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Geometric analysis and significance of mesoscopic shear zones in the Precambrian gneisses around the Kolar Schist Belt, south India

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Abstract—Mesoscopic shear zones are well preserved in the gneisses around the Kolar Schist Belt, located in the eastern part of the northern granite–greenstone association of the south Indian Precambrian terrain. The majority of these shear zones are of ductile to brittle–ductile type with both dextral and sinistral senses of movement. The detailed geometry and large-scale mapping show that sinistral shear zones strike dominantly NW, whereas dextral shear zones strike dominantly NE and form a conjugate pair. The bisectors of statistically preferred orientations of these two sets of shear zones indicate that they developed in response to an E–W subhorizontal compression which can be correlated to the late stage of the F_2 folding seen inside the schist belt. Displacement vectors along these shear zones are invariably subhorizontal, precluding the possibility of overthrusting or underthrusting relationship between the schist belt and surrounding gneissic terrains. If the schist belt is a major shear zone, the displacement across it can not be more than 15 km.

INTRODUCTION

FOR a long time structural geologists working in basement or crystalline gneisses have recognized that strain in these rocks is often localized in narrow zones which are loosely termed shear zones (Ramsay 1980, Ghosh 1985, Ramsay & Huber 1987). It is to be expected that during the same compressive strain, supracrustal rocks with well-preserved layering would respond by buckle folding or boudinage whereas the rather isotropic gneissic rocks would yield initially by homogeneous strain, subsequently leading to the development of shear zones. Such shear zones vary in size from hundreds of km (e.g. Coward 1980), through the scale of an outcrop (e.g. Ramsay & Allison 1979) to a microscopic scale (e.g. Simpson & Schmid 1983). Since Ramsay & Graham (1970) devised methods to estimate strain in shear zones there has been a considerable interest in recent years in this type of deformation. Analyses of shear zones provide us with many useful parameters such as shear strain, amount and direction of tectonic transport, percentage of volume change, and, from conjugate shear zones, compression direction (Ramsay 1980).

Mesoscopic shear zones are very well developed in the gneisses around the Kolar Schist Belt in the Precambrian of south India (Figs. 1 and 2). An analysis of these shear zones enables us to determine the compression directions during the development of these zones and places a reasonable constraint on the large-scale shear displacement.

GENERAL GEOLOGY

Like Precambrian terrains all the world over, the south Indian craton is characterized by a duality of tectono-metamorphic regimes: a southern granulite–gneiss association and a northern greenstone–granite association (Fig. 1). The Kolar Schist Belt (Fig. 2), located in the eastern part of the northern greenstone–granite association, is an 80 km long N–S-trending, 3–5 km wide belt, the greater part of which is composed of metamorphosed mafic–ultramafic rocks (Viswanatha & Ramakrishnan 1981, Rajamani *et al.* 1985). This linear belt occurs in a sea of 'Peninsular Gneiss'—an undifferentiated migmatitic gneiss complex of tonalite–

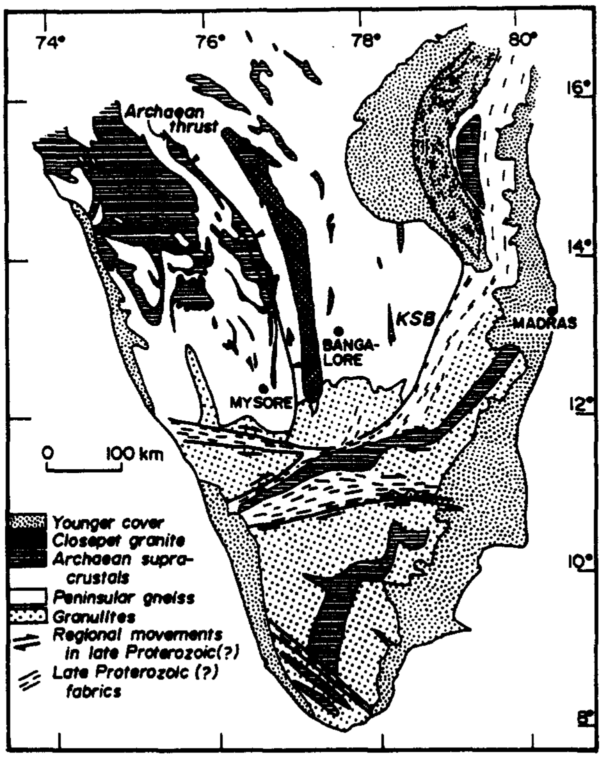

Fig. 1. Geological map of south India (simplified after Drury *et al.* 1984) showing the location of Kolar Schist Belt (KSB).

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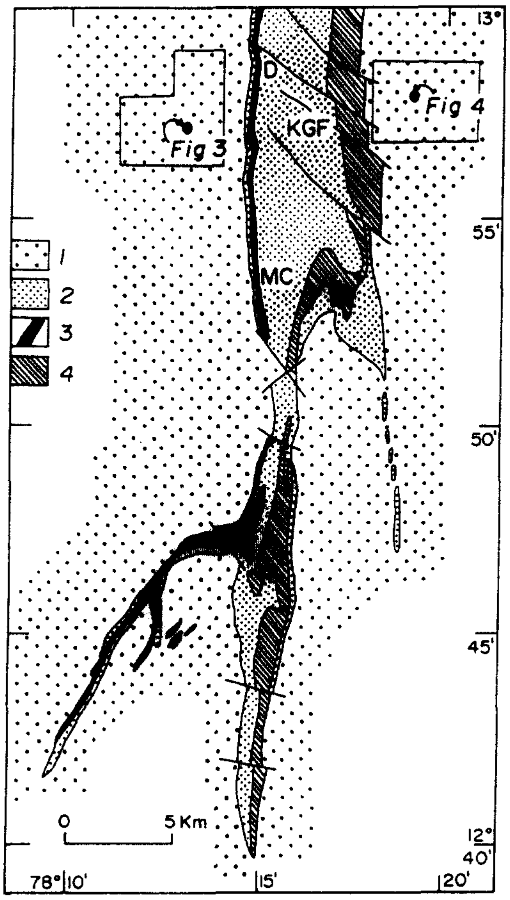


Fig. 2. Geological map of the Kolar Schist Belt (slightly modified after Viswanatha & Ramakrishnan 1981). 1. Undifferentiated Peninsular Gneiss; 2. metamorphosed mafic–ultramafic rocks (amphibolites); 3. banded ferruginous quartzite; 4. felsic volcanics and volcaniclastic sediments. D. Dodbetta; KGF, Kolar Gold Fields; MC, Mudge's Corner. Enclosed areas in the gneisses are the areas of study. Large filled circles are the locations of outcrops whose detailed structural maps are given in Figs. 3 and 4.

granodiorite composition with accompanying granitoid intrusive suites.

In recent years several workers have studied the Kolar Schist Belt in order to understand the deformational history of the belt (Viswanatha & Ramakrishnan 1981, Ghosh & Sengupta 1984, 1985, Hamilton & Hodgson 1986, Mukhopadhyay in press). Mesoscopic shear zones are well preserved in the banded ferruginous quartzite that crops out near the western margin, but within the schist belt (Ghosh & Sengupta 1985, Mukhopadhyay in press). Hamilton & Hodgson (1986) and Mukherjee *et al.* (1986) have also reported shear zones of mappable dimensions from metamorphosed mafic–ultramafic rocks of the schist belt.

