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limentational, structural and migmatitic history of the Archaean arwar tectonic province, southern India

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Abstract. The earliest decipherable record of the Dharwar tectonic province is left in the 3·3 Ga old gneissic pebbles in some conglomerates of the Dharwar Group, in addition to the 3·3–3·4 Ga old gneisses in some areas. A sialic crust as the basement for Dharwar sedimentation is also indicated by the presence of quartz schists and quartzites throughout the Dharwar succession. Clean quartzites and orthoquartzite-carbonate association in the lower part of the Dharwar sequence point to relatively stable platform and shelf conditions. This is succeeded by sedimentation in a rapidly subsiding trough as indicated by the turbidite-volcanic rock association. Although conglomerates in some places point to an erosional surface at the contact between the gneisses and the Dharwar supracrustal rocks, extensive remobilization of the basement during the deformation of the cover rocks has largely blurred this interface. This has also resulted in accordant style and sequence of structures in the basement and cover rocks in a major part of the Dharwar tectonic province. Isoclinal folds with attendant axial planar schistosity, coaxial open folds, followed in turn by non-coaxial upright folds on axial planes striking nearly N–S, are decipherable both in the "basement" gneisses and the schistose cover rocks. The imprint of this sequence of superposed deformation is registered in some of the charnockitic terranes also, particularly in the Biligirirangan Hills, Shivasamudram and Arakalgud areas. The Closepet Granite, with alignment of feldspar megacrysts parallel to the axial planes of the latest folds in the adjacent schistose rocks, together with discrete veins of Closepet Granite affinity emplaced parallel to the axial planes of late folds in the Peninsular Gneiss enclaves, suggest that this granite is late-tectonic with reference to the last deformation in the Dharwar tectonic province.

Enclaves of tonalite and migmatized amphibolite a few metres across, with a fabric athwart to and overprinted by the earliest structures traceable in the supracrustal rocks as well as in a major part of the Peninsular Gneiss, point to at least one deformation, an episode of migmatization and one metamorphic event preceding the first folding in the Dharwar sequence. This record of pre-Dharwar deformation and metamorphism is corroborated also by the pebbles of gneisses and schists in the conglomerates of the Dharwar Group.

Volcanic rocks within the Dharwar succession as well as some of the components of the Peninsular Gneiss give ages of about 3·0 Ga. A still younger age of about 2·6 Ga is recorded in some volcanic rocks of the Dharwar sequence, a part of the Peninsular Gneiss, Closepet Granite and some charnockites. These, together with the 3·3 Ga old gneisses and 3·4 Ga old ages of zircons in some charnockites, furnish evidence for three major thermal events during the 700 million year history of the Archaean Dharwar tectonic province.

Keywords. Sedimentation; structural history; migmatitic history, Dharwar tectonic province; Peninsular Gneiss; Closepet Granite.

For correspondence

1. Introduction

Studies on the interrelation between the supracrustal belts and host gneisses, the high- and low-grade supracrustal sequences, and the gneiss-granulite-granite lead to a better understanding of the evolution of Archaean tectonic provinces. The time relation between the Archaean supracrustal belts and the gneisses in which they occur as enclaves has been a subject of controversy all over the world. Whereas some workers consider these gneisses to be the basement, others on the basis of demonstrable evidence of the supracrustal rocks having been affected by the gneisses, contend that the latter are younger. A third view is that some of these supracrustal rocks are older, while some others are younger than the host gneisses ("older and younger greenstone belts"). Lastly, taking a cue from the pioneering work of Sederholm (1907, 1923 and 1926) a number of workers hold that the extensive gneissic terranes of the Archaean age have not evolved at a single stage, but are polycyclic, evolved through palingenesis in several phases (Read 1955). As elegantly demonstrated for the Lewisian Gneiss in Scotland by Sutton and Watson (1951) (confirmed much later by radiometric dating,

