Structures in the banded iron-formation of the southeastern Bababudan Hills, Karnataka, India

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The banded iron-formation in the southeastern Bababudan Hills display a macroscopic synformal bend gently plunging towards WNW. The bedding planes in smaller individual sectors show a cylindrical or conical pattern of folding. The dominant set of minor folds has WNW-ESE trending axial planes and the axes plunge towards WNW at gentle to moderate angles, though there is considerable variation in orientation of both axes and axial planes. A later set of sporadically observed folds has N-S trending axial planes. The macroscopic synformal bend within the study area forms the southeastern corner of a horse-shoe shaped regional synformal fold closure which encompasses the entire Bababudan range.

The minor folds are buckle folds modified to a varying extent by flattening. In some examples the quartzose layers appear to be more competent than the ferruginous layers; in others the reverse is true. The folds are frequently noncylindrical and the axes show curvature with branching and en echelon patterns. Such patterns are interpreted to be the result of complex linking of progressively growing folds whose initiation is controlled by the presence of original perturbations in the layers. Domes and basins have at places developed as a result of shortening along two perpendicular directions in a constrictional type of strain. Development of folds at different stages of progressive deformation has given rise to nonparallelism of fold axes and axial planes. The axes and axial planes of smaller folds developed on the limbs of a larger fold are often oriented oblique to those of the latter. Progressive deformation has caused rotation and bending of axial planes of earlier formed folds by those developed at later stages of the same deformational episode. Coaxial recumbent to nearly reclined fold locally encountered on the N-S limb of the macroscopic fold may belong to an earlier episode of deformation or to the early stage of the main deformation episode.

The E-W to ESE-WNW strike of axial plane of the regional fold system in the Bababudan belt contrasts with the N-S to NNW-SSE strike of axial planes of the main fold system in the Chitradurga and other schist belts of Karnataka.

1. Introduction

The Bababudan Hill range in Karnataka has the shape of a bent horse-shoe with closure to the east; its two arms have a general E-W trend in the eastern part, while towards the west these are bent to a nearly N-S trend (figure 1). The main range made up of banded magnetite quartzite encloses a lowland occupied by metabasic rocks. The magnetite quartzite generally dips inwards, and as a result the hills present steep slopes and formidable scarps, up to 100 metres high, at the outer side and gentle dip slopes at the inner side.

The first geological map of the Bababudans was prepared jointly by Slater (1908) and Sampat Iyengar (1908). They described the Bababudan Hills as being made up of banded ferruginous quartzite resting over a floor of hornblendic trap, while aphanitic green-stones alternating with quartzite form the uppermost beds. According to them the rocks show a basin like

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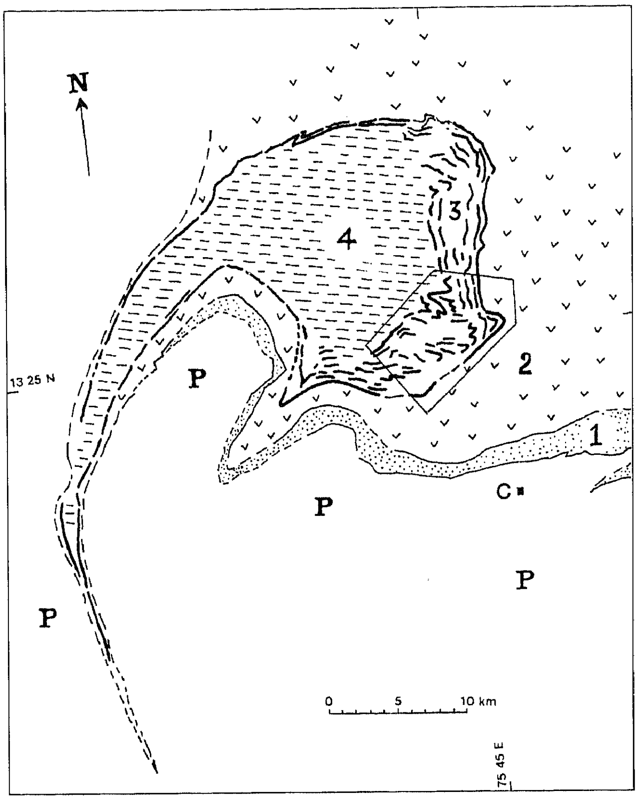

Figure 1. Generalized geological map of the Bababudan Hills. **P**: Peninsular Gneiss; Dharwar Supergroup; **1**: sandstone-conglomerate, **2**: metabasalt with quartzite, **3**: BIF, **4**: metabasalt. **C**: Chikmagalur Town. Study area is demarcated.