No detailed account of structures in the gneisses around the Kolar Schist Belt is available. Naha *et al.* (1986) proposed a structural unity for all the Precambrian rock groups, including the Peninsular Gneiss, of south India: two phases of near coaxial folding overprinted by a set of open cross folds were thought to have affected all the rock units. They also reported examples of vestigal pre-first folding structures in the Peninsular Gneiss. However, Mukhopadhyay (1986) contends that there is a marked heterogeneity in the deformation of the Peninsular Gneiss, and the deformation style is more complex than a simple superposition of two or more generations of folding. Drury & Holt (1980) and Drury *et al.* (1984) suggested that in the south Indian craton, the structures that formed at the close of Archaean time by northward accretion were later refolded and dislocated by large N–S strike-slip shear belts, which imparted intense and steep planar fabrics to large volumes of the crust. They also reported large E–W shear belts of probable Proterozoic age. However, no detailed analysis of these shear zones is available.

The mesoscopic shear zones in the gneisses were studied in detail in an area of about 21 km^2 on the eastern side, and in an area of about 19 km^2 on the western side, of the Kolar Schist Belt (see Fig. 2). In addition one outcrop on each side of the schist belt was mapped in detail at scales ranging from 1:50 to 1:10 using tape-and-compass and metre-grid methods. The maps presented in this paper (Figs. 3 and 4) are greatly reduced from original field maps. Further, more than 1200 compass readings on veins, foliations, lineations and shear zones have been plotted and analyzed on stereograms and rose diagrams.

ROCK TYPES

The gneisses around the Kolar Schist Belt include several granitoid components. Balakrishnan & Rajamani (1987) have described in detail the petrography, geochemistry and petrogenesis of these rocks. Isotope systematics and geochronology of the granitoids have been determined by Krogstad *et al.* (1988).

To the west of the schist belt the gneiss terrain includes at least two major components: a leucocratic Dosa Gneiss of larger areal extent and a much less dominant Dod Gneiss which is relatively more melanocratic (Fig. 3). The Dosa Gneiss is a coarse-grained granodioritic rock, essentially composed of plagioclase, quartz, K-feldspar, hornblende and biotite with minor proportions of apatite, sphene, zircon, epidote, garnet and sulphides. In hand specimen they are characterized by the presence of megacrysts of feldspars, which are commonly deformed. The coarse-grained Dod Gneiss is tonalitic to quartz-monzodioritic with up to 30% ferromagnesian minerals. The fact that Dod and Dosa include each other (see Fig. 3) and that they have similar zircon ages (Dosa Gneiss—2613 ± 10 Ma and Dod Gneiss—2633 ± 8 Ma, Krogstad *et al.* 1988) suggest that they are broadly coeval.

The Kambha Gneiss, the dominant rock type on the eastern side of the schist belt, is again a coarse-grained leucocratic granodioritic rock. In contrast to the Dosa Gneiss, the Kambha Gneiss lacks megacrysts of feldspar. Otherwise these two rock types are very similar in hand specimen appearance and mineral assemblage. However, Krogstad *et al.* (1988) have shown that the Dosa Gneiss is about 80 Ma older than the Kambha Gneiss (2532 ± 10 Ma) and, more significantly, isotope

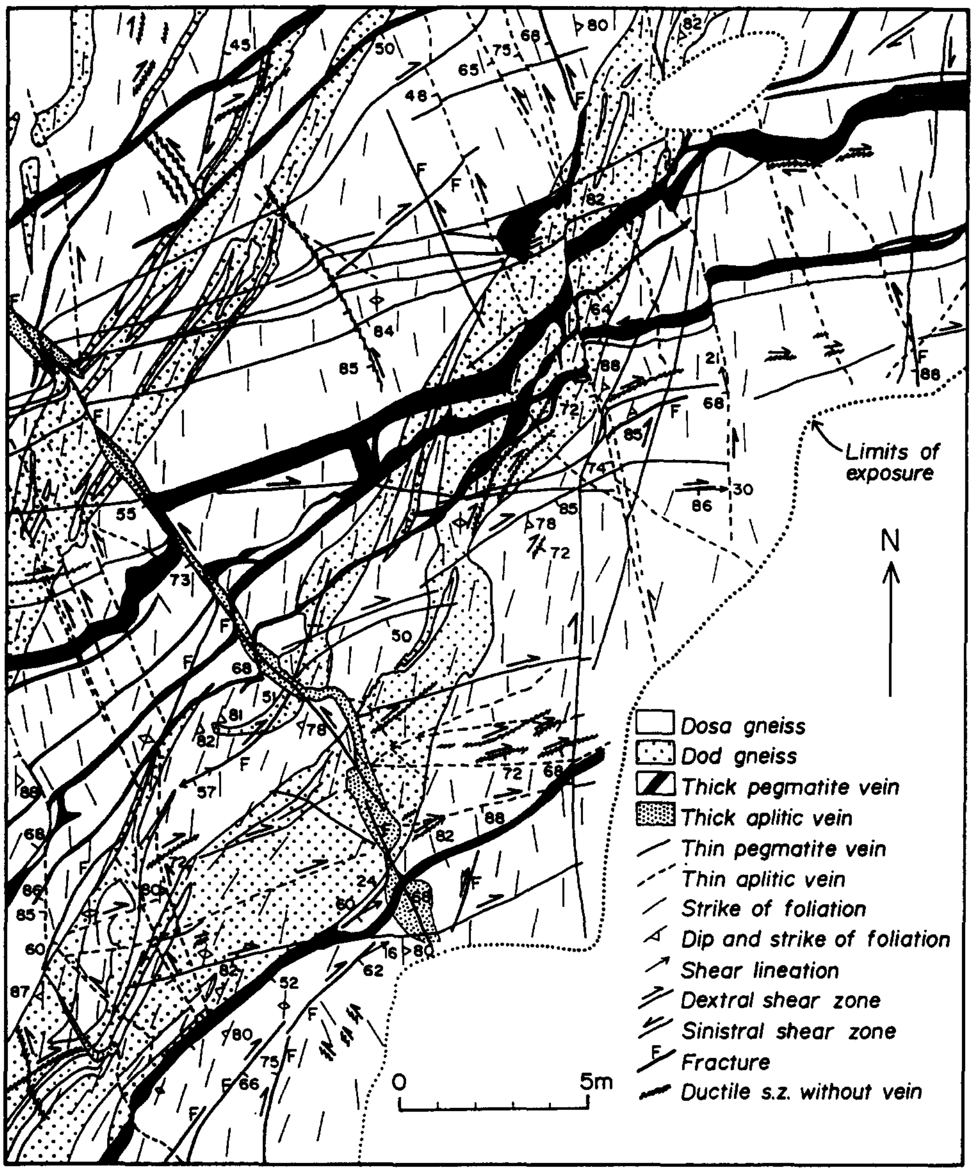


Fig. 3. Detailed structural map of an outcrop in the western gneisses. For location of the outcrop see Fig. 2.

systemics of these two rock types are distinctly different, suggesting that they are genetically unrelated. At places the Kambha Gneiss includes a medium- to coarse-grained dark-coloured component, here termed the Madura Gneiss (Fig. 4), which is quite distinct from the Dod Gneiss to the west. The Madura Gneiss occurs as folded bands and probably represents diabase dykes now partially absorbed and deformed.

Gneisses on both sides of the schist belt include rafts of banded gneiss (Fig. 4) and mafic xenoliths of variable sizes and shapes. Several generations of fine-grained granitic dykes (see Fig. 4), as well as aplitic and pegmatitic veins, have invaded the gneisses. However, aplitic and pegmatitic veins are much more common in the western gneisses, where shear zones have commonly propagated along these veins (see Fig. 3).

Most of the coarse-grained gneiss is foliated. The intensity of development of foliation varies from almost unfoliated homogeneous rocks to very well foliated rocks with sporadic gneissic banding. Foliation is defined by the parallel alignment of biotite flakes, clusters of ferromagnesian minerals, and elongated quartz and feldspar. On either sides of the schist belt foliation planes are subvertical with a nearly N–S strike (Fig. 5). Superposed folds and boudinage structures are abundant: these are outlined by the gneissic banding, and by migmatitic layering in gneiss and migmatized mafic xenoliths. Mesoscopic shear zones affect and disrupt all these structures indicating that there was pre-shearing deformation(s) in the gneisses. However, in this paper we have not attempted to decipher the pre-shearing deformational history in the gneisses.

