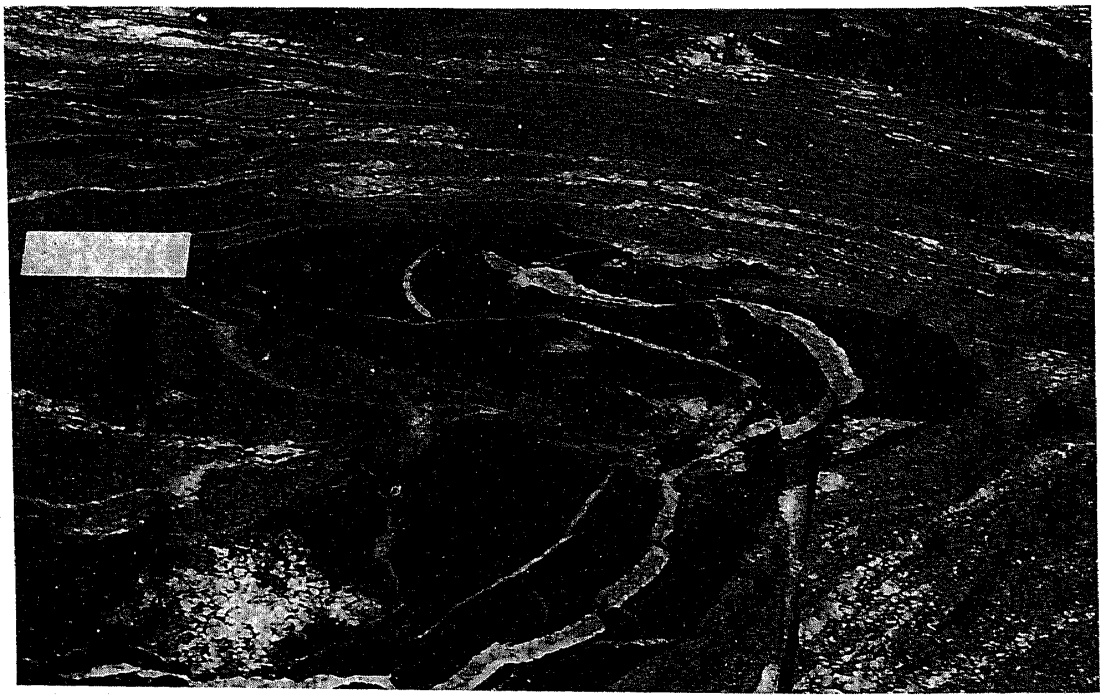

Figure 10. Amphibolite palaeosome in migmatitic Peninsular Gneiss involved in DhF_1 isoclinal folding. Veerasandra, southeast of Bangalore.

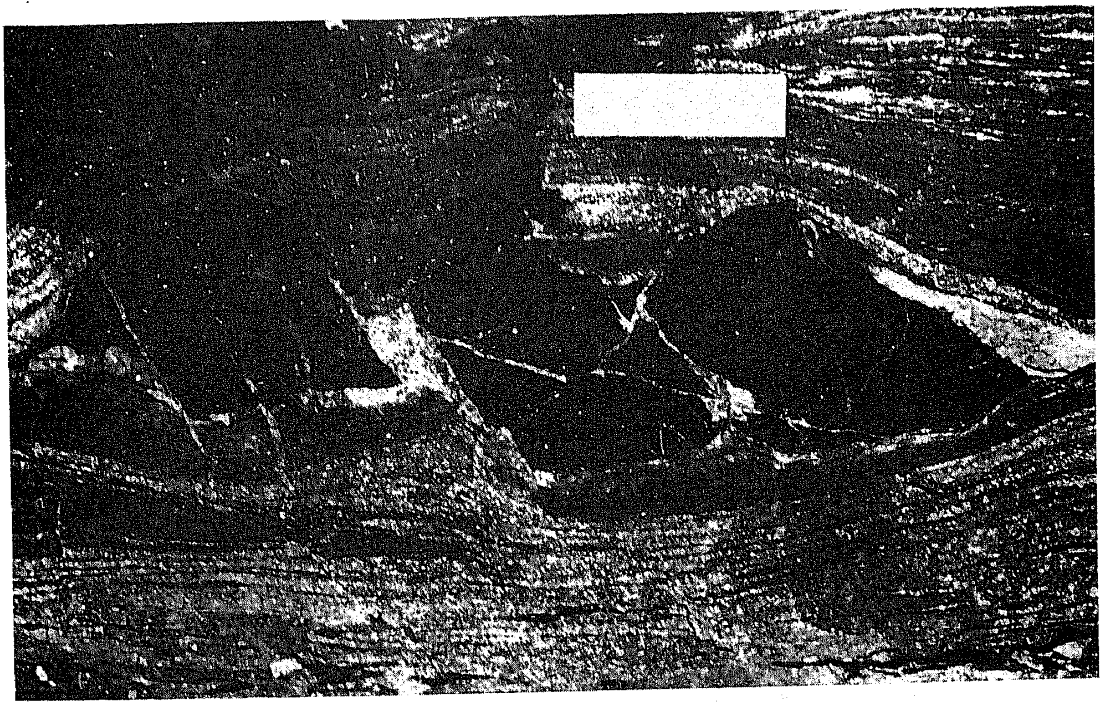

Figure 11. Boudinaged amphibolite palaeosome displaced by shearing. Veerasandra, south-east of Bangalore.

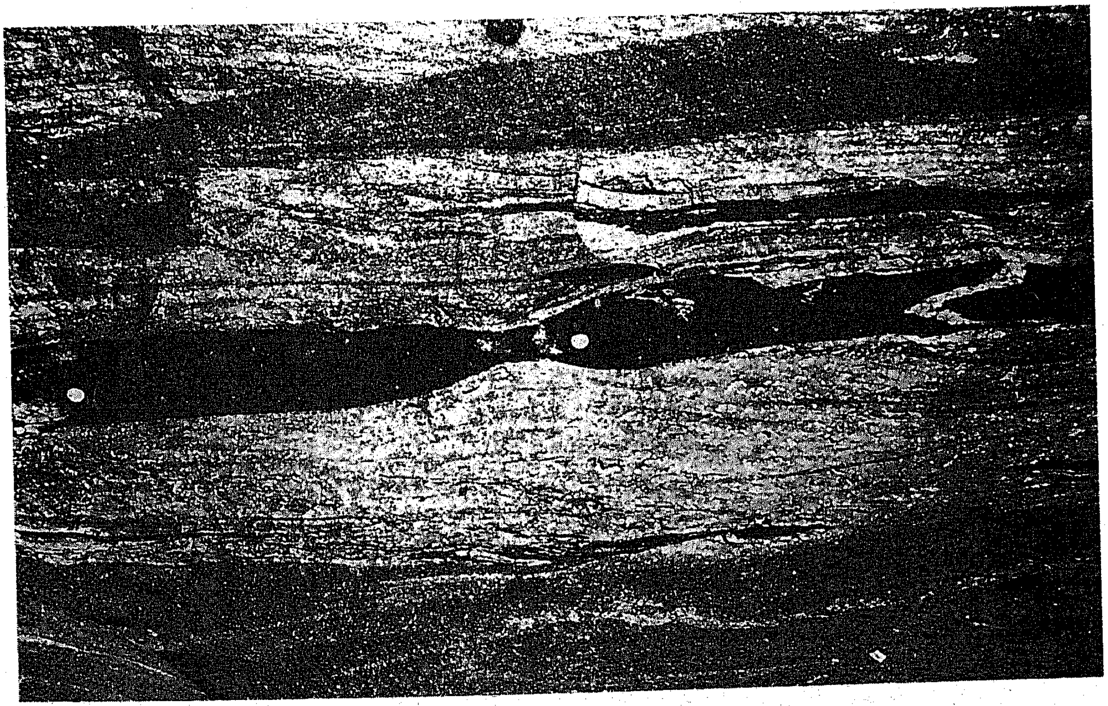

Figure 12. Buckle folding and pinch-and-swell structure in the Peninsular Gneiss with mafic enclaves. Rajajinagar, Bangalore.

boudins in the amphibolite bands in the limb regions. These boudins may be rhomb-shaped bordered by shear fractures (figure 11), or sausage-shaped (boudinage *sensu stricto*) with bending folds in the boudin necks traced by the quartzofeldspathic layers. Evidence of synkinematic migmatization during this folding is brought out dramatically by the features shown in figure 12. Here, an amphibolite palaeosome shows pinch-and-swell structure parallel to the axial planes of a set of isoclinal folds in the host gneiss. Some quartzofeldspathic veins from the gneissic host invading into the amphibolite have been buckle folded. This implies that, in an early stage when the palaeosome was more competent (mafic rock), compressive strain resulting in the folding in the gneisses caused the pinch-and-swell and boudins to form in the mafic band. Metamorphism and migmatization concomitant with this deformation resulted in the mafic band being transformed into an amphibolite, whereas the host rock became a more competent quartzofeldspathic gneiss. Quartzofeldspathic veins transecting this amphibolite at low angles to the compressive strain were buckle folded at this stage. Figure 12 thus provides convincing evidence of migmatization synkinematic with the DhF_1 folding, with change in ductility contrast during migmatization. Inequant amphibolite inclusions elongated parallel to foliation in host gneisses indicate that the palaeosomes were ductile enough to be flattened during the DhF_1 deformation.

These isoclinal early folds have been involved in coaxial refolding (DhF_{1a}) which is usually open; no axial planar fabric has developed with this folding (figure 13). This has resulted in divergent orientation of banding as well as axial planes of the isoclinal folds in mesoscopic scale. Change in the DhF_1 isoclinal folds from recumbent/reclined to upright attitude, with constant orientation of the fold axis within a small distance, points to DhF_{1a} folding in a larger scale. That in general the strike of gneissosity is EW in some areas (south of Bababudan belt, west of Holenarasipur, east of Hosadurga and around Gundlupet) and nearly NS in other regions (Bangalore, Kolar, Chitradurga etc.) may be a reflection of open coaxial refolding of a still larger scale. It may be added in parenthesis that, although the Peninsular Gneiss as a whole has been described as tonalitic gneiss, potash feldspar-rich bands involved in DhF_1 and DhF_{1a} folding in some areas indicate that the gneisses are not tonalitic everywhere.

Figure 13. True profile of an almost recumbent DhF_1 fold in the Peninsular Gneiss involved in refolding. Belagola near Mysore.