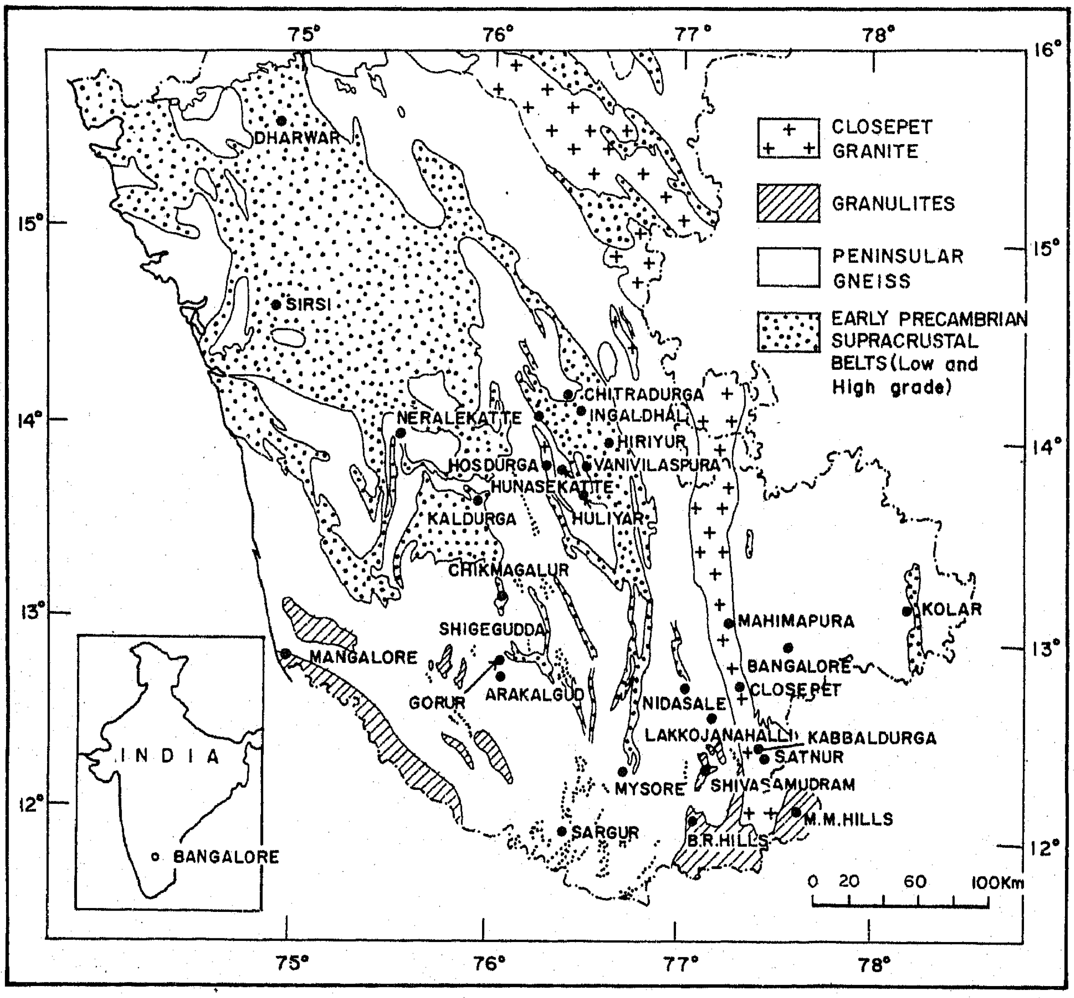

Figure 1. Geological map of the Dharwar tectonic province, with the localities mentioned in the text shown.

see Read and Watson (1975), p. 44–47), relicts of an older basement are left in small enclaves with a fabric athwart to that in the host gneisses.

There is also a divergence of opinion regarding the time relation between the granulites and gneisses occurring side by side. Some consider that the granulites have formed by progressive metamorphism in which the gneisses of the amphibolite facies represent an intermediate stage. The other point of view is that after the rocks were raised to granulite facies, they were involved in retrogression leading to the formation of gneisses of lower grade. Field association and microstructures of critical minerals in relation to deformational episodes can be helpful in resolving this problem. In an attempt at tracing the evolution of the Dharwar tectonic province of south India, we have addressed some of these issues primarily from the view point of sedimentational, structural and migmatitic history.

The Dharwar tectonic province comprises Archaean supracrustal belts (the Dharwar schist belts) consisting of metasedimentary and meta-igneous rocks surrounded by granitoid gneisses termed the Peninsular Gneiss. Within these gneisses, in the southern part in particular, granulites dominantly composed of charnockites and granulite grade metasedimentary rocks (khondalites) crop out. Finally a large body of potash-rich granite, the Closepet Granite, occurs in the east-central part of the Peninsular Gneiss terrane (Figure 1).

2. The Peninsular Gneiss

The Peninsular Gneiss, originally believed to be the basement on which the supracrustal sequence now occurring as number of discrete linear belts was deposited ("Fundamental Gneiss" of Foote 1886), was subsequently considered to be a migmatitic complex which affected the Dharwar sequence (Smeeth 1915; Rama Rao 1940). In recent years, a number of workers have veered round to the view that the gneisses are indeed the basement for the Dharwar supracrustal sequence (Radhakrishna 1967; Swami Nath and Ramakrishnan 1981). For supracrustal rocks which have demonstrably been affected by the gneisses, they erected a separate stratigraphic unit, the Sargur Group. Structural and stratigraphic relations among the different parts of the supracrustal sequence and the Peninsular Gneiss can help in resolving this controversy.

The Peninsular Gneiss is a migmatitic complex similar to the gray gneisses in many other shield areas of the world. The gneissic host in the migmatitic complex is predominantly granodioritic, and has been invaded by pegmatites and aplites. Numerous palaeosomes of diverse shape, size and composition include amphibolite, ultramafic schists, high alumina schists, metamorphozed iron formation, quartzite and marble. Some of the smaller enclaves present throughout the gneissic terrane are tonalitic in composition.

A major part of the Peninsular Gneiss is characterized by structures of three main phases. The first of these is a set of isoclinal folds [DhF_1; DhF_{1a} etc. refer to the different folding events affecting the Dharwar supracrustal rocks. The same terminology has been used where they have affected other rock groups (Naha *et al* 1990)] on gneissosity, with long limbs and sharp hinges, showing all characters of buckle folds modified by flat tening (figure 2). An axial planar foliation is ubiquitous in these folds. They have been involved in near-coaxial open folding of the axial planes (DhF_{1a};

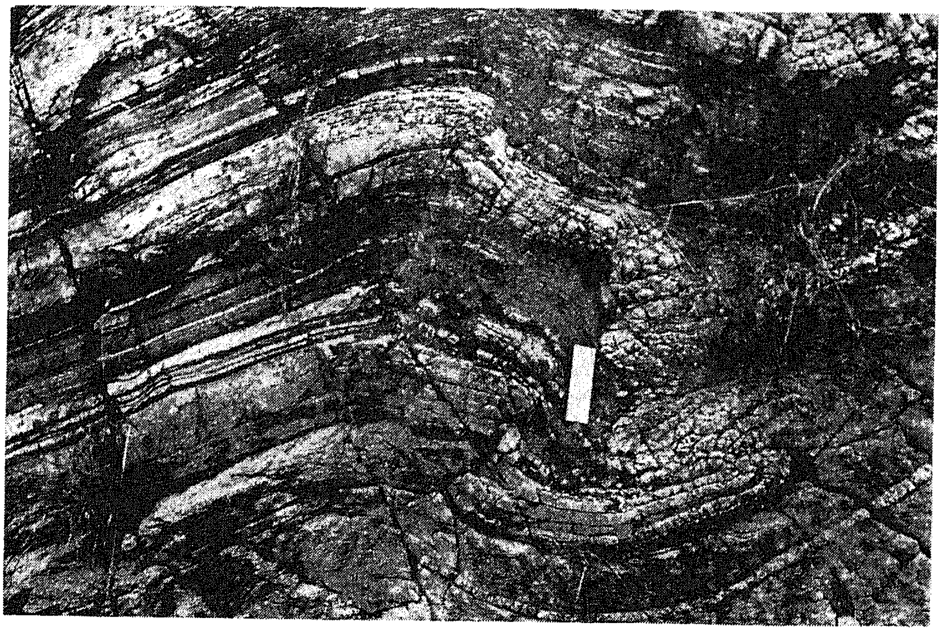

Figure 2. True profile of an almost recumbent DhF_1 isoclinal fold in the Peninsular Gneiss near Mysore, involved in coaxial refolding (taken with permission from *Geol. Rundschau.* vol. 79, 1990).

figure 2). On these structures, a set of upright folds with axial planes striking nearly N–S has been superimposed (DhF_2; Naha *et al* 1986, 1990). At places a schistosity defined by biotite has developed parallel to the axial planes of these folds (figure 3). The last deformational event in these rocks are warps (DhF_3) on EW axial plane at some places, affecting all the earlier structures.