GEOMETRY OF SHEAR ZONES

The shear zones vary widely in size. The strike lengths of shear zones range from about 5 cm to over 500 m whereas the width varies from about 3 mm to about 1 m. All the three basic types of shear zones (Ramsay 1980),

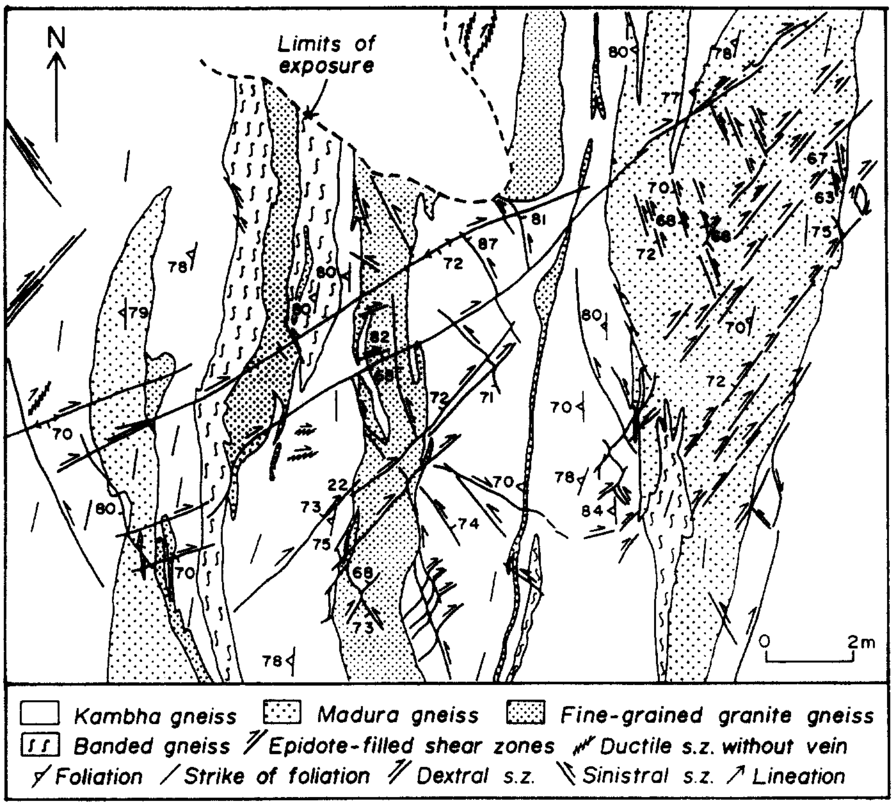


Fig. 4. Detailed structural map of an outcrop in the eastern gneisses. For location of the outcrop see Fig. 2.

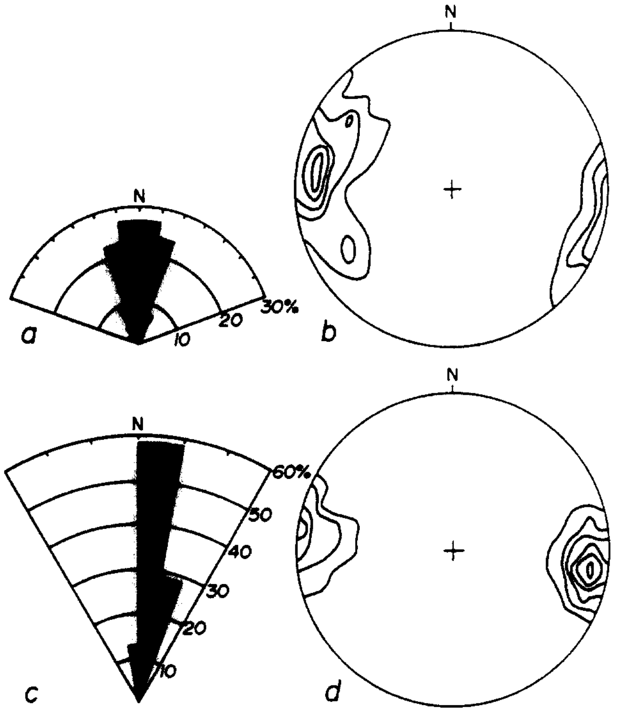


Fig. 5. Orientations of foliation planes from the gneisses. (a) Rose diagram of 393 strikes of foliation planes from the western gneisses. (b) Stereogram of 47 poles to foliation planes from the western gneisses, contours: 1–5–10–15–20% per 1% area. (c) Rose diagram of 130 strikes of foliation planes from the eastern gneisses. (d) Stereogram of 35 poles to foliation planes from the eastern gneisses, contours: 1–5–10–15–20–30% per 1% area.

viz., ductile, brittle–ductile and brittle shear zones are present in the area of study (Figs. 6 and 7). However, ductile and brittle–ductile shear zones are much more common than brittle shear zones.

In *ductile* shear zones the deformation and differential displacements of the walls are accomplished entirely by ductile flow, and on outcrop scale at least no sharp discontinuities are present (Figs. 6a,c–f and 7a,b & e). Pegmatite and aplite veins crossing such shear zones can be traced continuously through the zone though they may be thinned (Figs. 7a & b) or even boudinaged (Fig. 6a) where tangential displacement is very large in comparison to the width of the shear zones. Where veins are not present, pre-shear foliation planes are sigmoidally curved in the shear zones; from these the sense of displacement can be easily determined (Figs. 6c,d & f). *Brittle* shear zones, on the other hand, show clear-cut discontinuities between the sides of the zones and the shear zone walls are almost unstrained (Figs. 7c,d,h & j). Veins or contacts between gneisses affected by brittle shear zones show displacements along sharp planes which are akin to fault planes or shear fractures. *Brittle–ductile* shear zones are ductile shear zones with fault-like features at the centre of the zones against which marker layers are displaced abruptly (Fig. 6b). Very often epidote veins are present at the centre of such zones marking the brittle part of the shear zone (Figs. 4 and 6b). Ductile and brittle shear zones are, therefore, end members in a continuous spectrum with brittle–ductile shear zones as intermediate types.