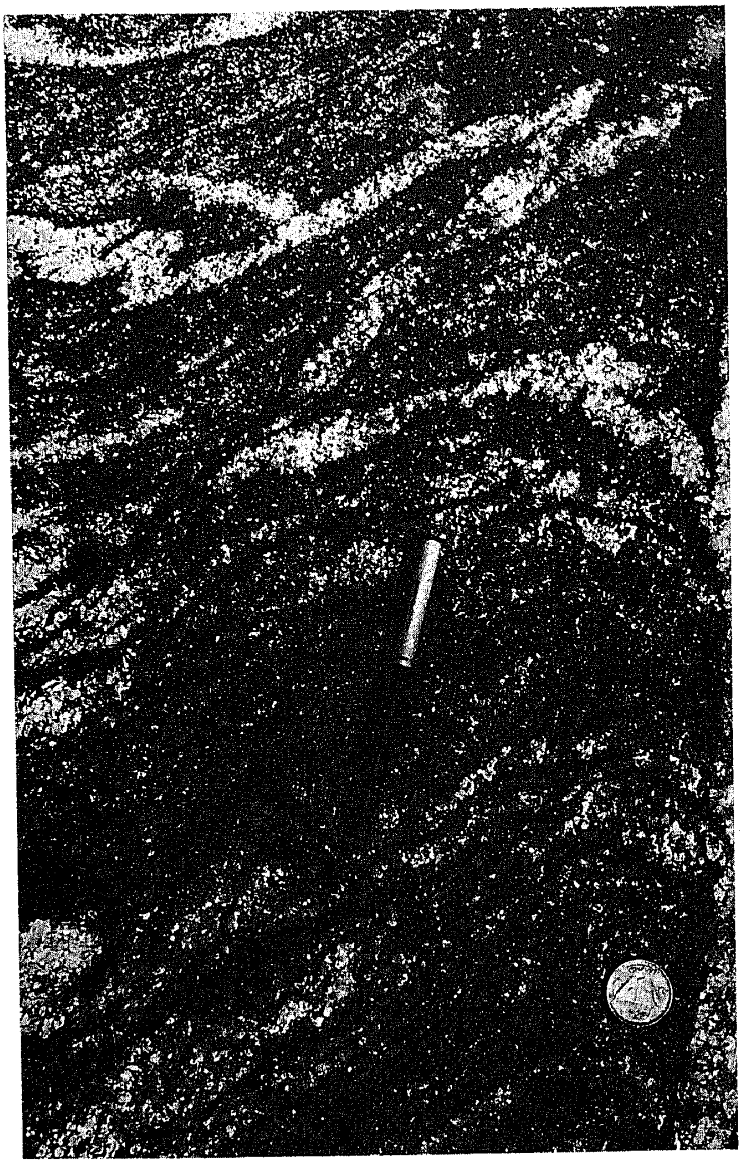

Figure 14. DhF_1 isoclinal folds in Peninsular Gneiss involved in DhF_2 folding with axial planar cleavage parallel to pen, east of Kengeri, Bangalore.

A set of upright folds with axial planes striking nearly NS has been superimposed on the early structures in the Peninsular Gneiss as in the supracrustal rocks (DhF_2, figure 14). These folds range in tightness from open to isoclinal style. An axial planar foliation marked by biotite is associated with these folds at many places. Small shear zones parallel to these axial planes have been noted at a number of instances. But even at this stage, quartzofeldspathic veins have been emplaced along the NS planes, indicating that migmatization was significant even during the later stage of DhF_2 folding.

The foregoing description underscores the fact that the Peninsular Gneiss is a polyphase migmatite developed over a protracted period of time, starting from the first deformation of the supposed cover rocks. However, the record of a still older event (DhF_*) is left in a large number of small enclaves several metres across, distributed throughout the gneissic terrane. These enclaves are amphibolitic, dioritic and tonalitic

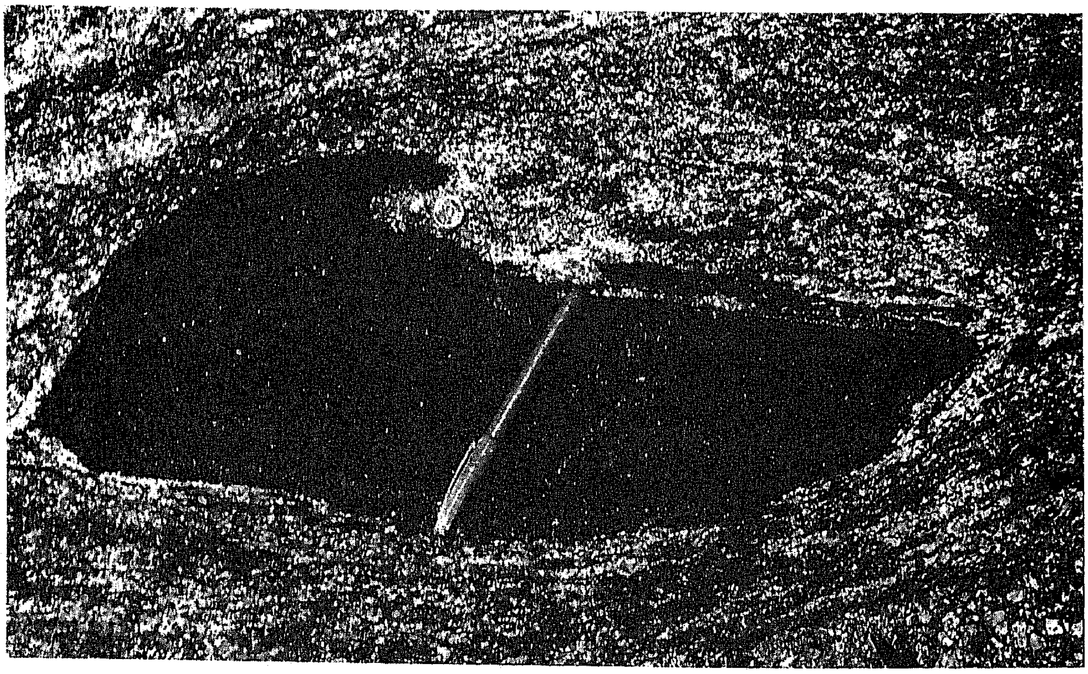

Figure 15. Mafic enclave in Peninsular Gneiss with DhF_* foliation parallel to pen at a high angle with DhF_1 foliation in the host gneiss. Chikballapur.

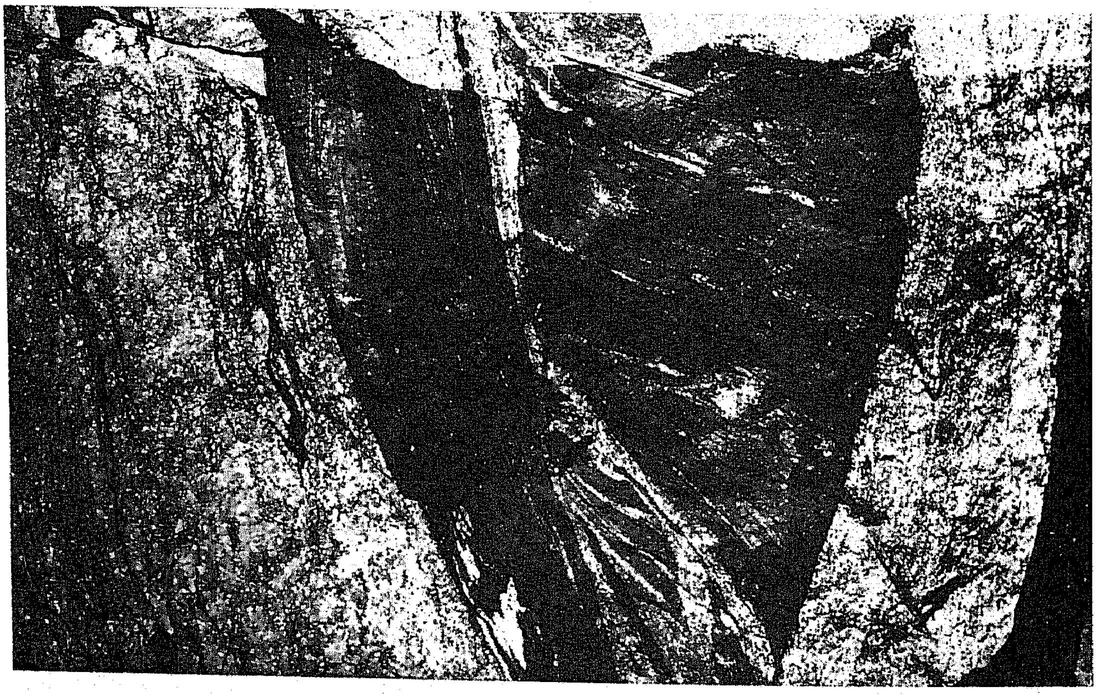

Figure 16. Mafic enclave in Peninsular Gneiss with foliation parallel to the axial plane of DhF_* folds parallel to pencil, at a high angle to foliation in the gneissic host in the right hand side. Hulimavu, south of Bangalore.

gneisses in which quartzofeldspathic bands occur as veins, lending a migmatitic appearance to these rocks. The foliation within these enclaves is discordant with the dominant foliation and axial plane of the DhF_1 folds (figure 15). The shapes of many of these enclaves preclude the possibility of their foliation having been rotated from their

Figure 17. Isoclinally folded (DhF_*) and migmatized amphibolite boudinaged and subsequently involved in DhF_1 folding in the gneissic host. Nidasale west of Bangalore. **A** – axial trace of DhF_* fold; **B** – axial trace of DhF_1 fold.

initial orientation parallel to that of the gneissic host. This implies that these foliations are earlier than that related to DhF_1 folding. This interpretation is strengthened by the features shown in figure 16. Here isoclinal folds traced by quartzofeldspathic bands in an amphibolite enclave have their axial planes transected by the foliation and the axial planes of the isoclinal folds in the gneissic host on one side. In the opposite side, foliation in the enclave is dragged into parallelism with that of the gneissic host. We are justified in concluding that an episode of deformation (DhF_*), a metamorphic event and a phase of migmatization preceded the DhF_1 deformation. This interpretation is also borne out by figure 17. Here, migmatized amphibolite boudins are involved in isoclinal folding which can be tied with the DhF_1 folding in the host gneisses. These enclaves, retaining the traces of an earlier structure, are the only clue to the oldest rocks.