Evolution of the Peninsular Gneiss by migmatization synkinematically with DhF_1 folding is indicated by (a) quartzofeldspathic veins of diverse orientation showing coplanar DhF_1 folds of different tightness, (b) boudinaged quartzofeldspathic veins parallel to the axial planes of DhF_1 isoclinal folds, and (c) evidence of changing ductlity of the host gneisses vis-a-vis the amphibolite inclusions during DhF_1 deformation as detailed in Naha *et al* (1986, 1990). However, migmatization was also attendant with DhF_2 folding. This is borne out by the emplacement of pegmatites and aplites parallel to the axial planes of these folds, development of axial planar schistosity traced by the parallel orientation of undeformed biotite, and the absence of post-crystalline deformation except for minor undulose extinction in the quartz and feldspar grains aligned parallel to their axial planes.

These gneisses, with evidence of superposed deformation, are replete with enclaves of migmatized amphibolites and tonalitic gneisses up to several metres across. These enclaves show a deformational event (DhF_*) which is prior to and overprinted by the DhF_1 folds. This event, which is absent in the main body of the Peninsular Gneiss as well as in all the other rock types, is registered by the following structural features: (a) isoclinally folded amphibolite palaeosome boudinaged in the limbs and affected by DhF_1 folding (figure 4); (b) amphibolite inclusions involved in long drawn-out isoclinal folds with their axial planes transected by and drawn into parallelism with the isoclinal folds of the DhF_1 generation (Naha *et al* 1990, figure 3); (c) an axial planar fabric in amphibolite inclusions overprinted by foliation parallel to the axial planes of the DhF_1 folds in the host gneisses (Naha *et al* 1990, figure 3); and (d) tectonic

Figure 3. Hinge zone of DhF_2 fold in banded gneiss with an axial planar schistosity parallel to scale. Exposure near Bangalore University (taken with permission from *Geol. Rundschau.* vol. 79, 1990).

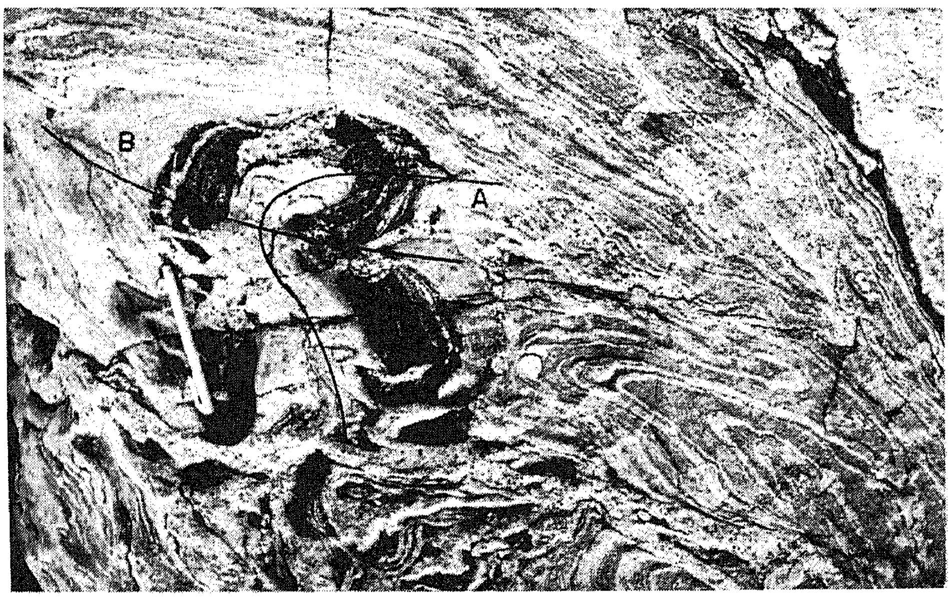

Figure 4. Isoclinally folded and migmatized amphibolite boudinaged in the limbs and subsequently involved in DhF_1 folding in the gneissic host: exposure near Nidasale. A—axial trace of DhF_* fold; B—axial trace of DhF_1 fold (taken with permission from *Geol. Rundschau.* vol. 79, 1990).

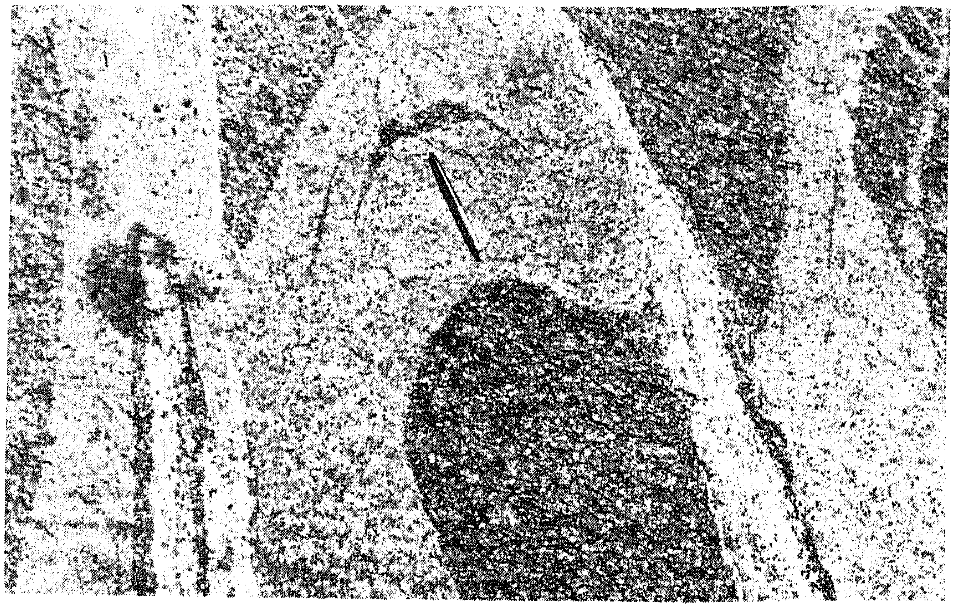

Figure 5. Hinge zone of a DhF_1 fold in Peninsular Gneiss (pen parallel to axial trace) with dark enclaves having a planar fabric (DhF_*) with different orientation in different positions. Exposure near Neralekatte.

inclusions of amphibolite and dioritic gneisses of different shapes having their foliation at diverse angles with the planar fabric of the host gneisses (figure 5). In some sectors, such as near Gorur, Hunasekatte east of Hosadurga and near Neralekatte, Peninsular Gneiss probably retains the original orientation of DhF_1 structures over a large tract.