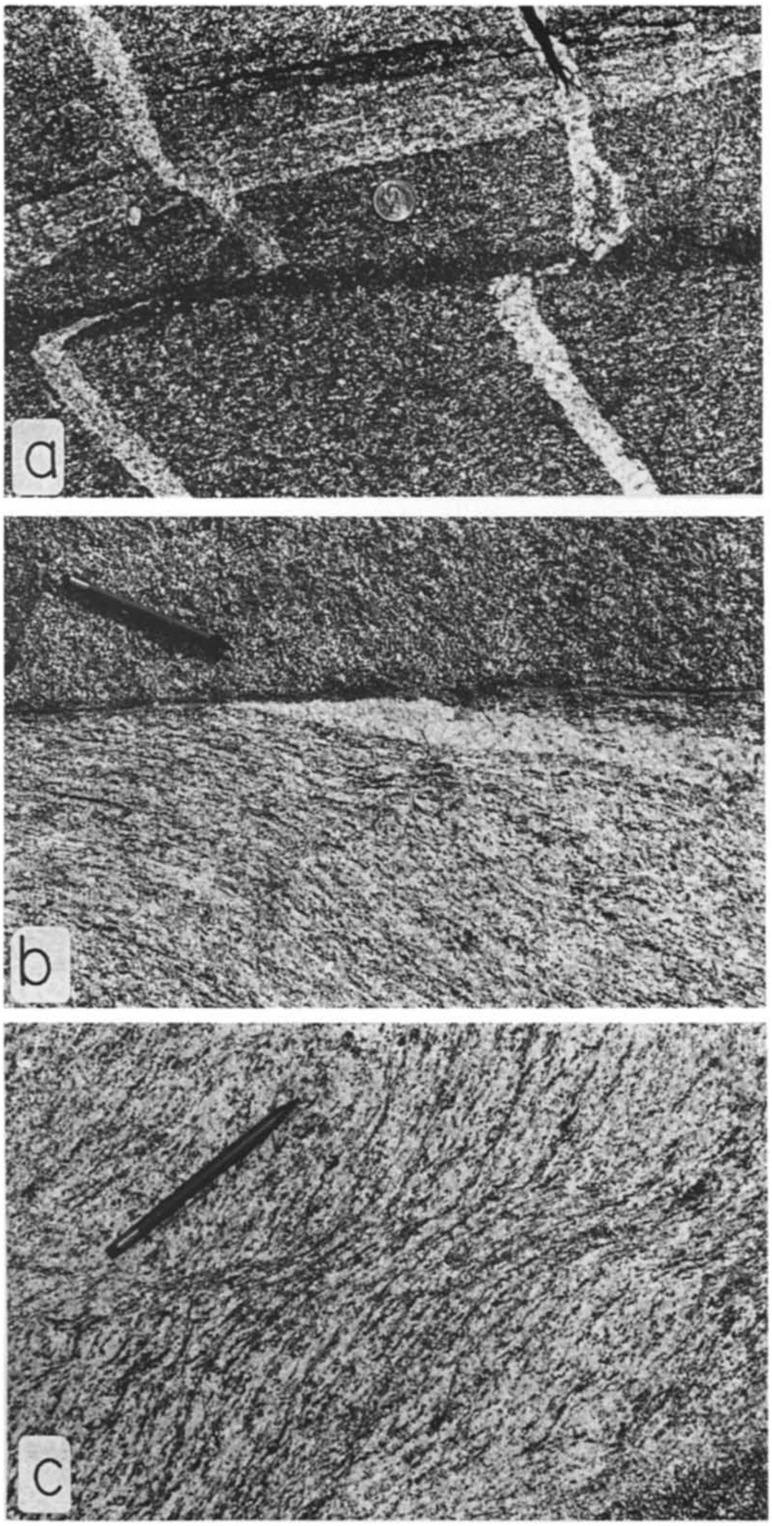
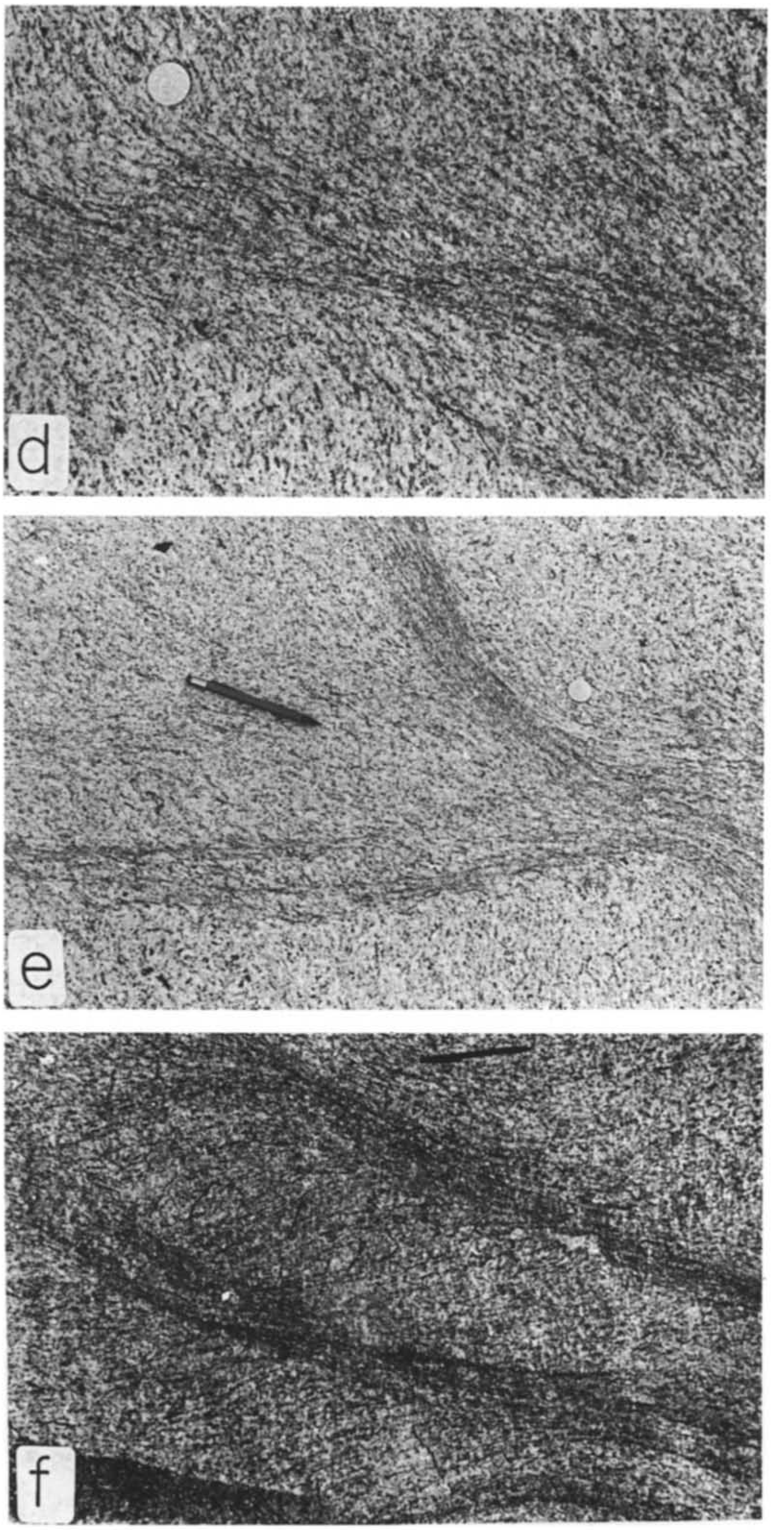


Fig. 6. Examples of shear zones. (a) Dextral shear zone with dilation affecting pegmatite veins which are boudinaged. The shear zone strikes 017° (left). (b) Brittle–ductile shear zone at the contact between Madura Gneiss (top) and Kambha Gneiss. Note that the zone is occupied by an epidote vein. Pencil points N. (c) Dextral shear zone in Kambha Gneiss traced by sigmoidally curved pre-shear foliation. Pencil points N. (*Continued.*)



(Fig. 6. *Continued.*) (d) Sinistral shear zone with well developed shear foliation in almost unfoliated Kambha Gneiss. Right-hand side 158°. (e) Conjugate ductile shear zone with well developed shear foliation in unfoliated Kambha Gneiss. Note the development of *S*- and *C*-surfaces in the sinistral shear zone (bottom). Pencil points N. (f) Pre-shear foliation deflected and sigmoidally curved by a set of dextral shear zones giving pseudo *S*- and *C*-surfaces.