2.3 *Structures in the granulites*

As detailed in an earlier communication (Naha *et al* 1993a), charnockite, enderbite and mafic granulite occur in diverse structural setting in the Dharwar terrane. The more common variety is a banded one, dominant in the southern part of the terrane. The other variety, which comprises mainly charnockite (Pichamuthu 1961), occurs as patches and veins which are at places pegmatitic. The banded granulites have been involved in isoclinal folding (DhF_1, figure 18) with hypersthene developed along the axial plane. The limbs of these folds affecting mafic granulites have been stretched and torn at many places, giving rise to boudins. In the boudin necks charnockite has developed in these instances. These isoclinal folds have been involved in open folding with axial planes usually striking nearly NS (DhF_2). Depending on the initial

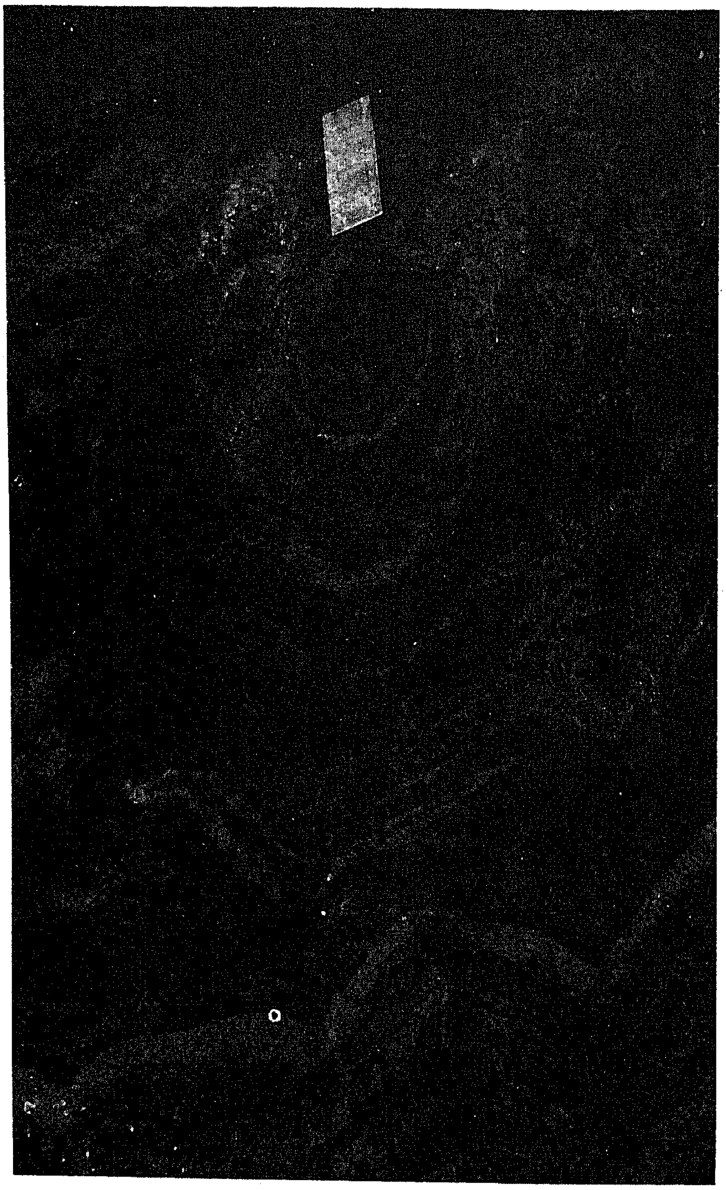

Figure 18. Isoclinal folds in banded charnockite-enderbite involved in open folding. Note a fabric parallel to the axial plane of later fold. Sivasamudram.

orientation of the axes of the early folds, this superimposition has resulted in either type 1 interference (where the two axes as well as axial planes are at high angles; figure 19) or type 3 interference pattern, where the two axes are nearly coincidental. The hook shaped pattern of the type shown in figure 18 can in some instances, be due to superposition of DhF_{1a} on DhF_1. But due to lack of three-dimensional outcrops it is difficult to prove the nature of this superposition in each individual outcrop. At a number of places hypersthene crystals have formed parallel to the axial planes of these later folds (DhF_2) also in several localities (B. R. Hills, Lakkojanhalli, Kabbal, Chandakavadi). Peninsular Gneiss involved in DhF_2 folding have hypersthene grains developed along the axial planes of the later folds. Patchy charnockite (figure 20) has formed at a number of places in the tensional domains of the DhF_2 buckle folds in the Peninsular Gneiss. Lastly along shear planes as well as tensional joints both in banded

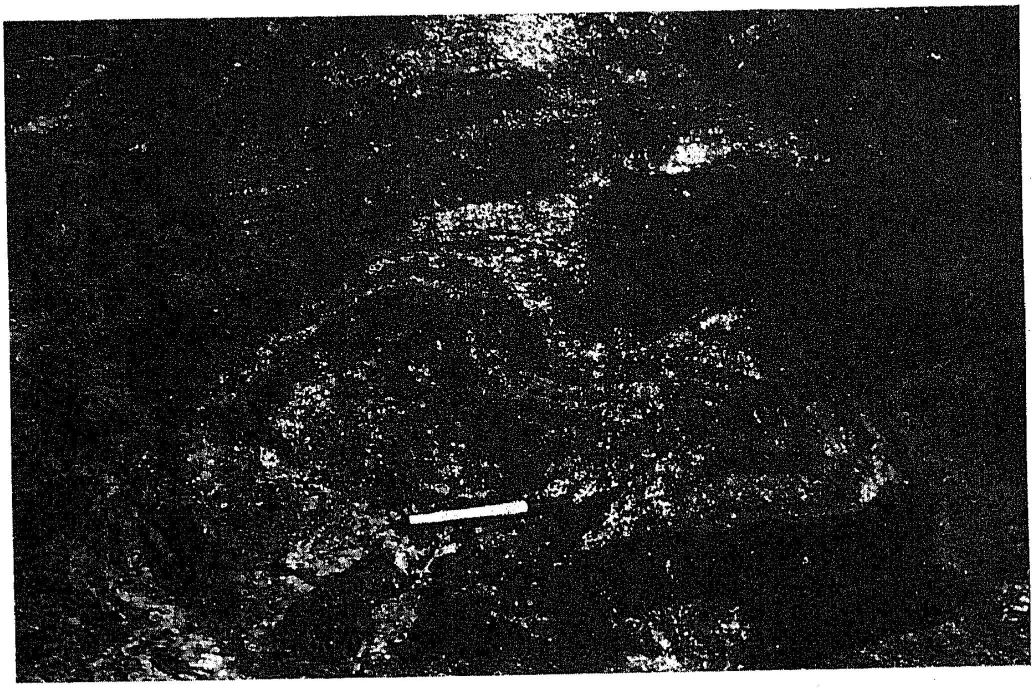

Figure 19. Type 1 interference pattern in banded granulite (enderbite) due to superposition of DhF_2 folding on DhF_1 isoclinal folds. Kajur quarry near Mercara.

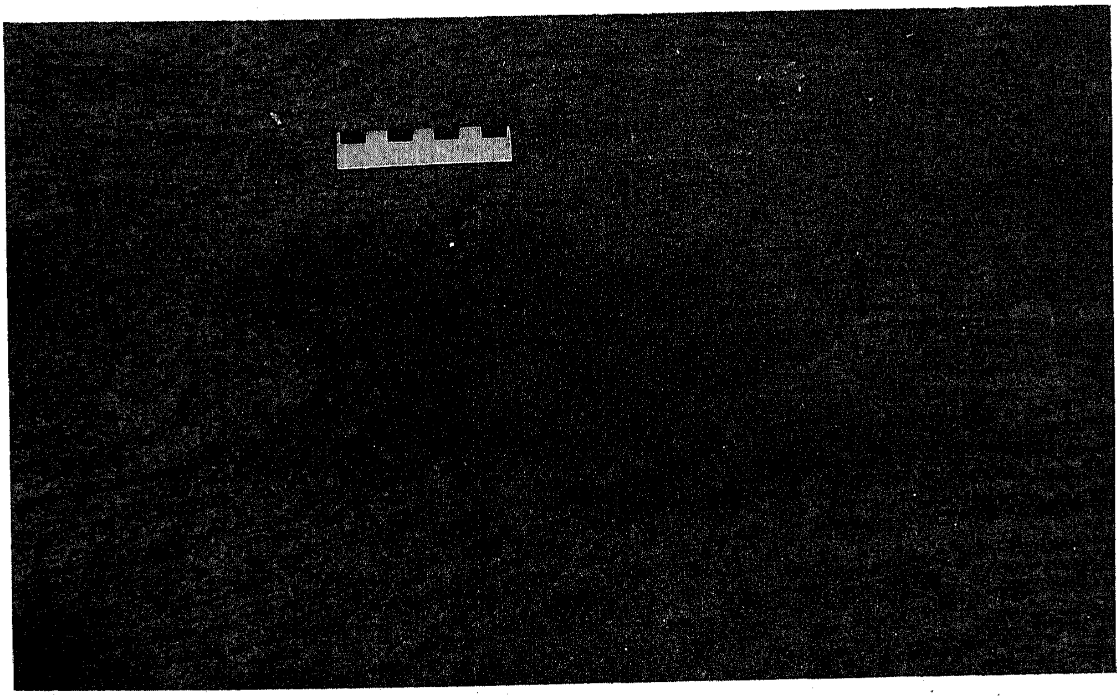

Figure 20. Patchy charnockite in Peninsular Gneiss with gneissosity passing uninterruptedly through charnockite, scale divisions in cm. Lakkojanahalli, southwest of Bangalore.

granulites and Peninsular Gneiss, veins of charnockite are noticeable. In some instances these veins are pegmatitic.

The relation between the charnockites and the Closepet Granite *vis-a-vis* the DhF_2 folding is particularly significant. In a number of instances hypersthene crystals oriented parallel to the axial planes of DhF_2 folds have formed in the Closepet Granite. Pegmatitic veins of charnockite along the shear planes and tensional joints in Closepet Granite are also noticeable. These veins are at places traversed by Closepet Granite veins pointing to an overlapping time relation between the formation of the Closepet Granite and patchy charnockite (cf. Friend 1983).

Instructive examples of superposed folding in charnockite are seen near Arakalgud (west of Holenarasipur), where mesoscopic isoclinal folds with their axial planes striking EW are noticeable in charnockites at the hinge zone of a southerly closing fold of later generation in the scale of map.

2.4 *Structures in the Closepet Granite*

A large body of granite extending from Bellary in the north to near Kabbaldurga in the south was named by Smeeth (1915) as the Closepet Granite and was considered by him to be the last phase of granitic intrusion into the Dharwar supracrustal rocks. The rock was described as porphyritic granite with phenocrysts of potash feldspar. However, Foote (1886) had earlier described the same rock as Bellary gneiss because of its obvious gneissic fabric. Whereas Smeeth (1915) and Sampat Iyengar (1920) took the Closepet Granite to be an intrusive body, Radhakrishna (1956) considered it to be of metasomatic origin.