3. The Dharwar supracrustal sequence

The Dharwar supracrustal sequence has been classified into a lower Bababudan Group and an upper Chitradurga Group. The Bababudan Group comprises detrital and non-detrital sedimentary rocks associated with dominantly subaerial amygdular lava flows. The detrital sediments consist of oligomictic clast-supported quartz pebble conglomerates and quartz arenites. Pelitic rocks are virtually absent in the association. The quartzites are characterized predominantly by trough cross-bedding (figure 6), although herring-bone cross bedding is seen in rare instances. Aeolian ripple marks are noticed at some places. In sectors, where correction for folding was possible, the cross-bedding shows unimodal distribution of palaeocurrents indicating, in conjunction with other lines of evidence, that the quartzites are fluvial deposits. Quartz grains are generally not surrounded by micaceous minerals except in rare arkosic variants. They are mature to supermature mineralogically and submature to mature texturally. Among detrital non-opaque heavy minerals, zircon is dominant, indicating the presence of granitic rocks in the provenance. REE studies of these rocks show pronounced negative europium anomalies, also pointing to the granitic character of the source area (Srinivasan *et al* 1990). These lines of evidence led Srinivasan and Ojakangas (1986) to assign a stable platformal environment for the quartzites and conglomerates of the Bababudan Group. The detrital sediments accumulated as braided fluvial deposits on a peneplaned basement. The interbedding of mafic flows

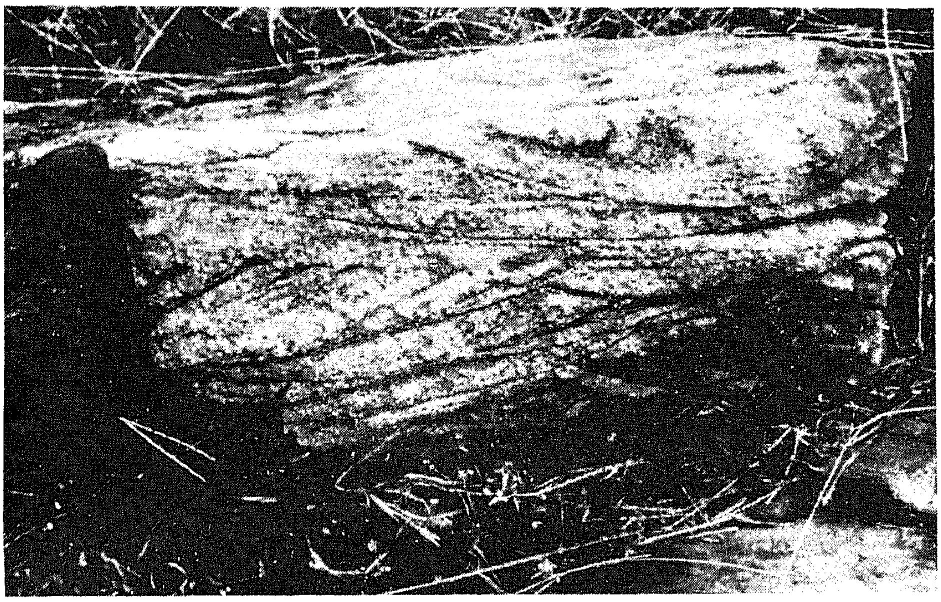

Figure 6. Trough cross-bedding in the quartzite of the Bababudan Group, west of Shigegudda.

with quartzites indicates intermittent rifting of the platform. The continuation of overall stability of the environment throughout the deposition of the Bababudan Group, however, is testified by the deposition of beds of banded iron formation with very strong persistence in strike at the top of the Bababudan Group.

The Vanivilas Formation of the overlying Chitradurga Group is composed of quartz arenite, shale and carbonate, typical of shelf environment. The quartzites show trough as well as planar cross beds and large-scale cross beds with tidal aspects. Wave ripples are also noticed in them at places. The cross-bedding shows bimodal bipolar orientation. The carbonate rocks consist of cherty dolomites and limestones. At places, columnar stromatolites characteristic of intertidal zones are well developed in the cherty dolomites (Srinivasan *et al* 1988). Capping these shelf sediments are banded iron formation which, along with the carbonate rocks, constitute a marker horizon traceable along strike for long distances in the Dharwar supracrustal belts, implying considerable stability in the environment of sedimentation during the deposition of the Vanivilas Formation.

Overlying the sedimentary rocks of the stable zone is a suite of polymictic conglomerates, graywackes, banded iron formation and submarine volcanic rocks, constituting the upper part of the Chitradurga Group (the Ingaldhal Volcanics and Hiriyur Formation). The polymictic conglomerates vary in their character from olisthostromes to graded bedded conglomerates. They are usually mud supported and immature. Pebbles in these conglomerates consist of gneisses derived from the gneissic crust that preceded the formation of the supracrustal sequence (figure 7). The rock formations of the Bababudan Group (quartz pebble conglomerates, quartzites amygdular volcanics, BIF) and Vanivilas Formation (quartzites, cherty dolomites) also supplied to the pebble population in these conglomerates. The conglomerates are not only at the base of the graywacke-pillow lava sequence, but occur interbedded with the graywacke also. The graywackes may be thin or thick-bedded with dominant graded bedding. Slump and flame structures, and rare flute marks and parting