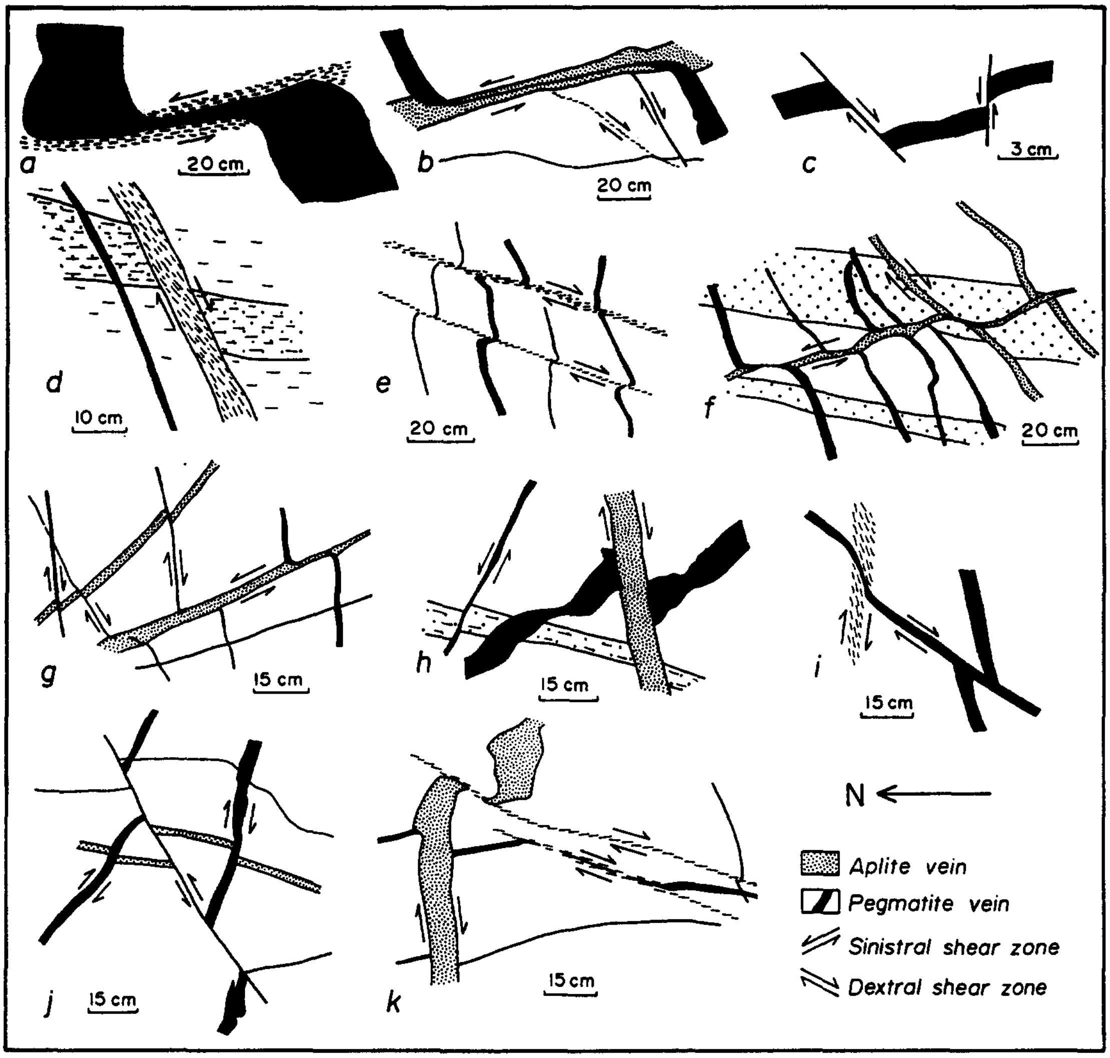


Fig. 7. Sketches of shear zones (drawn from colour transparencies). All the sketches are oriented with north to the left. (a) Ductile sinistral shear zone with well-developed shear foliation offsetting a pegmatite vein. (b) A pegmatite vein very much thinned but still continuous across a sinistral shear zone occupied by an aplite vein. Dextral shear zones to the lower right offset a thin aplite vein (bottom). (c) Conjugate brittle shear zones affecting a pegmatite vein. (d) A dextral shear zone occupied by aplite vein displaces Dod Gneiss (dotted). Shear foliation in aplite vein is noticeable. (e) Ductile dextral shear zones affecting a set of pegmatite veins. (f) A set of veins displaced by a sinistral shear zone. Note that the Dod Gneiss (dotted) is dextrally offset along some of the veins. (g) A set of dextral shear zones occupied by pegmatite veins are offset by aplite-filled sinistral shear zone. (h) Conjugate brittle shear zones with dextral shear zone occupied by an aplite vein and a sinistral shear zone occupied by a pegmatite vein. (i) A dextral brittle–ductile shear zone affected by a later ductile shear zone with the same sense of movement. (j) Conjugate brittle shear zones. Note that the dextral shear zones, occupied by pegmatite veins, are displaced by a sinistral shear zone devoid of any vein. (k) Thin pegmatite veins dextrally offset against an aplite vein. Both the aplite and pegmatite veins are offset by a set of ductile and dextral shear zones.

Both sinistral (e.g. Figs. 6d and 7a,b & f) and dextral (e.g. Figs. 6a & b and 7e) shear zones are present and they offset each other. In general sinistral shear zones strike NW whereas zones with a dextral sense of movement strike NE. Most of the shear zones dip very steeply or are vertical. In the western gneisses shear zones have usually propagated along pegmatite and aplite veins (Fig. 3); the sinistral shear zones are occupied by aplite veins, and pegmatite veins occupy dextral shear zones, though the reverse relation has also been noted at a few places. In the eastern gneisses, as well as in many outcrops in the western gneisses, shear zones have not propagated along any vein (Figs. 6b–f). Pre-shear foliations are deflected and are sigmoidally curved in ductile shear zones (Figs. 6c,d & f); the acute angle between the pre-shear foliation in the shear zones and the shear zone walls gives the sense of movement. A new foliation is very well developed in these zones, especially where they are occupied by aplite veins (Fig. 7d) or where shearing affects homogeneous unfoliated rocks (Fig. 6e). These shear foliations dip very steeply and are nearly parallel to the walls at the centre of the zone, but make an appreciable angle with the shear direction near the walls. In well-foliated rocks or where shear zones propagate along pegmatite veins shear foliations are poorly developed or absent.

Shear zones are often greenish in colour because of the presence of epidote, and fractures in brittle–ductile and brittle shear zones are often filled with epidote (Figs. 3 and 6b). On shear surfaces epidote grains usually define a mineral lineation. Slickenside lineations have also been noted on brittle–ductile and brittle shear

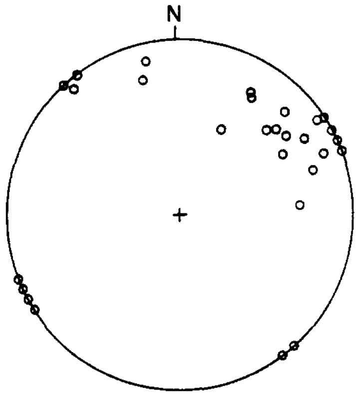


Fig. 8. Stereographic plot of shear lineations from the whole area.

zones. These shear lineations are invariably horizontal or plunge gently (Fig. 8) indicating dominant strike-slip movement along the shear zones.

A set of shear zones with the same sense of movement commonly remain parallel to each other over a considerable distance (see Figs. 3 and 4). In such cases sets of dextral and sinistral zones crosscut each other and enclose rhomb-shaped areas essentially unaffected by shearing. Where veins are absent, ductile shear zones may curve, anastomose or merge with each other enclosing lozenge-shaped pods of less deformed rocks. Pre-shear foliations affected by anastomosing shear zones may give the appearance of *S*- and *C*-surfaces (cf. Berthé *et al.* 1979). However, true *S*- and C-surfaces are locally developed in unfoliated rocks in places (Fig. 6e).

Most of the shear zones die out within metres. Near the terminations ductile shear zones may widen with concomitant decrease in strain. An increase in strain area is expressed by fanning of shear bands whereas decrease in strain is indicated by decrease in the angle between shear zone walls and foliation planes. Some of the ductile shear zones narrow down as their terminations are approached and essentially grade, without any significant change in strike direction, into brittle–ductile shear zones which in turn pass into brittle shear zones or a zone containing brittle fractures.