Our studies have shown that barring a few places, the Closepet Granite is a gneissose rock with large tablets of potash feldspar in parallel orientation lending a banded appearance to the rock. Enclaves of Peninsular Gneiss of different dimensions are legion throughout the Closepet Granite country including the central part. Although Friend (1983) considered it to be a post-tectonic granite body of anatectic origin, in

Figure 21. Peninsular Gneiss (white) involved in DhF_2 folding occurring as enclave in Closepet Granite. The foliation in the Closepet Granite host defined by feldspar megacrysts is accordantly folded. Mahimapura, northwest of Bangalore.

a number of instances the foliation defined by the feldspar megacrysts is involved in DhF_2 folding as registered in the adjacent Peninsular Gneiss enclaves (figure 21). The axial planes of these folds strike nearly NS. The orientation of the gneissosity of the Closepet Granite varies accordantly with the boundary of the Peninsular Gneiss inclusions in a number of instances. Feldspar megacrysts oriented parallel to the axial planes of DhF_2 folds in the granite are also common. Lastly, in a few instances homophanous granite with potash feldspar megacrysts in random orientation have been observed.

The presence of a large number of enclaves of Peninsular Gneiss, with parallel orientation of gneissic foliation in adjacent enclaves, precludes the possibility of invasion of a large magmatic body. The foliation defined by the feldspar megacrysts following the boundary of the small Peninsular Gneiss inclusions, however, points to localized melt-crystal mush. Alignment of feldspar phenocrysts parallel to the axial planes of DhF_2 folds indicates that the emplacement of the Closepet Granite was in a dynamic environment. Boudins of potash feldspar megacrysts present in some instances parallel to the axial planes of DhF_2 folds suggest that flattening continued even after the emplacement of granite in some places (figure 22). Summarizing, the Closepet Granite evolved by anatexis of the Peninsular Gneiss during the DhF_2 folding, the crystallization outlasting the folding movement in some places.

3. Macroscopic structures

Structures in the scale of hand specimen and outcrop are duplicated in large scale also in all the supracrustal belts. As mentioned earlier, the Bababudan belt apparently shows the only aberrant pattern. The simplified map of this area showing the limits of

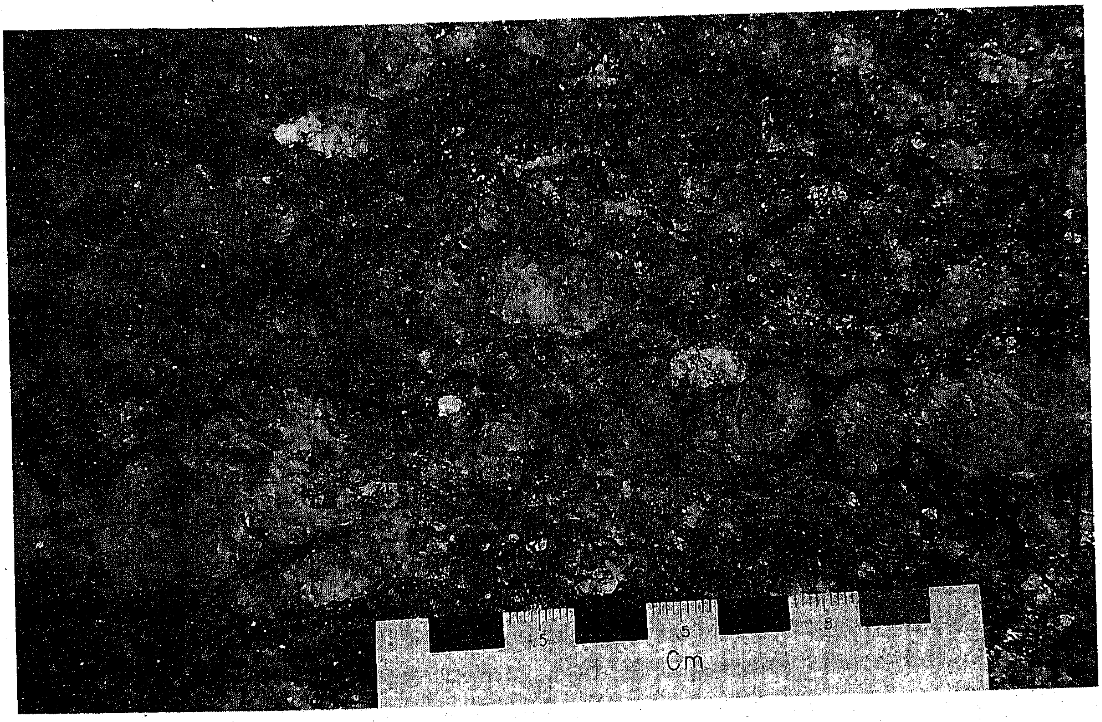

Figure 22. Pinch-and-swell structure shown by feldspar megacrysts defining an axial planar foliation in the Closepet Granite, Mahimapura, northwest of Bangalore.

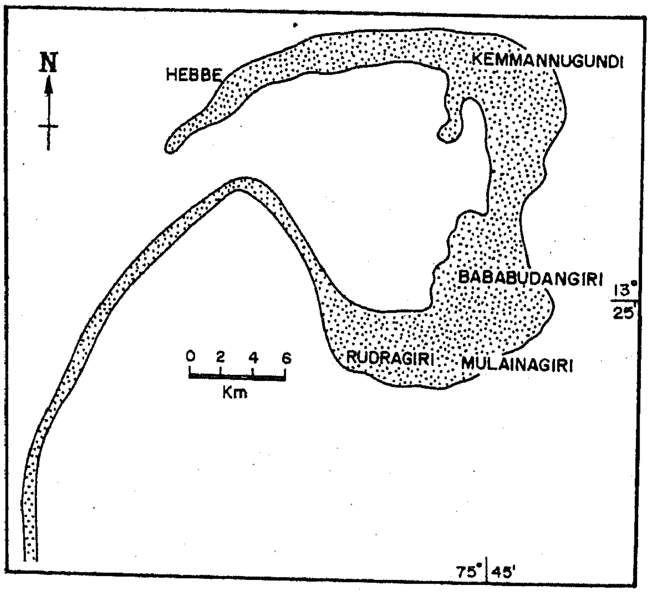

Figure 23. Simplified map of the Bababudan area showing the limits of the iron formations (after Naha and Chatterjee 1982).

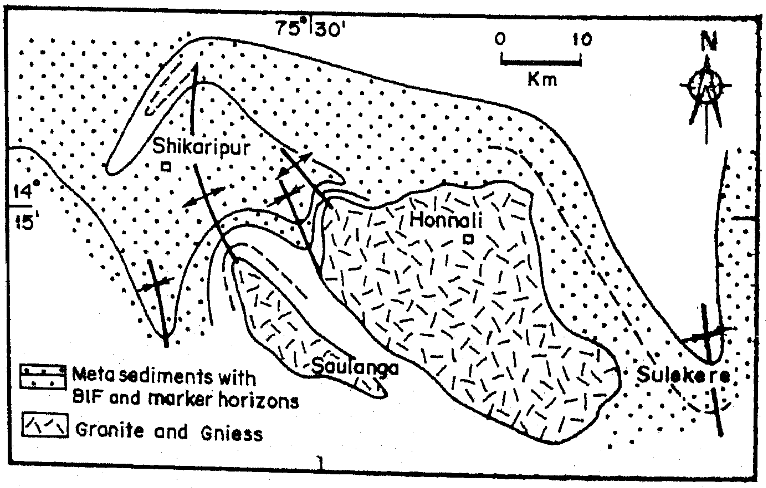

Figure 24. Map of a part of the Shimoga supracrustal belt showing the pattern of refolding, F_2 antiformal and synformal axial traces are shown (after Mukhopadhyay 1986, figure 5).

the iron formation displays a peculiar horse-shoe pattern (figure 23). In mesoscopic scale folds of all the three generations are observable here. However, both DhF_{1a} and DhF_2 folds are open. As shown by Naha and Chatterjee (1982), the termination south of Hebbe represents the acute hinge zone of the large-scale isoclinal DhF_1 fold with a steep plunge. In the sector between Hebbe and Kemmannugundi and around Rudragiri, the dome-and-basin type interference patterns are present in large scale. By contrast, in the sector between Mulainagiri and Kemmannugundi, the DhF_1 isoclinal folds affected by near coaxial DhF_{1a} folds have resulted in type 3 inter-ference pattern, with a large number of reclined folds plunging WNW to NW. Large-scale DhF_2 folding on nearly NS axial plane has resulted in a mirror image pattern on macroscopic scale, so that the folds plunge to the east in the eastern part of the

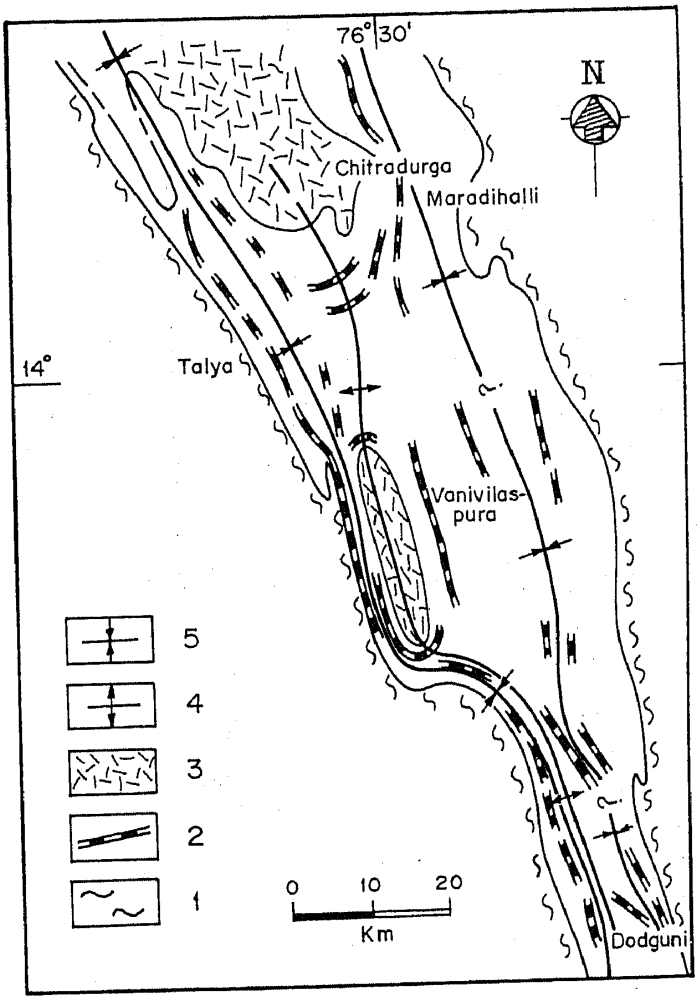

Figure 25. Geological map of the Chitradurga supracrustal belt: (1) Peninsular Gneiss; (2) Chitraduga supracrustal rocks with BIF bands; (3) Granite; (4) Dodguni-Serankatte antiform (F_2); (5) F_1 synforms (after Mukhopadhyay *et al.* 1981, figure 2).