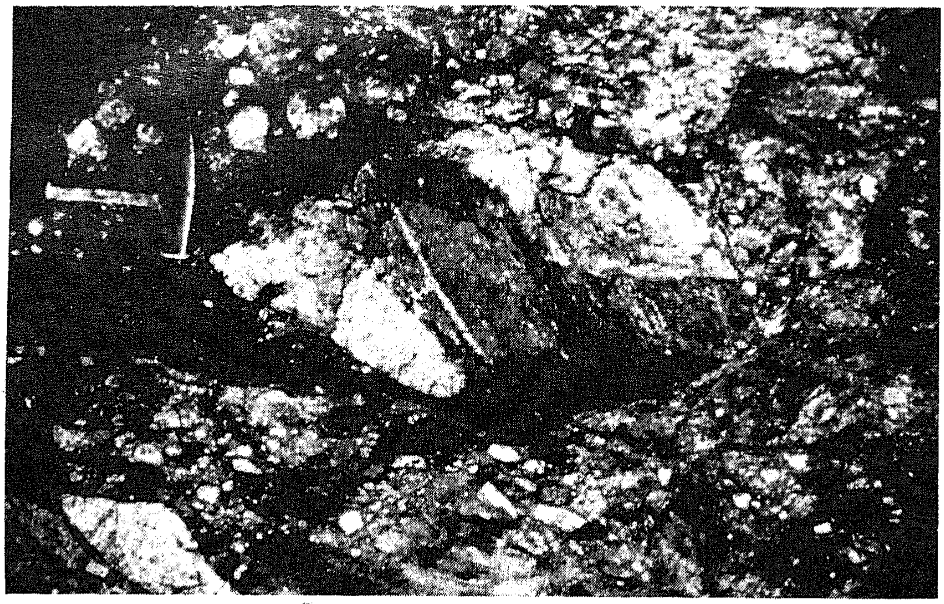

Figure 7. Pebble of banded gneiss in the Kaldurga conglomerate.

lineations have been noted. Complete Bouma cycles occur at places, but partial Bouma beds consisting of Bouma A and B layers are more frequently observed. Petrographic studies show immature sedimentary textures. Volcanic glass fragments derived from contemporaneous submarine volcanism have also been noted, in addition to the extrabasinal terrigenous detritus. The sedimentary structures, association with volcanism, immaturity of rocks and extensive thickness of the graywacke deposits indicate their deposition as turbidites in a mobile depositional environment. Accumulation of sediments of the upper part of the Chitradurga Group in a tectonically unstable environment is also borne out by the iron formations which show strike impersistence unlike the iron formations in the shelf zones. These characteristics of the sedimentary rocks suggest that Dharwar sedimentary basin evolved from a stable to a mobile regime (Srinivasan and Naqvi 1990).

The supracrustal sequence, like the Peninsular Gneiss was involved in three episodes of deformation (Naha *et al* 1986; Mukhopadhyay 1986). The first of these deformations (DhF_1) resulted in isoclinal folding of small to large scales (figure 8) with the development of an axial planar schistosity. An open folding nearly coaxial with the first one (DhF_{1a}) followed. On these structures a set of non-coaxial upright folds with strikes of axial planes varying from NNW to NNE (DhF_2) was superimposed. A crenulation cleavage parallel to the axial planes of these folds has developed at a number of places. These latest folds vary in their tightness from open to nearly isoclinal ones, both in small scale and in the scale of map. Axial plane folding, folded boudinage and interference patterns of diverse types (figure 9; see also Naha *et al* 1986, figure 5) are legion throughout the Dharwar sequence. The superposed folds of the Dharwar supracrustal sequence has given rise to different map patterns. Tight to isoclinal folding of DhF_2 generation has resulted in the map patterns seen in the Kolar, Kudremukh and Holenarasipur supracrustal belts, whereas the map patterns of the Bababudan and Shimoga belts are a consequence of open later folding (see Naha *et al* 1986; Naha and Mukhopadhyay 1990). In many instances the terminations of the supracrustal belts are demonstrably fold hinges of earlier or later generations. The

Figure 8. Type 3 interference pattern due to isoclinal DhF_1 fold involved in near-coaxial DhF_{1a} folding in banded iron formation west of Chitradurga.

Figure 9. Type 2 interference pattern due to superposition of open DhF_2 folding (scale parallel to axial plane) on isoclinal DhF_1 folds (hinge near the coin) in metamorphozed cherty dolomite. Exposure north of Huliyar.

patterns of the supracrustal belts, therefore, should not be taken as palinspastic maps as implied by some workers (Radhakrishna 1983). They are in fact due to a combination of shapes of original sedimentary troughs and large-scale folding of successive generations (modified by topography). Like the Peninsular Gneiss, the supracrustal rocks have also been affected by a mild deformation in the last phase resulting in gentle upright folds on axial planes striking EW (DhF_3).

There is thus a striking similarity in the style and sequence of the folds in both the supracrustal rocks as well as gneisses which are believed by some workers to be the basement. Extensive migmatization in the gneisses synkinematically with the DhF_1 deformation of the supracrustal rocks points to large-scale remobilization of gneisses even if they were the basement. That the Peninsular Gneiss in its present state does not have a stratigraphic entity (basement for the Dharwar supracrustal rocks) is also proved by its presence in the core of an antiformal syncline traced by supracrustal rocks, e.g., the Kandavadi fold in the Chitradurga belt (Naha and Srinivasan 1988). Here also the gneiss schist interface transects the stratigraphic boundary with the gneisses formed by migmatization synkinematic with DhF_1 deformation. Only small enclaves with an earlier fabric oblique to and overprinted by DhF_1 deformation support the inference that parts of the original basement have escaped reconstitution.

According to one school of thought enclaves of some "high-grade" supracrustal rocks in the Peninsular Gneisses belong to a sequence (Sargur Group) older than the Dharwar supracrustal group (Swami Nath and Ramakrishnan 1981). Structural style and sequence in these rocks are identical with those in the Dharwar Group as shown elsewhere (Naha *et al* 1986). The supposed angular unconformity between the Sargur and the Dharwar Groups as postulated by some workers (Viswanatha *et al* 1982) is also non-existent; this inference was based on the angular relationship between the depositional fabric in one group of rocks and the deformational-cum-metamorphic fabric in the other (Naha *et al ibid*). Furthermore, the rocks of the so-called Sargur Group belonging to the amphibolite facies pass gradually into lower amphibolite and greenschist facies in the rocks of the Dharwar Group without any break. Also, rock units of the Dharwar Group pass uninterruptedly into those of the supposed Sargur Group, e.g., in the Yadiyur-Karighatta, Hiriyur-Javanahalli and Honakere sectors of the Chitradurga supracrustal belt (Ghosh Roy and Ramakrishnan 1985; Srinivasan 1988; unpublished work of the authors). Lastly rocks of the Dharwar Group have been invaded by the Peninsular Gneiss just as the rocks of the so-called Sargur Group, e.g., in the Javanahalli belt. Thus, there is no structural, stratigraphic or metamorphic basis for treating these medium grade supracrustal rocks as belonging to separate, older group (Naha *et al* 1986; Srinivasan 1988).