ORIENTATION OF SHEAR ZONES AND DETERMINATION OF COMPRESSION DIRECTIONS

Detailed maps of outcrops on both sides of the schist belt (Figs. 3 and 4) clearly show that there are preferred orientations of sinistral and dextral shear zones. Sinistral shear zones usually strike in the northwestern sector whereas dextral shear zones have their strikes in the northeastern sector. Figure 9 shows the stereographic plots of shear zones. Most of the outcrops in the area are

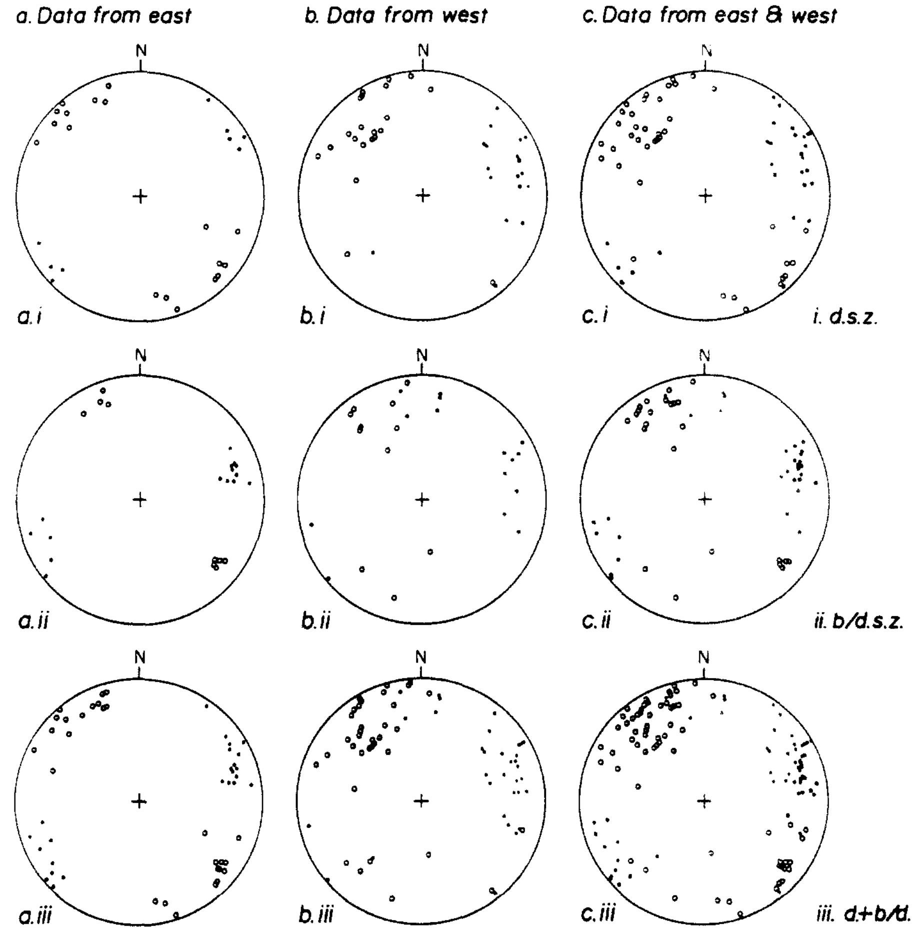


Fig. 9. Stereographic plots of poles to the walls of shear zones. (a) Data from east of the schist belt. (b) Data from west of the schist belt. (c) Combined data from east and west. (i) Ductile shear zones. (ii) Brittle–ductile shear zones. (iii) Combined data of ductile and brittle–ductile shear zones. Dots, sinistral shear zones; open circles, dextral shear zones.

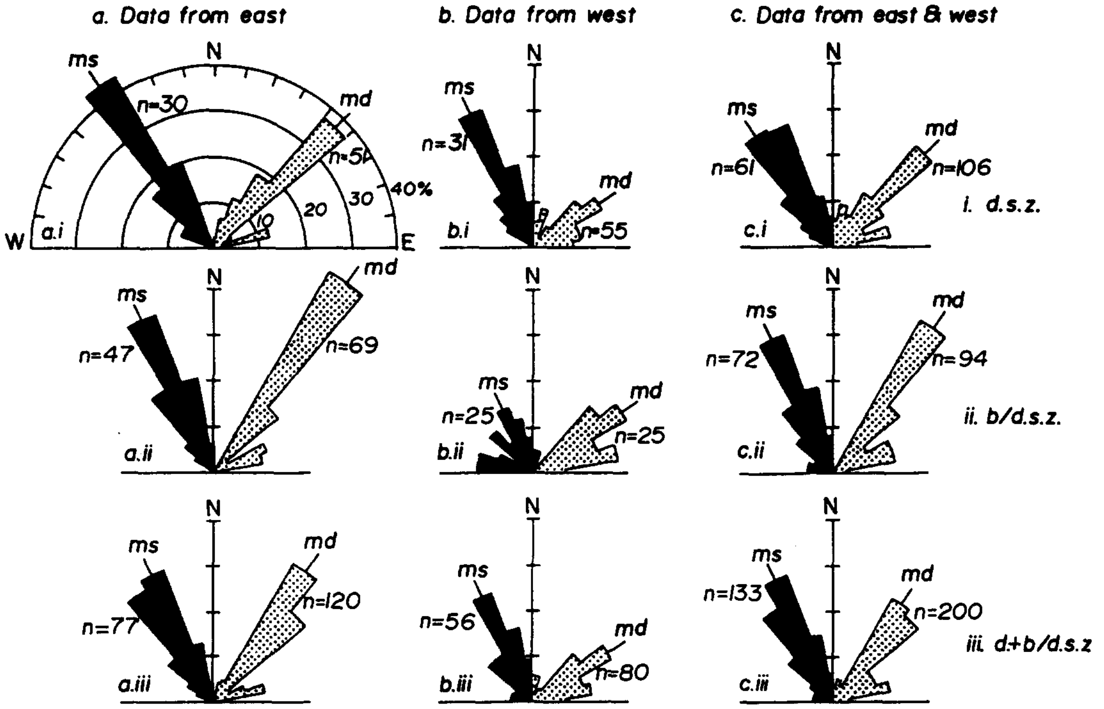


Fig. 10. Rose diagrams of strikes of shear zone walls. The diagrams have been arranged the same way as in Fig. 9, i.e. Figs. 10(a.i), etc., are equivalent to those in Fig. 9. Scales in all the diagrams are the same as in (a.i). ms, modal sinistral; md, modal dextral.

flat horizontal surfaces so that the third dimension is not easily seen, and in many outcrops only strike directions can be measured. However, because most of the shear zones dip very steeply (Fig. 9), strike directions are more significant than the amount of dip. Therefore, in addition to stereograms, rose diagrams of strikes of shear zones have also been prepared (Fig. 10) where preferred orientations are dramatically highlighted. Data from east (Figs. 9a and 10a) and west (Figs. 9b and 10b) of the schist belt as well as combined data from east and west (Figs. 9c and 10c) have been plotted separately. Diagrams for ductile (Figs. 9i and 10i), brittle–ductile (Figs. 9ii and 10ii) and combined ductile and brittle–ductile (Figs. 9iii and 10iii) shear zones have also been prepared separately. This has been done to check if there is any significant variation in orientation between shear zones from east and west of the schist belt and between ductile and brittle–ductile shear zones. It should be mentioned here that the data plotted in Figs. 9 and 10 include data from the whole area (see Fig. 2) and not from mapped outcrops only. Data collected on brittle shear zones are too few for any meaningful statistical analysis.