Kemmannugundi-Mulainagiri range. The peculiar map pattern of the Bababudan area is due to the *open* folding of the later phases. Another area which shows a comparable pattern is a part of the Shimoga belt near Shikaripur. It has also been interpreted as due to later open folds affecting early isoclinal folds (Mukhopadhyay 1986; figure 24). The gradual swing in strike of foliation as well as axial planes of DhF$_1$ folds from nearly NS to almost EW over a wide area around Gundlupet, south of Mysore (see Janardhan *et al* 1979) has been interpreted as due to coaxial refolding in large scale (Naha *et al* 1986).

The same sequence of structures of three generations are noticeable in large scale in the long, narrow, linear Chitradurga supracrustal belt from Gadag in the north to Dodguni in the south (figure 25). Isoclinal folds of early generation affected by folding on axial planes striking nearly NNW can also be proved by primary sedimentary structures (cross stratification) in the Hirekandavadi area west of Chitradurga (Naha and Srinivasan 1988; figure 26), and the Dodguni area south southeast of Chitradurga (Mukhopadhyay and Ghosh 1983; figure 27). In the Chitradurga arc traced by banded iron formation, superposition of folding is particularly clear (figure 28), with different relationship among S, Z and M folds in mesoscopic scale in different sectors (Mukhopadhyay *et al* 1981; Mukhopadhyay and Baral 1985).

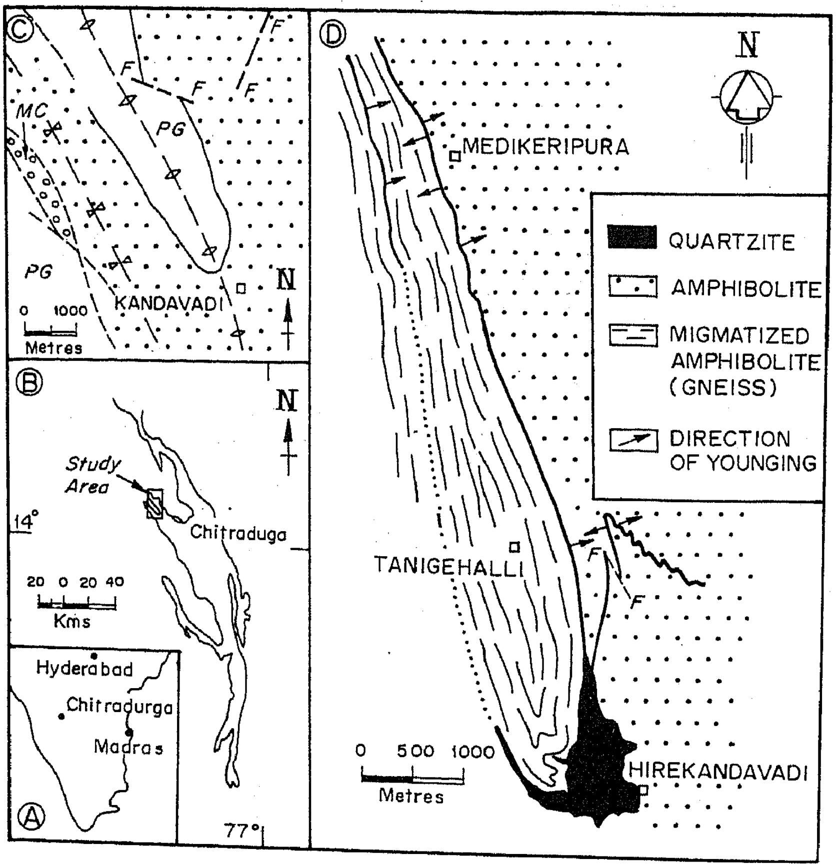

Figure 26. Geological map of Hirekandavadi area, west of Chitradurga showing the younging directions from cross bedding in quartzites.

West of Chitradurga in the Hirekandavadi area a south-southeasterly plunging anticline was described by Chadwick *et al* (1981). Large-scale mapping, coupled with determination of younging directions from cross stratification and relation of stratification and axial planar cleavage, has shown that this southerly closing fold is a second generation antiform which has affected both stratification and cleavage (figure 29). South of Hirekandavadi and west of Vanivalaspura an antiform with axial culmination having gentle NNW plunge in the north and steeper ESE to SE plunge in the south has a granitic body – the Seranakatte granite – in the core (figures 30a and b). Here also isoclinal first folds have been involved in refolding in large scale on subvertical axial plane striking NNW (figure 31).

Thus, in the Chitradurga belt large-scale refolding on steep axial planes striking NNW are demonstrable throughout. The regional plunge variation of these later folds (with subvertical plunge in the Chitradurga arc; gentle northerly plunge in the Dodguni area; gentle southerly plunge of the Hirekandavadi antiform; gentle northerly plunge in the northern and southeasterly plunge in the southern part of the Seranakatte gneiss west of Vanivilaspura) may be a result of the latest folding on vertical axial planes striking ENE (DhF$_3$). Late granitic intrusion in the core of the Chitradurga arc might have steepened the plunge here to near verticality. Overprinting of DhF$_2$ folding on isoclinal folds of the DhF$_1$ fold system, with or without the intervention of DhF$_{1a}$ folding, is demonstrable in large scale in the Kudremukh belt in the west, Holenarasipur, Nuggihalli and Nagamangala belts in the central part, and Kolar in the

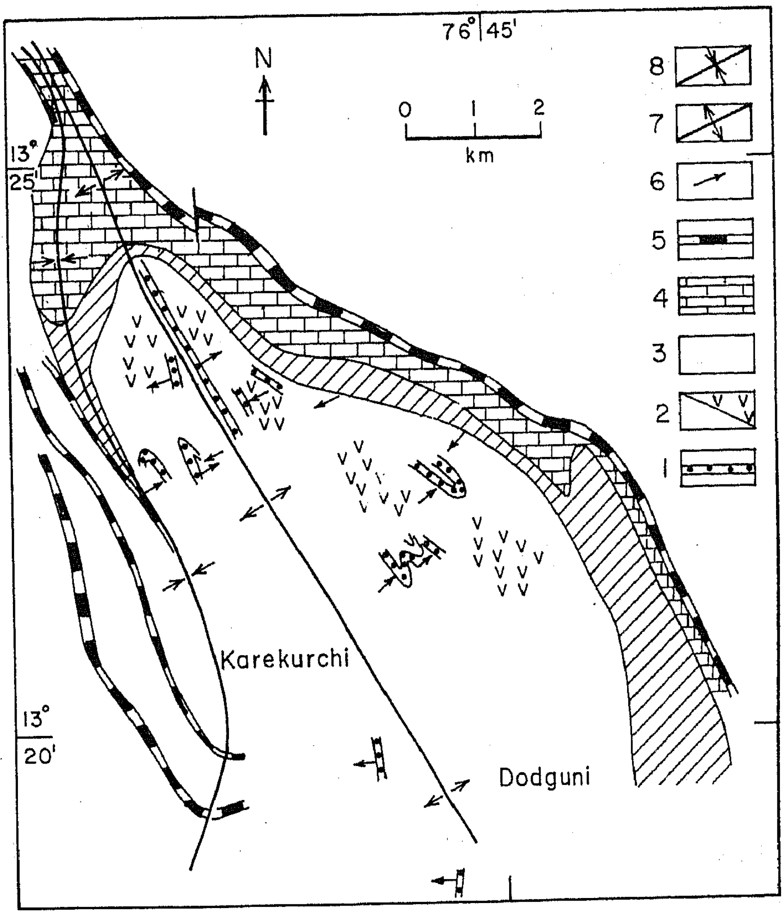

Figure 27. Geological map of the Dodguni area (after Mukhopadhyay and Ghosh 1983, fig. 1). (1) Quartzite; (2) Chlorite-mica schist with metavolcanic rocks; (3) Manganiferous phyllite; (4) Marble; (5) BIF; (6) younging direction; (7) Dodguni antiform (F_2); (8) Karekurchi synform (F_1).

eastern part. The variation in detail in the map patterns of the different supracrustal belts is a reflection of the *tightness of later folding* accentuated by shearing (see also Ghosh and Sengupta 1985, and Mukhopadhyay 1989). It is for this reason that the Kolar and Kudremukh belts are long and narrow in contrast with the Holenarasipur belt. In all these supracrustal belts the terminations are fold hinges, so that the present disposition cannot be taken to represent the shape of the original sedimentational troughs (not palinspastic maps) as some workers postulate (Radhakrishna 1983).

4. Supracrustal rock – Peninsular Gneiss relation

As mentioned in the introductory remarks, the presence of two supracrustal groups – Dharwar and Sargur – was suggested on the basis of their relationship with the Peninsular Gneiss. The Sargur Group is supposed to have been affected by the Peninsular Gneiss, whereas the Dharwar Supergroup of Swami Nath *et al* (1981) overlies the Peninsular Gneiss. Implicit in this argument is the assumption that the Peninsular Gneiss has a stratigraphic significance and is therefore of a particular age. As detailed in the preceding section on the Peninsular Gneiss, it has evolved