4. The basic granulites and charnockites

It is known that there is a general increase in the grade of metamorphism of the supracrustal rocks in the Dharwar tectonic province southward (Pichamuthu 1962). In this context the question of time of granulite metamorphism in the Dharwar province is of special significance. Basic granulites and charnockites crop out in patches within the Peninsular Gneiss around Kabbaldurga. As one moves towards the south, these rocks become increasingly dominant along with metapelites and iron formation belonging to granulite facies.

These granulite facies rocks range from two pyroxene feldspar garnet granulites (basic granulite) to hypersthene-feldspar-quartz granulites of granitic composition (charnockite *sensu stricto*). They are usually medium-grained, granoblastic, but coarse to very coarse pegmatitic varieties have been noted both in the basic and acidic types. The pegmatitic variants and some of the medium-grained rocks are devoid of any preferred orientation. However, in a major part, these granulitic rocks show a distinct planar fabric. This is represented by a banding where acid and basic granulites alternate. These banded rocks have been involved in attenuated isoclinal folds with sharp hinges. Flattening normal to the axial planes of these folds has resulted in boudinage parallel to the limbs and axial planes. The more brittle basic granulites form boudins, whereas the more ductile charnockites have flown into the boudin necks, occurring as coarse-grained rocks. Coarse-grained to pegmatitic charnockite bands occurring as slightly transgressive veins have been involved in coplanar folding accordantly with the basic granulite host, with the interlimb angles larger. Lastly, hypersthene grains are aligned parallel to the axial planes of these folds, lending an axial planar foliation to these rocks (figure 10). All these lines of evidence indicate that these granulites have formed synkinematically with the first folding (DhF_1). The more acidic types continued to develop up to the end phase of DhF_1 folding, when

Figure 10. Tight to isoclinal folding (DhF_1) in charnockite with hypersthene aligned parallel to axial plane; B R Hills.

flattening (with development of boudinage) replaced buckling. Small charnockite boudins parallel to the axial planes of isoclinal folds in the Peninsular Gneiss also point to the formation of charnockites during DhF_1 folding. The competency relation between the acid and basic granulites deduced from the boudinage is also borne out by the shapes of folds. At some places alternate basic granulite bands show parallel folding in the hinge zones of very tight to isoclinal folds with two such bands coalescing in the limbs, the intervening space between the hinges having been occupied by charnockites. This implies that the much more ductile charnockite has flown into the hinge zones from the limbs where they have been thinned to zero thickness. Hypersthene and plagioclase in some of these granulites show strong post-crystalline deformation, so that the formation of some of the granulites at an early stage of DhF_1 folding cannot be totally ruled out.

These isoclinal folds in banded granulites have been involved in near-coaxial open folding (DhF_{1a}) which has led to type-3 interference patterns in some instances (figure 11). Some outcrops with pods and patches of basic granulite within charnockites might represent relict hinges of folds of two generations because of this type of interference. Boudins of DhF_1 generation have been affected by this open folding (figure 12).

Isoclinal folds in banded granulites have also been affected by open folding with

Figure 11. Isoclinal folds in charnockite involved in open folding; Shivasamudram.

Figure 14. Charnockites in patches and along shear zones in the Peninsular Gneiss; Lakkojanahalli.

however, are the coarse-grained charnockite patches without any directional orientation in the Peninsular Gneiss (figure 14). Finally, charnockites have developed along both ductile and brittle shear zones (which may be conjugate), with alignment of hypersthene along the shear planes in some instances. But, for a major part these charnockites of the later generation are bereft of any megascopic deformational structure.

The foregoing structural relations indicate that granulites have developed at least in two discrete phases, the first synkinematically with DhF_1 folding and the second with DhF_2 folding, with charnockitization outlasting the deformation.

The formation of granulites in relation to the deformational episodes, as deduced in mesoscopic scale, is confirmed by the map pattern of charnockites in some areas. Thus the map patterns of charnockite bands around Arakalgud and south of Sathnur match with those of the supracrustal belts (Pichamuthu and Srinivasan 1983; Naha *et al* 1986; figure 3). The map pattern of the Arakalgud charnockite band shows a southerly closing fold with the strike of the axial plane N–S. However, in the scale of outcrop a number of isoclinal folds with axial planes striking E–W in the hinge zone suggest that the large southerly closing fold is of later generation equivalent to DhF_2 folds in the supracrustal belts. In addition to the time relation, this geometrical relation would imply that the protoliths of these granulites were concordant igneous (sills and/or lava flows) or sedimentary bodies. This is also borne out strikingly by interlayered metasedimentary rocks and charnockites involved in identical fold patterns in a number of instances, as for example in M M Hills.

5. The Closepet Granite

The Closepet Granite comprises quartzofeldspathic rocks having different proportions of quartz and feldspar with divergent textures and varying grain size. The common feature in all these different types is the presence of potash feldspar as the dominant constituent. Also, barring rare exceptions, the Closepet Granite is a well-foliated rock with feldspar megacrysts defining the banding. These "granites" range from fine-grained aplites to coarse-grained pegmatites, and from rare unfoliated granites through gneissose granites and granitic gneisses with distinct preferred orientation of feldspar megacrysts and mica tablets, to augen gneisses with feldspar eyes floating in a quartzofeldspathic gneissose base. Inclusions of Peninsular Gneiss ranging from a few centimetres to tens of metres across are present within the granite. Significantly, these inclusions are not restricted to the boundary zone of the granite; numerous inclusions of the Peninsular Gneiss are present even in the heart of the Closepet Granite body (e.g., near Ramanagaram). In zones with Closepet Granite and Peninsular Gneiss inclusions showing a planar fabric, the foliation from one passes to the other undeviated. At a number of places, the feldspar alignment within the granite swerves sympathetically with the border of the inclusions. In zones where the s-surfaces in the Peninsular Gneiss enclaves show DhF_2 folding with the development of a DhF_2 axial planar schistosity, the banding in the Closepet Granite as defined by the feldspar megacrysts is also involved in accordant folding (figure 15). An axial planar schistosity has also developed in the granitic rock in such instances. Veins of Closepet Granite ranging from centimetres to a few metres width show pinch-and-swell

Figure 15. Peninsular Gneiss (dark) 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.