structure. A revised map of the Bababudan belt was published by Viswanatha and Ramakrishnan (1981), who presented a new stratigraphic succession and described the major structure in the belt as a westerly plunging syncline. The swing to the N-S trend of the regional strike at the western side is said to be caused by a major NNW trending shear zone, an interpretation later supported by Drury *et al* (1984). Naha and Chatterjee (1982) interpreted the structural pattern in terms of a set of isoclinal folds (F_1) superposed by nearly coaxial upright open folds (F_2) and still later N or NE trending upright open folds (F_3). Chadwick *et al* (1985a, 1985b) slightly modified the succession proposed by Viswanatha and Ramakrishnan (1981) and described the Bababudan syncline as "an open east-west fold which curves gently westwards into a tight cusp trending north". They commented on the complexity of the patterns of small scale folds and interpreted them to be indicative of "synchronous refolding".

In the course of the present study, detailed structural investigations were carried out in the southeastern corner of the horseshoe. As the rocks are highly magnetic, structural measurements could not be made with the help of a normal compass; a special solar compass was designed for this purpose.

The rocks have suffered a low greenschist facies metamorphism. Cummingtonite-grunerite, magnesioriebeckite and acmite have developed in the ferruginous rocks.

2. Patterns of minor structures

2.1 *Behaviour of bands of different lithology*

The banded ferruginous quartzite exhibits varieties of minor folds. These were initiated as buckle folds as evidenced by near parallel fold forms and convergent dip isogons in certain bands, the dependence of the arc length of folds on the thickness of competent bands and the frequent disharmony of the fold forms. The results of isogon analysis of minor folds have been published elsewhere (Niyogi and Baral 1972). Variation of orthogonal thickness of layers showing convergent isogons indicate that flattening has accompanied the process of buckling. Individual bands or multilayers with a number of thin bands showing convergent isogons alternate with others showing parallel or divergent isogons. Presumably the latter behaved as incompetent layers which adjusted themselves to the forms assumed by the more competent layers.

The studies reveal no systematic relation in the relative competency of the iron oxide and quartzose bands. At places the quartzose layers have a near perfect parallel geometry with strongly convergent isogons; the intervening iron oxide layers display divergent isogons and class 3 geometry (figure 2a). In other examples, within a multilayer both quartzose and iron oxide layers show convergent isogons; the degree of convergence in the quartzose layers may be stronger or weaker than in the ferruginous layers. Bands of nearly the same composition may exhibit convergent isogons at one level within a fold and divergent ones at a different level. Again, in some folds it is the massive iron oxide bands which behave as the

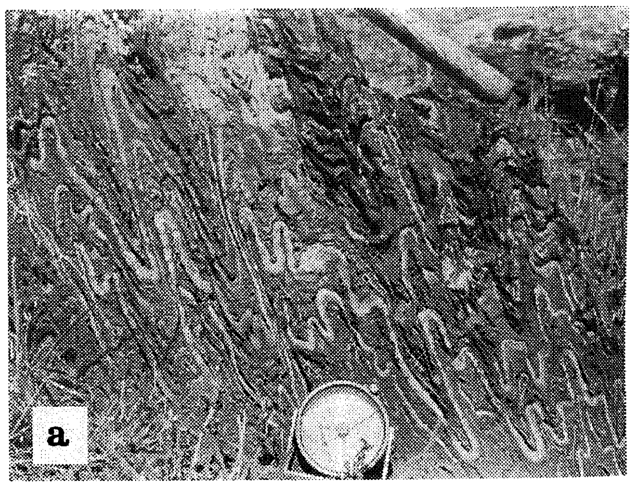

Figure 2. (a) Mesoscopic fold in multilayer; competent quartzite layer with class 1 geometry, incompetent magnetite layer with class 3 geometry.

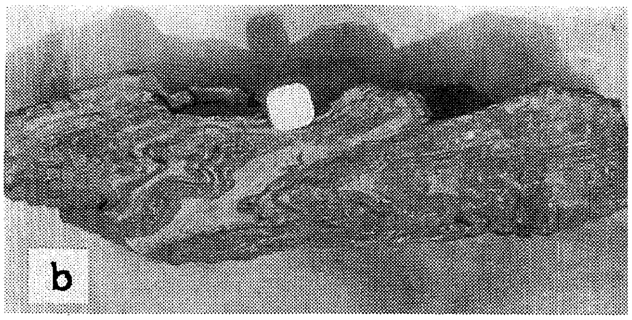

Figure 2. (b) Mesoscopic fold in multilayer; competent iron oxide layers (dark coloured) show disharmonic folding with class 1 geometry, incompetent quartzose layers (lighter coloured) show class 3 geometry.