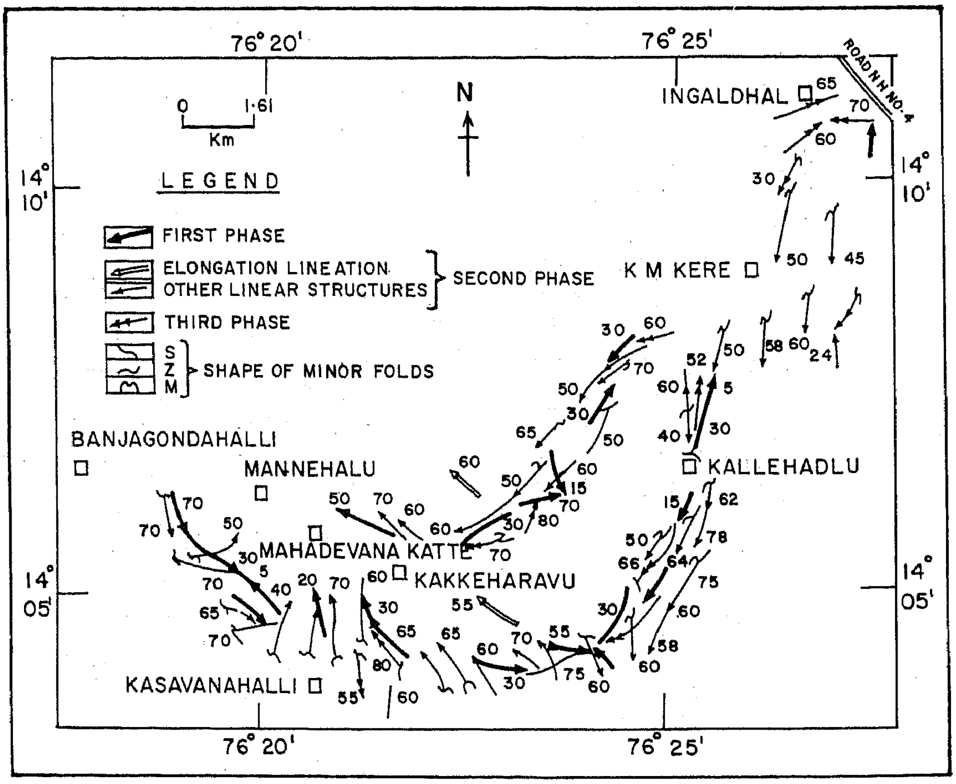

Figure 28. Generalized trend map of the linear structures of three generations south of Chitradurga.

over a protracted period of time. As radiometric data show, the Peninsular Gneiss comprises components ranging in age from 3500 Ma to 2500 Ma (Friend and Nutman 1991; Nutman *et al* 1992; Peucat *et al* 1993; Naha *et al* 1993b). Indeed, migmatization of different phases connected with the evolution of the Peninsular Gneiss is so obvious in the field, that some of the proponents of the Sargur concept have themselves now subdivided the gneisses into different groups such as 'Peninsular Gneiss' and 'Dharwar batholith' (Chadwick *et al* 1996) and 'Hoysala Gneiss' and 'Peninsular Gneiss' (Ramakrishnan 1994). As emphasised by Srinivasan and Naha (1996), the moment the Peninsular Gneiss of diverse ages is accepted, its stratigraphic import is lost, and the Sargur-Dharwar division loses its basis. It is much more important to differentiate the various components of the Peninsular Gneiss on structural, petrological and radiometric data than giving new names to gneisses which cannot be distinguished in the field. The Javanahalli belt, the largest belt of the Sargur Group according to the original suggestion of Swami Nath and Ramakrishnan (1981), shows demonstrable evidence of having been affected by the Peninsular Gneiss (Ghosh Roy and Ramakrishnan 1985). Structural and stratigraphic continuity of these rocks into the rocks of the undoubted Chitradurga Group, has led one of the proponents of the Sargur concept to concede that these rocks belong to the Dharwar Supergroup (Ghosh Roy and Ramakrishnan 1985). Similar evidence is also seen around Karighatta near the southern termination of the Chitradurga belt (Srinivasan 1988). Srinivasan (1988) and Srinivasan and Naha (1996) have shown that the supposed lithological dissimilarity between the Sargur and Dharwar supracrustal rock is a reflection of the grade of metamorphism. It has been shown that shorn of metamorphic impress, both

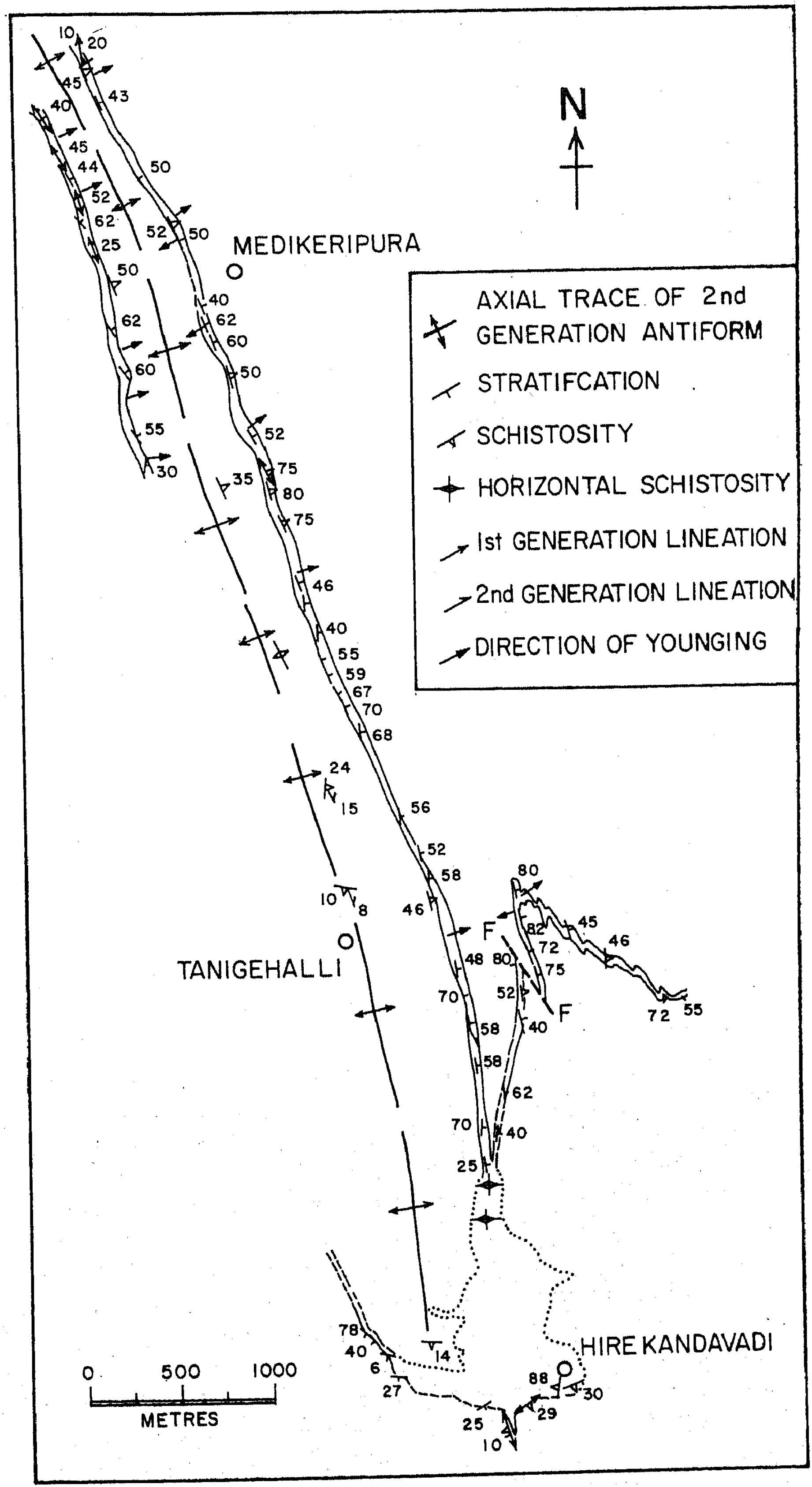

Figure 29. Structural map of the Hirekandavadi area showing the antiformal synclinal structure. Gneiss around Tanigehalli is in the core of the syncline as inferred from younging directions given by cross bedding.

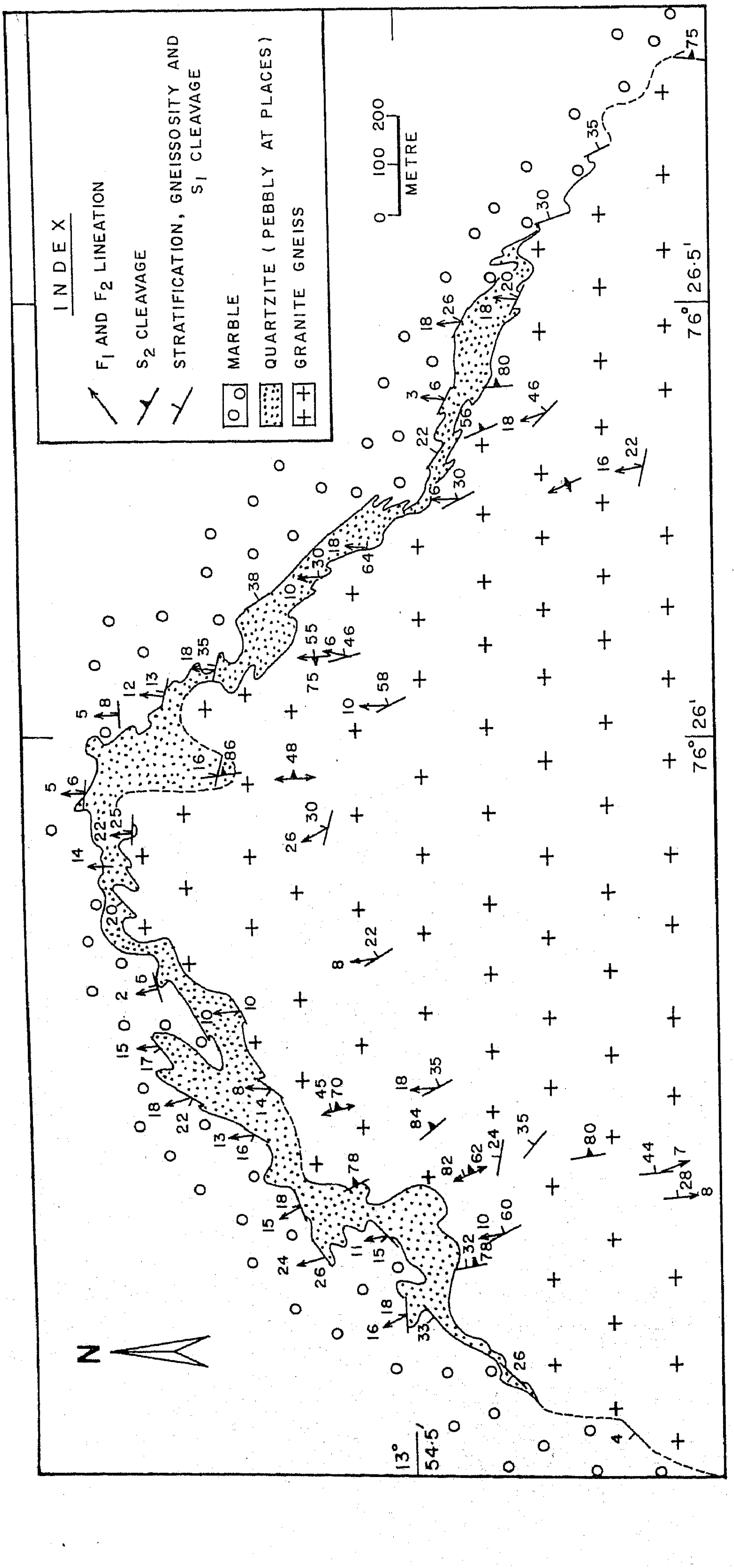

Figure 30(a). Geological map of the northern part of the Serankatte granite gneiss area.