Figures 9 and 10 show that most of the sinistral shear zones trend approximately NW–SE whereas dextral shear zones, in general, trend approximately NE–SW. Modal strikes of sinistral and dextral shear zones in all the rose diagrams (Fig. 10, Table 1) have similar orientations. A synoptic stereogram and rose diagram also give similar modal orientations of two sets of shear zones (Fig. 11).

In many outcrops sinistral and dextral shear zones form a conjugate pair (Figs. 6e and 7c,g,h & j). In some places sinistral shear zones offset dextral shear zones (Figs. 7g & j); elsewhere dextral shear zones displace sinistral shear zones. An early formed shear zone may be displaced by a later formed zone with the same or opposing sense of displacement (Figs. 7g,i–k). In a progressive deformation this is the general relationship between simultaneously developing sinistral and dextral shear zones (Ramsay 1980, Ramsay & Huber 1987).

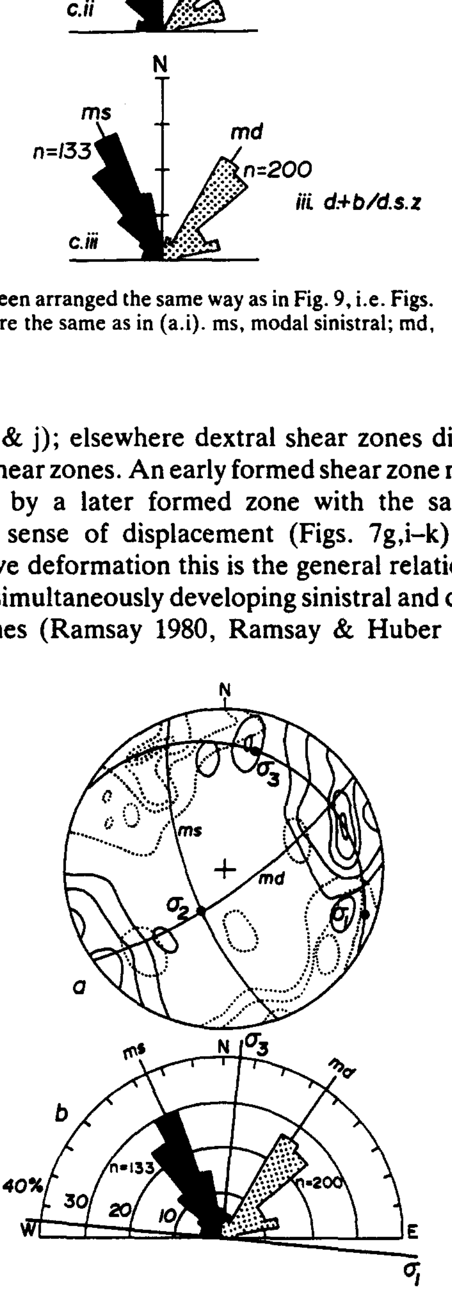


Fig. 11. Synoptic orientation diagrams of all the ductile and brittle-ductile shear zones from the whole area. (a) Continuous contours, 56 poles of sinistral shear zone walls, contours: 0.5–3–6–12–18% per 1% area. Dashed contours, 65 poles of dextral shear zones, contours: 0.5–3–6–9–12% per 1% area. (b) Synoptic rose diagram. ms, modal sinistral. md, modal dextral. σ_1, σ_2 and σ_3 are maximum, intermediate and minimum compression directions, respectively.

Table 1. Modal orientations of shear zones and compression directions as determined from rose diagrams in Fig. 10

Types of shear zones	Area (Fig. No.)	Sense of displacement	Modal orientation	Compression direction σ_1	σ_3
Ductile	East	Dextral	N 45°	N 95°	N 5°
	(10a.i)	Sinistral	N 325°		
	West	Dextral	N 55°	N 105°	N 15°
	(10b.i)	Sinistral	N 335°		
	East + West	Dextral	N 45°	N 95°	N 5°
	(10c.i)	Sinistral	N 325°		
Brittle–ductile	East	Dextral	N 35°	N 95°	N 5°
	(10a.ii)	Sinistral	N 335°		
	West	Dextral	N 55°	N 105°	N 15°
	(10b.ii)	Sinistral	N 335°		
	East + West	Dextral	N 35°	N 95°	N 5°
	(10c.ii)	Sinistral	N 335°		
Ductile + Brittle–ductile	East	Dextral	N 35°	N 95°	N 5°
	(10a.iii)	Sinistral	N 335°		
	West	Dextral	N 55°	N 105°	N 15°
	(10b.iii)	Sinistral	N 335°		
	East + West	Dextral	N 35°	N 95°	N 5°
	(10c.iii)	Sinistral	N 335°		

Therefore, the NW-striking sinistral shear zones and NE-striking dextral shear zones may be taken as a conjugate pair developed during the same deformational episode, and they may be used to determine the principal compression directions.

It is well known that in contrast to brittle deformation (Anderson 1951) the obtuse bisector between the shear planes in ductile deformation parallels the maximum compression direction (σ_1). The minimum compression direction (σ_3) is given by the acute bisector and the zone intersection parallels the intermediate compression direction (σ_2). However, this geometry of stress axes is strictly correct at the time of initiation of shear zones. During progressive deformation, the shear zones will rotate with respect to each other and the stress field. Also, because the shear zones are likely to be strain-softened, there is probably quite a range of possible stress orientations that could activate them without initiating new ones. Ramsay and Huber (1987, p. 615) show that though the shear zones rotate during a progressive deformation, the directions of bulk shortening (obtuse bisector) and bulk stretching (acute bisector) maintain nearly constant orientations. Therefore, unless the shear field undergoes significant change, bisectors of preferred orientations of conjugate shear zones should give a reasonable measure of the large-scale compression directions (e.g. Park 1981).

From the bisectors of modal strike directions of shear zones from each of the rose diagrams (Fig. 10) σ_1 and σ_3 directions have been determined (Table 1). Since the shear zones dip very steeply it has been assumed that σ_1 and σ_3 should be subhorizontal and σ_2 should be plunging steeply. In all cases σ_1 is nearly E–W and σ_3 is nearly N–S (Table 1). The synoptic rose diagram (Fig. 11b) gives trends for σ_1 and σ_3 of 095° and 005°, respectively, with steeply plunging σ_2. Stereographic plots of all the shear zones also give well defined modal orientations of sinistral and dextral shear zones, the bisectors of which give orientations for σ_1, σ_2 and σ_3 of 06°/105°, 66°/208° and 23°/015°, respectively (Fig. 11a). Therefore it may be concluded that all the shear zones in the gneisses on either sides of the belt have formed in response to a nearly E–W subhorizontal compression.

It should be mentioned here that a few of the sinistral shear zones have strikes in the northeastern sector and a few dextral shear zones have strikes in the northwestern sector (see Figs. 9 and 11a). Such zones have been ignored in the rose diagrams for clarity of presentation. These shear zones with apparent contradictory orientations may have formed during the relaxation period at the waning phase of the deformation episode when compression was replaced by extension in the same direction.

Figure 11 clearly shows that though there are preferred orientations of both sinistral and dextral shear zones, there is a large variation in the orientation of these zones. We may consider two possibilities. First, the rocks at the scale of outcrop are inhomogeneous due to the presence of foliation, varying mineralogical composition and the presence of intrusive veins and dykes. These inhomogeneities should have resulted in local perturbations of the compressive strain direction. Secondly, during progressive deformation early formed shear zones would rotate towards the extension direction more than the later formed zones, giving rise to a spread in orientation of the shear zones (Ramsay & Huber 1987). The amount of scatter in the orientations as seen in Fig. 9 suggests that both these mechanisms were probably responsible for the variation in orientation of shear zones. Nevertheless statistically determined bisectors of shear zones would still give the compressive directions without significantly large error.