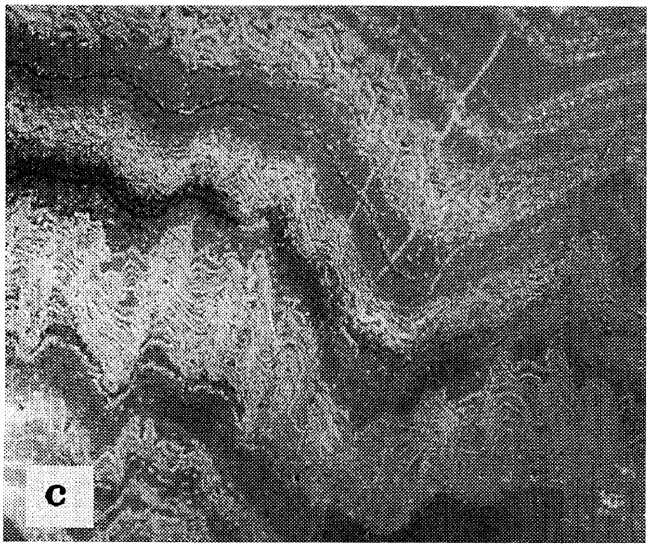

Figure 2. (c) Photomicrograph of polished sample in reflected light, finely laminated iron oxide layer (bright bands) with disharmonic smaller wavelength folds, multilayer as a whole shows larger wavelength folds. Width of photograph is 4.2 mm.

more competent units showing strongly disharmonic minor folds whose wavelengths are proportional to layer thickness and the quartzose bands adjust themselves to the space between the layers (figure 2b). An interesting feature is shown by certain iron oxide bands which are finely laminated. The unit as a whole shows relatively large wavelength folds while the fine lamination within it is minutely crinkled (figure 2c). This is analogous to internal buckling discussed by Biot (1965). A structure resembling crenulation cleavage is developed in such units.

It is concluded that the relative competency is controlled not only by the bulk mineralogical composition but by other factors also, such as texture, grain size, nature of lamination and interlayering and physico-chemical environment of deformation (Niyogi and Baral 1972). In general, it has been found that a fine-grained massive homogeneous layer is more competent than a finely laminated unit.

Some of the fine grained massive iron oxide bands are ruptured into fragments with the interstices filled up by quartz which is often fibrous. The ruptured bands are involved in folding (figure 2d); the individual fragments follow the fold form and one may ride over the other in the manner of microthrusts. This prefolding stretching might reflect an earlier stage of deformation or might be pretectonic, pertaining to the sedimentation or diagenetic stage.

2.2 *Patterns of variation of fold axes orientation*

Though statistically the axes of a set of minor folds in a hand specimen or within an individual exposure are subparallel, individual folds are frequently noncylindrical. The cross sectional shape of a fold varies in the direction parallel to the fold axis. Folds often die out in both directions along the axis, and then the bedding

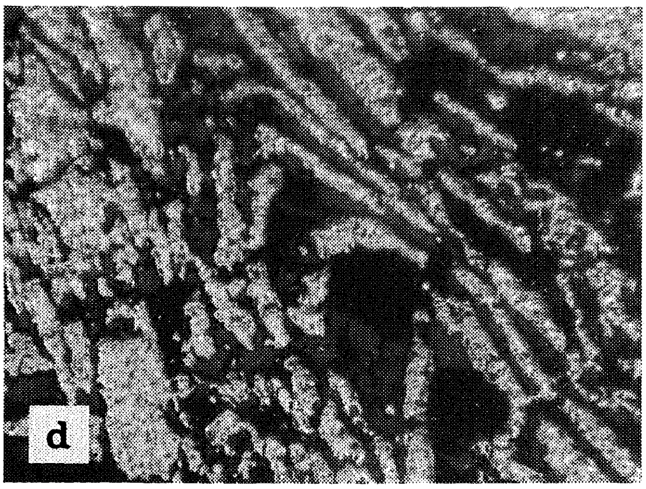

Figure 2. (d) Photomicrograph of polished sample in reflected light, ruptured iron oxide layer involved in folding. Width of photograph is 0.9 mm.