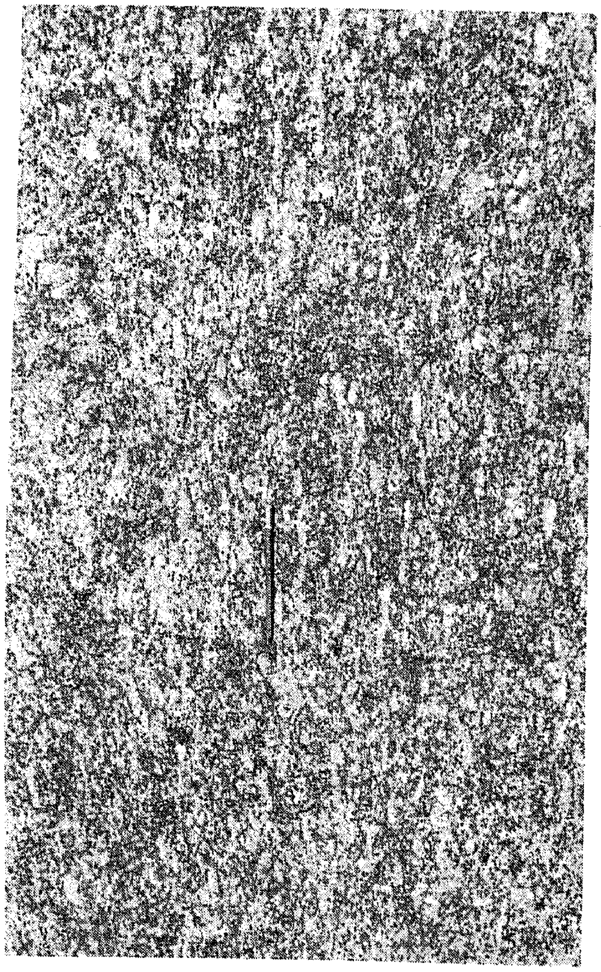

Figure 16. Feldspar augen in Closepet Granite aligned parallel to the axial planes of DhF_2 folds; Mahimapura.

and boudinage structure parallel or subparallel to S_2 schistosity (axial plane of DhF_2 folding). In the porphyritic variant of the granite, the feldspar megacrysts aligned parallel to the axial planes of DhF_2 folds also show pinch-and-swell and boudinage structures in a few instances. Lenticular boudins of feldspar have finally led to augen structure in Closepet Granite (figure 16). In a few instances folded (DhF_2) Peninsular Gneiss enclaves have been invaded by porphyritic granite in the scale of metres. The folded gneissosity in the Peninsular Gneiss passes uninterruptedly through the discrete Closepet Granite patches separating the enclaves. That some of these patches of granite are structureless implies generation of granitic melt locally without destroying the fold geometry of the Peninsular Gneiss. Some shear zones parallel to or at an angle with the S_2 schistosity have affected both the Peninsular Gneiss inclusions and the host granite. Quartzofeldspathic veins related to the Closepet Granite have been emplaced along these shear zones also, with the alignment of the feldspar megacrysts parallel to the shear surfaces.

Closepet Granite is believed by some workers to be post-tectonic (Friend 1983). However, the foregoing descriptive details of the granite and the arguments given below lead us to conclude that the Closepet Granite was emplaced late-kinematically with DhF_2 deformation, the final phase of the granitic emplacement outlasting the movement.

The earliest phase of the Closepet Granite is represented by the granites with banding defined by feldspar megacrysts involved in DhF_2 folding. The boudinage and pinch-and-swell structures shown by these megacrysts, when aligned parallel to the axial planes of folds, indicate that they must have been emplaced prior to flattening connected with the folding event. Veins of Closepet Granite along foliation in Peninsular Gneiss are considered to have been emplaced in a dynamic milieu during the DhF_2 deformation. Discordant veins involved in DhF_2 folding also belong broadly to the same generation. Closely associated in time are the granites where a distinct planar fabric defined by feldspar and/or mica has developed parallel to the axial planes of the DhF_2 folds.

Veins of Closepet Granite oblique to the foliation in the Peninsular Gneiss host and unaffected by DhF_2 folding have been emplaced in a static environment when DhF_2 movement had ceased. These, as well as the structureless granite pockets in Peninsular Gneiss, represent the last stage of formation of the Closepet Granite. Integrating, it may be concluded that the Closepet granite was emplaced syntectonically with reference to the DhF_2 folding in the Dharwar province. At some places, the emplacement outlasted the DhF_2 deformation. The retention of the structural geometry of the Peninsular Gneiss enclaves, large and small, within the Closepet Granite, precludes the possibility of the emplacement of a large magmatic body. Evidence of local melting and swerving of primary foliation around the enclaves, indicate that the Closepet Granite could not have formed by *in situ* metasomatism as suggested by some workers. An anatectic melt with a large number of enclaves of Peninsular Gneiss remaining as restites and emplacement in an essentially solid framework during the later phase of DhF_2 folding seems to explain all the known features.

6. Interrelation of the Peninsular Gneiss, charnockite and Closepet Granite

The sequence of development of the Peninsular Gneiss, the charnockites and basic granulites, and the Closepet Granite in relation to the deformational episodes affecting the Dharwar supracrustal rocks leads us to the following inferences regarding the interrelation of the different rock groups:

(i) The most dominant structures in the Peninsular Gneiss are a set of isoclinal folds on gneissosity which can be correlated with the earliest decipherable folds on lithological layering (DhF_1) in the supracrustal rocks of the Dharwar Group. Evidence has been adduced to demonstrate that migmatization synkinematic with DhF_1 deformation was a major event in the evolution of the Peninsular Gneiss. The banded acid and basic granulites also show isoclinal folding of the DhF_1 phase with basic granulites boudinaged and charnockites in the boudin necks in a number of instances. Charnockite pockets at the necking points of DhF_1 boudins in Peninsular Gneiss point to the formation of the charnockites from the gneisses during the later phase of DhF_1 deformation. However, charnockite cores in basic granulite boudins occurring as palaeosomes within the gneisses indicate that the formation of charnockites at a few places preceded the emplacement of the Peninsular Gneiss.

(ii) Enclaves of migmatized amphibolites and tonalitic gneisses in the scale of metres with a fabric earlier than and overprinted by DhF_1 structures in the gneissic host point to a metamorphism, migmatization and deformation preceding the DhF_1 folding

(DhF_*). These structures, which are present only in the palaeosomes within the Peninsular Gneiss, are absent in the supracrustal sequence, the granulites and the Closepet Granite.

(iii) DhF_1 folds in the Peninsular Gneiss have been involved in near-coaxial open-folding, followed by non-coaxial upright folding on axial planes striking nearly N–S. A schistosity (S_2) has developed parallel to the axial planes of the DhF_2 folds, attendant with migmatization in a number of instances. Likewise, coaxial refolding and non-coaxial upright folding has affected the DhF_1 folds in charnockites and layered granulites. An axial planar schistosity of DhF_2 generation with hypersthene forming along these planes have been noted in a number of places.