SHEAR STRAIN

In the present area all the shear zones are highly heterogeneous; that is, the shear strain varies rapidly

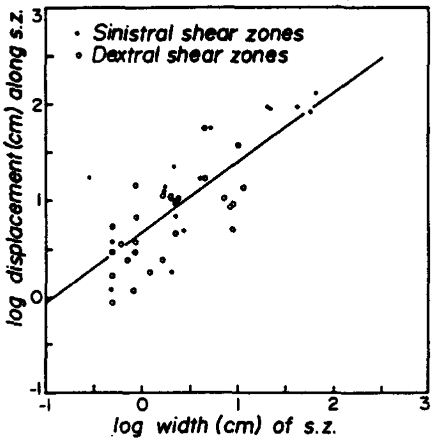


Fig. 12. Displacement vs width plot of ductile shear zones. See text for discussion.

across a shear zone. The shear strain is very large at the centre of the zones but diminishes rapidly towards the zone walls on either sides (Figs. 7a & b).

Shear strain and displacements across a shear zone can be measured directly if a marker layer crosses such a zone, or indirectly using the schistosity variation method developed by Ramsay & Graham (1970). In the present area a large number of acidic veins cross shear zones and are displaced. It has been shown that the shear zones dip steeply with essentially subhorizontal displacement vectors. Therefore, on horizontal outcrop surfaces displacements and widths of shear zones can be measured directly from displaced veins.

Figure 12 shows the plots of width vs displacement of both sinistral and dextral shear zones from the whole area. The data have been plotted on logarithmic scales to accommodate measurements from shear zones that have a wide range of size (cf. Mitra 1979). Linear regression of data on logarithmic scales scatter about a best-fit straight line with a correlation coefficient of 0.85, a slope of 0.74 and an intersection with the ordinate axis at log 4.57. Sinistral and dextral shear zones when plotted separately also give a similar result. From these the relationship between the width of the ductile shear zones (w) and displacement (s) on them is given by:

$$s = 4.57w^{0.74}. \qquad (1)$$

Since the slope of the line is close to 1, on a linear scale the data should also lie about a straight line. Linear regression of the data on linear scales gives the following relationship between displacement and width of the shear zones with a correlation coefficient of 0.85:

$$s = 1.82w + 7.61. \qquad (2)$$

It should be noted here that not all the shear zones and veins are vertical, nor are all displacement vectors horizontal. Therefore, in many cases, displacements measured on horizontal surfaces are in reality the horizontal component of the true displacement. However, in the present area the geometry of shear zones and veins are such that the differences between the horizontal component and the true displacement would be small. Since the shear zones and veins are very sharply defined, error in measurement is small in most cases. Finally, the effect of volume change has been neglected in this calculation since very few shear zones show evidence of dilation (e.g. Fig. 6a). The scatter of data about the straight-line fit (Fig. 12) is an effect of all these factors.

SUMMARY AND CONCLUSIONS

From the foregoing description of mesoscopic shear zones in the gneisses around the Kolar Schist Belt it is apparent that the steeply dipping NW-striking sinistral and NE-striking dextral shear zones form a conjugate pair. Obtuse bisectors of these paired shear zones give nearly subhorizontal E–W maximum compression directions on both sides of the schist belt. The subhorizontal minimum compression is in a N–S direction and the intermediate compression direction is vertical or plunges steeply. Shear lineations on the shear surfaces are invariably horizontal or plunge gently, pointing to dominant strike-slip movement along shear zones. The fact that the intermediate compression direction (σ_2) is subvertical strengthens this conclusion.

Mesoscopic shear zones (Ghosh & Sengupta 1985, Mukhopadhyay in press) and shear zones of mappable dimensions (Hamilton & Hodgson 1986, Mukherjee *et al.* 1986) are also present in the schist belt. Mukhopadhyay (in press) has shown that prior to the onset of shearing the rocks in the schist belt were involved in two sets of folding on a large scale. The first set of folds (F_1) were isoclinal and recumbent or gently plunging reclined with N–S axial trend. They developed in response to an E–W simple shear acting on subhorizontal layers (Fig. 13a). The F_1 folds were coaxially refolded by upright F_2 folds formed due to an E–W pure shear (Fig. 13b). When the F_2 folds became isoclines (Fig. 13c), further compression in the same direction resulted in the development of shear zones at a low angle to the northerly striking and steeply dipping foliation planes (Fig. 13d). Since the shear zones in gneisses on both sides of the schist belt also developed due to E–W subhorizontal compression it is reasonable to conclude that the shear zones in the gneisses and the schist belt are broadly contemporaneous, and are late-kinematic with respect to the F_2 folding seen inside the schist belt. The gneisses were also deformed prior to the initiation of shearing. The foliations in the gneisses have an orientation similar to that of the orientation of the F_1–F_2 axial planes in the schist belt. However, until more detailed work on the pre-shearing deformational history of the gneisses is available, a definite comparison between the pre-shearing deformation in the gneisses vis-à-vis the schist belt cannot be made.

It has been noted that the contact between the schist belt and the gneisses are zones of intense shear. In these zones the outcrops are poor and rocks are highly weathered, and a meaningful structural analysis could not be attempted. However, since most of the shear

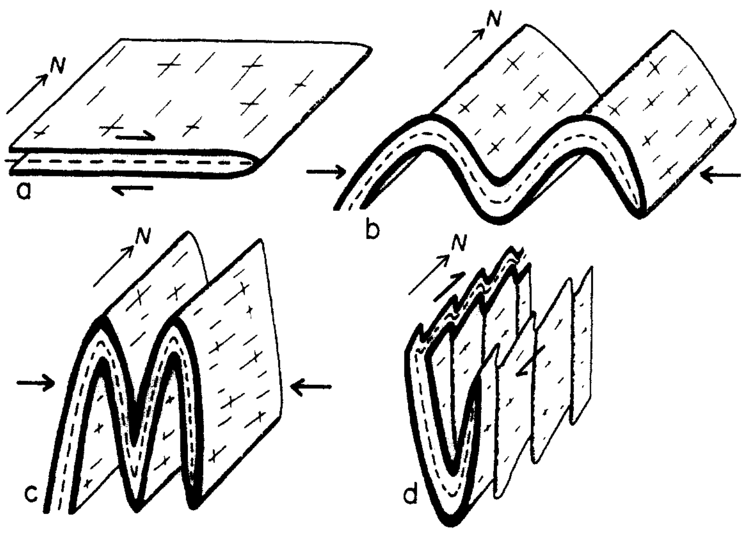


Fig. 13. Schematic diagrams showing the sequence of development of early structures in the Kolar Schist Belt (after Mukhopadhyay in press). (a) Isoclinal F_1 fold with northerly trend of axes developed in response to an E–W simple shear. (b) Coaxial refolding of F_1 folds by open F_2 folding in response to a pure shear in an E–W direction. (c) Tightening of F_2 folds into isoclines. (d) Development of asymmetrical folds due to shearing acting at a low angle to layering and early axial planes.

zones are of strike-slip type, it follows that the displacements along shear zones at the margins of the belt should also be subhorizontal. We can therefore rule out the possibility of an underthrusting or overthrusting relationship between the schist belt and the gneissic terrains.

There is a good correlation between the width of the shear zones and displacements along them at small to intermediate scales. If we assume the schist belt to be a major shear zone, the total displacement across the approximately 4 km wide belt would be about 13 km (equation 1) or 15 km (equation 2). In the present area, however, both sinistral and dextral shear zones are equally well developed. These two sets of shear zones with opposing sense of movement and developing simultaneously would tend to lock each other, otherwise voids would be created. Further, displacements would take place along discrete shear zones and the cumulative displacement should be less than anticipated. Therefore, the actual displacement across the schist belt should probably be much less. Although there is evidence to suggest that the schist belt is highly sheared (Hamilton and Hodgson 1986, Mukherjee *et al.* 1986) the displacement across the schist belt was probably small.

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