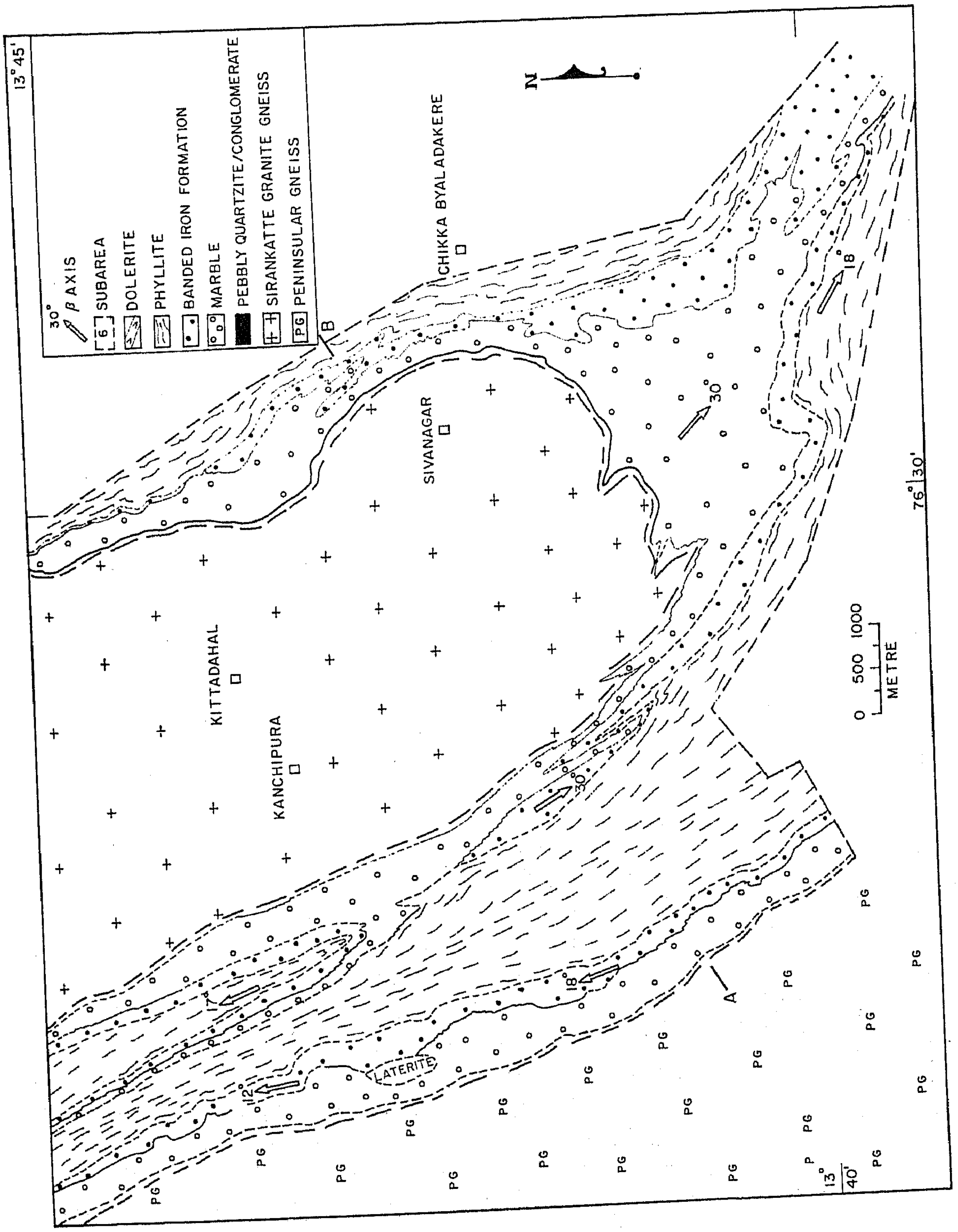

Figure 30(b). Geological map of the southern part of the Serankatte granite gneiss area. Dolerite dykes and subarea boundaries have been omitted in the map.

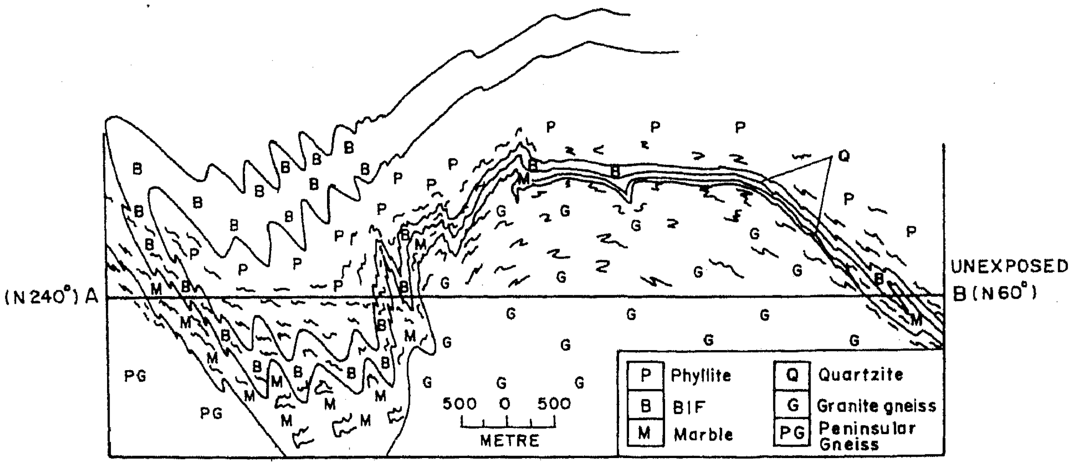

Figure 31. Vertical section along the line A–B of figure 31b normal to an average axial trend of N150°.

the groups of rocks comprise pelitic, psammitic and carbonate rocks and banded iron formation.

As described in the foregoing section, all the supracrustal rocks throughout the Dharwar tectonic province show identical structural sequence. Therefore the argument of structural complexity in separating younger supracrustal belts from an older one does not stand serious scrutiny (Radhakrishna and Vasudev 1977).

One critical criterion forwarded by the proponents of the Sargur concept is the presence of an angular unconformity at a number of places, suggesting that there was a diastrophic event intervening between the deposition of the rocks of the Sargur Group and the Dharwar Supergroup. Three localities were mentioned in this context. In the Shigegudda area the NNW to NW 'lithology strike' of the Peninsular Gneiss and the ultramafic schists of the Sargur Group is supposed to be transected by the stratification planes of the pebbly quartzite of the Dharwar Supergroup (Viswanatha *et al* 1982). As detailed mapping of that area has shown (figure 32), this obliquity is between the foliation of the Peninsular Gneiss and the ultramafic schists on the one hand, and the stratification planes of the metasedimentary rocks on the other. It has also been shown that there is an axial planar cleavage in the rocks of the Dharwar Supergroup which continues as the dominant foliation parallel to the axial planes of isoclinal folds in the rocks of the supposed Sargur Group (Naha *et al* 1986). Angular relation between a plane of depositional significance and a plane of deformational/metamorphic significance cannot be cited in favour of an angular unconformity. Furthermore, superposition of a later folding on younger and older rocks across a plane of angular unconformity would result in fold axes and lineations of diverse attitudes in the two groups of rocks (Naha 1993). It may be mentioned here in parenthesis that the suggestion of an angular unconformity between the supposed Sargur and the Dharwar Groups near Jayachamarajapura (Venkata Dasu *et al* 1991) is based on faulty premises. Here, the contact between two igneous rocks (now metamorphosed) or between a metaigneous rock and a metasedimentary rock has been taken to mark the plane of angular unconformity. By no definition of angular unconformity is this conclusion tenable.

A third area where a Sargur-Dharwar angular unconformity was suggested is in the Honakere arm of the Chitradurga schist belt by the abutting of the nearly EW-trending

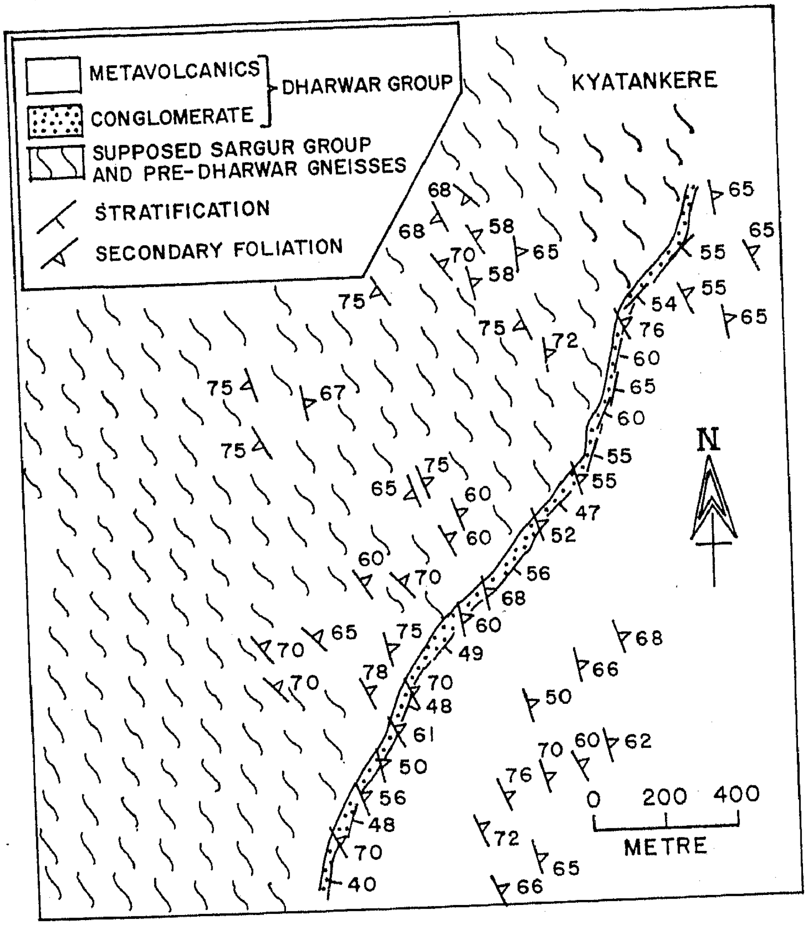

Figure 32. Map of the northern part of the Shigegudda schist belt, showing the continuity of the axial planar schistosity of the Dharwar Supergroup in the supposed Sargur Group and the pre-Dharwar Peninsular Gneiss.

rocks of the Sargur Group against the NS-trending rocks of the Chitradurga Group. The detailed map around Barikoppalu southeast of Nagamangala shows that the structure in actuality represents the hinge and the limb zones of a large-scale refolded fold involving the quartzite of the Dharwar Supergroup (Naha *et al* 1995b; figure 33).