(iv) That the Closepet Granite was emplaced synkinematically with the DhF_2 deformation is indicated by folding of layers defined by alignment of megacrysts, attendent with axial planar foliation traced by feldspar and mica grains. Cross-cutting veins of potassic granite unaffected by any folding provide evidence for granite emplacement outlasting the deformation.

(v) Closepet Granite and charnockites are closely associated in a number of places (see also Friend 1981). In some instances banded acid and basic granulites of earlier (DhF_1) generation with axial planes striking WNW have been invaded by diversely oriented veins of Closepet Granite as well as by pegmatitic charnockites. The latter grades into granite in a number of places. Elsewhere, mutual intrusive relation of Closepet Granite and pegmatitic charnockite has been noted. Both the Closepet Granite and charnockites of the second generation occur along shear zones, in pockets and as discordant veins in the Peninsular Gneiss and the banded charnockites of the first generation. All these features indicate that the charnockites of the second generation (Kabbal type) and the Closepet Granite are closely related in time (cf. Friend 1983) and have evolved during the later phase of DhF_2 folding. As in the Peninsular Gneiss a minor phase of deformation (DhF_3) caused warps on nearly EW axial planes in all the other rock types.

7. Discussion

Linking the geological events traced in the foregoing section with the available radiometric ages is beset with difficulties because of (a) paucity of data compared to the complex geology of a large terrane; (b) ages gathered by different methods of varying reliability; and (c) lack of structural-stratigraphic control of many of the samples dated. Therefore, our attempt at tying the evolutionary history of the Dharwar province detailed above with geochronological data is necessarily conjectural.

The available radiometric age data for the Peninsular Gneiss show a range from 3·3 to 2·5 Ga (Beckinsale *et al* 1980; Taylor *et al* 1988), with three peaks at around 3·3, 3·0 and 2·5 Ga. The Sm-Nd whole rock isochron age of volcanic rocks rocks of lower part of the Dharwar sequence (Bababudan Group) is $3{\cdot}02 \pm 0{\cdot}23$ Ga (Drury *et al* 1983); and the T-DM model age for the volcanic rocks of the upper part of the Dharwar sequence (Chitradurga Group) is between 2·99 and 3·06 Ga (Taylor *et al* 1988). The charnockites and other granulites have yielded ages of 2·9 and 2·5 Ga (Buhl 1987; Mahabaleswar and Peucat 1988; Peucat *et al* 1989). (There is a report of 3·4 Ga U–Pb age of zircon in charnockites of B R Hills, Buhl (1987); quoted in Field Guide, LPI Tech. Rept. No. 88–06, p. 265). But this is supposed to be the age of the

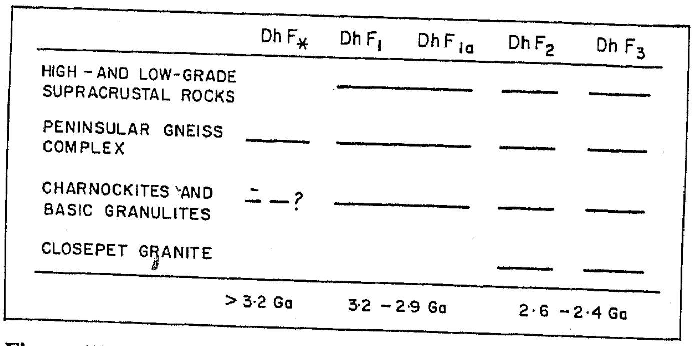

Figure 17. Summary of evolution of the components of the Dharwar tectonic province with references to deformational episodes.

protolith, *not* metamorphic age; Raith, personal communication). Lastly the Closepet Granite has furnished an age of about 2·6–2·5 Ga (Taylor *et al* 1988).

The depositional, metamorphic and migmatitic history of the various rock groups in the framework of the different tectonic episodes, points to evolution of the Dharwar province on the following lines (figure 17). The supracrustal belts of the Dharwar province developed on a gneissic crust of about 3·3 Ga age. 3·3 Ga age of gneissic pebbles of the Kaldurga Conglomerate justifies such a surmise. The small enclaves of migmatite, amphibolite and tonalitic gneisses, distributed throughout the Peninsular Gneiss terrane, with evidence of at least one earlier structural, metamorphic and migmatitic event, indicate that the Peninsular Gneiss basement did not form at one stage, but in successive stages. This stable crust supported the early platformal and shelf sedimentation of the Bababudan Group and lower part of the Chitradurga Group, coupled with mainly subaerial volcanism of age around 3·0 Ga as registered in the Bababudan volcanics. This initial stability was a temporary one and was followed by rifting and volcanism together with sinking of the sedimentational trough, leading to a mobile environment. This resulted in the outpouring of submarine pillow lavas of 2·9 Ga and deposition of turbidite graywackes in the upper part of the Chitradurga Group.

In the next stage large-scale tangential compressive strain caused very tight to isoclinal folds to form in the supracrustal sequence. Presence of flat-lying folds of this generation over a considerable area (as for example in parts of the Bababudan belt; cf. Drury *et al* 1984) implies that subhorizontal simple shear in conjunction with pure shear affected the horizontal supracrustal sequence in some zones. Dominantly pure shear in the later stages of this movement led to coaxial upright folding. Metamorphism and large-scale migmatization accompanied the first intense movement resulting in the evolution of the Peninsular Gneiss to its present state. This migmatization which, on the basis of the available geochronological data, can be taken to be at about 2·9 Ga, has largely blurred the basement-cover interface. Metamorphism during this stage resulted in a variation from greenschist to granulite facies at different tectonic levels. After a significant time gap, a thermal and deformational event at 2·5 Ga affected the metamorphic and migmatitic rocks. Essentially E–W horizontal compression during this stage gave rise to upright folds on axial planes striking nearly N–S, reorienting the supracrustal belts to their present attitude. In this phase also, there was renewed metamorphism whose effect is discernible in the metamorphic rocks as well as the Peninsular Gneiss. Migmatization synkinematic with DhF_2 and granulite metamorphism of the second phase are a consequence of this event. Partial melting during this stage resulted in the formation of the potash-rich Closepet Granite whose emplacement was controlled by the orientation of the DhF_2 folds.

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