At some localities, e.g., at Kartikere and Kalsapura (south of Bababudan), basal conglomerates point to the presence of an erosional unconformity between the gneiss and the Dharwar Supergroup. However, the basement has been reworked to a large extent.

A number of round or oval shaped granitic bodies occur within the rocks of the Dharwar Supergroup. Foote took some of them to be basement inliers. Pichamuthu (1974) hinted that these granites within the supracrustal rocks might be mantled gneiss domes. By contrast, Swami Nath *et al* (1976) suggested that these bodies might represent horst type uplift of the gneissic basement. However, detailed studies for suggesting a viable structural model have been carried out so far in only one of these granite bodies—the Serankatte granite-gneiss west of Vanivilaspura (Naha *et al* 1995a). This granite-gneiss body is bordered in some parts by a conglomerate. It is a quartz pebble conglomerate in the northern part, but in the southern part granite-gneiss pebbles are also found. It has been shown that the mesoscopic structures both in the metasedimentary cover and the Serankatte gneiss comprise isoclinal folds involved

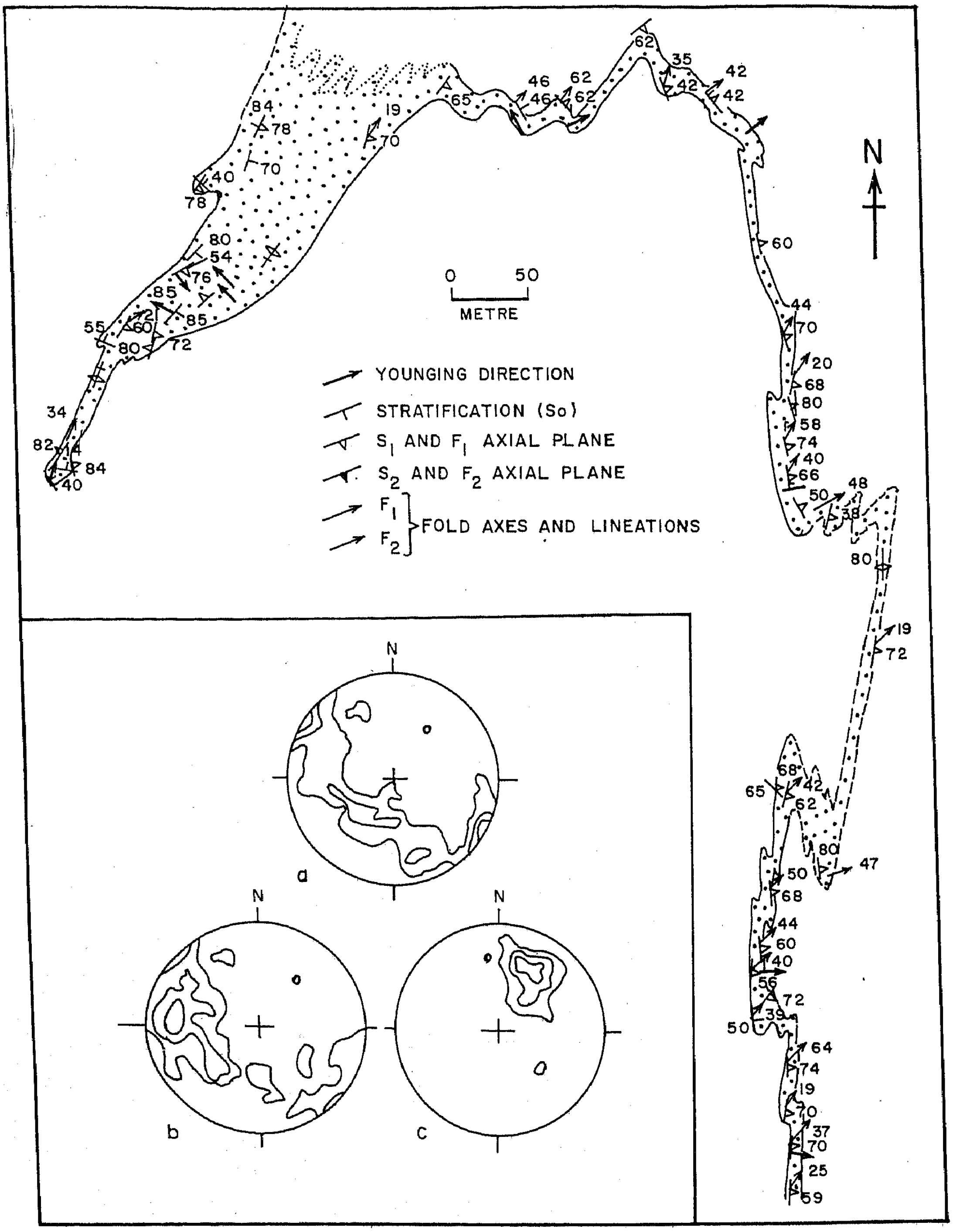

Figure 33. Detailed map of a quartzite band aound Borikoppalu.

in practically coaxial upright folding. An axial planar foliation, both in the granite-gneiss and in the metasedimentary rocks, is also involved in the open DhF_2 folds, the axial planes of which strike NNW to N. A number of discrete shear planes parallel to the axial planes of these second folds point to the importance of brittle deformation in the granite during DhF_2 folding. As the detailed structural maps of the northern and southern parts of the Serankatte granite-gneiss body and adjacent metasedimentary envelope show, the structures of large scale duplicate those of small scale (figures 30a and b). The gneissic body occupies the core of a slightly overturned antiform of second generation with axial culmination (figure 31). The antiform plunges gently NNW in the northern part, and SSE to ESE in the southern part. The Serankatte gneiss body is therefore a mantle gneiss dome of second generation.

One area where Chadwick *et al* (1981) considered the Peninsular Gneiss to form the core of a southerly plunging anticline rimmed by quartzites of the Dharwar Supergroup is the Hirekandavadi fold west of Chitradurga. Detailed mapping here has shown that, the Hirekandavadi fold is an antiform of the second generation affecting isoclinal early folds (Naha and Srinivasan 1988). As the younging direction from cross stratification in the quartzites show, this antiform is a syncline (figure 26). And, if the Peninsular Gneiss has any stratigraphic entity, it has to be younger than the quartzite of the Dharwar Supergroup here (Naha and Srinivasan 1988; Naha *et al* 1993b). According to our observation, the gneisses here have developed by synkinematic migmatization during the first folding of the rocks of the Dharwar Supergroup.

5. Conclusions

Structural-stratigraphic studies carried out by us over a wide region in the Dharwar tectonic province lead us to the following conclusions:

1. Structures of three generations – two major and one minor – are decipherable in all the supracrustal belts, the Peninsular Gneiss and the banded granulites. Isoclinal folds of the first generation (DhF_1) are coaxially folded into open folds (DhF_{1a}); these have been involved in upright folding of varying tightness (DhF_2) with the axial planes striking nearly N-S (NNW to NNE). Late warps (DhF_3) with axial planes striking nearly EW have accentuated the variation in plunge of the DhF_2 folds in some places. The so-called Dharwar orogenic trend represents the strikes of the axial planes of the DhF_2 folds of large scale. This structural history runs counter to the views expressed by Chadwick *et al* (1981, 1985) who consider that a major part of the supracrustal rocks (Dharwar supracrustal belts) has a much simpler structural history.
2. Notwithstanding the claim made by a number of workers (Viswanatha and Ramakrishnan 1976; Viswanatha *et al* 1982; Radhakrishna 1983; Swami Nath and Ramakrishnan 1983; Chadwick *et al* 1985; Venkata Dasu *et al* 1991) that there are two supracrustal sequences (Sargur and Dharwar) separated in time by the Peninsular Gneiss and in space by an angular unconformity, not a single instance of *angular* unconformity stands critical scrutiny.
3. The Peninsular Gneiss is a polyphase migmatite-gneiss complex. Both radiometric and structural dating indicates that it has an extended history of deformation and metamorphism ranging from pre-Dharwar (DhF_*) to DhF_2 events. While the fact that the gneissic layering has been affected by DhF_1 suggests the possibility of gneissic banding being partly pre-Dharwar, the structural history in a dominant portion of the gneissic complex being identical with that of the supracrustal rocks, points to extensive reworking of the basement as well as synkinematic evolution of the gneiss during the deformation of the supracrustal rocks. These latter processes have rendered the extent and history of the pre-Dharwar rocks largely obscure. Having evolved over a protracted period of time, the Peninsular Gneiss has no

stratigraphic significance. Thus the strongest reason for dividing the supracrustal sequence into an older Sargur Group and a younger Dharwar Supergroup intervened by the Peninsular Gneiss loses its validity. Further, the structural relations underscore the fact that the Peninsular Gneiss could not have acted as a brittle basement when the supposed cover rocks of the Dharwar Supergroup were folded. This observation nullifies the claim of brittle deformation of the Peninsular Gneiss during the folding of the Dharwar Supergroup (Chadwick 1994).

4. Two varieties of charnockites differing in age and in process have been identified. The banded charnockite-enderbite-mafic granulite has been involved in the same plan of superposed deformation as the Peninsular Gneiss and supracrustal rocks. By contrast, the patchy charnockites formed during the later phase of DhF_2 folding and are coeval with the emplacement of the Closepet Granite (Naha *et al* 1993a).
5. The Closepet Granite considered earlier to be post-tectonic (Friend 1983) is dominantly a gneissic rock emplaced late-tectonically with reference to DhF_2 folding. Numerous enclaves of Peninsular Gneiss in Closepet Granite often with parallel internal fabric in adjacent enclaves, precludes invasion of the granite as a large magmatic body. Local anatexis affecting the Peninsular Gneiss seems to have played a dominant role in the evolution of the Closepet Granite.
6. A deformational episode, a metamorphic event and a phase of migmatization preceding the first folding of the supracrustal rocks are preserved in scores of small enclaves throughout the Peninsular Gneiss country. These inclusions provide the only clue to the oldest components in the Dharwar tectonic province on which the supracrustal rocks were deposited. The Peninsular Gneiss in its present state is thus an extensively remobilized complex (Naha *et al* 1990, 1991).

Acknowledgements

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