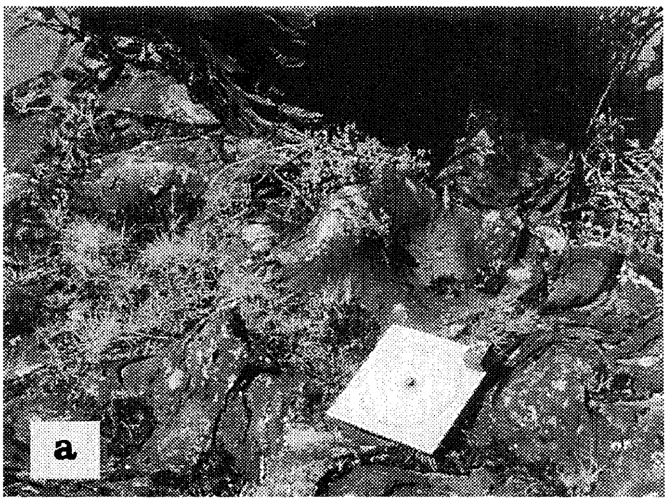

Figure 3. (a) Irregular domes and basins on the bedding surface, no definite fold axis is recognizable. Edge of solar compass is about 15 cm.

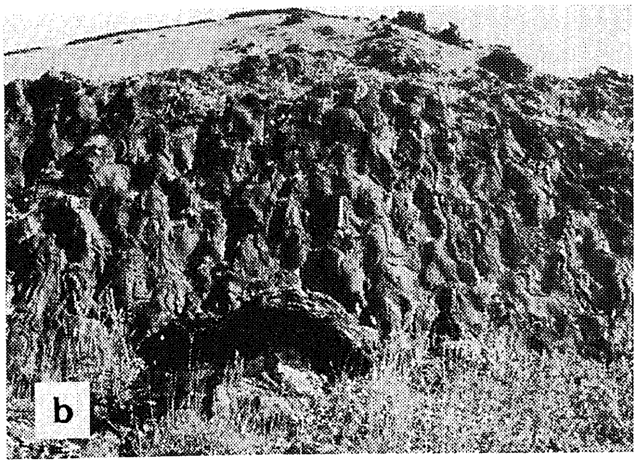

Figure 3. (b) Elliptical domes and basins, a statistical fold axis is recognisable.

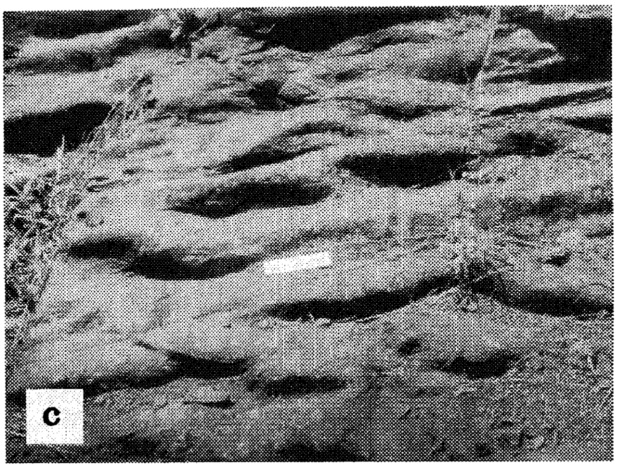

Figure 3. (c) Elongate domes and basins.

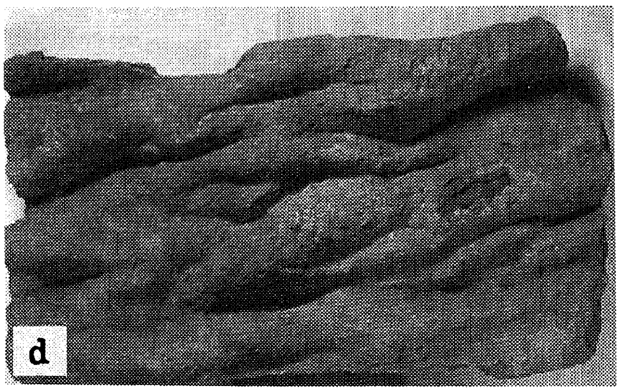

Figure 3. (d) Complex fold pattern with ropy appearance. Width of photograph represents about 25 cm.

surface has the appearance of a collection of elliptical or circular pods (figures 3a, b, c). More complex patterns give rise to coiled and ropy appearance of the surface (figure 3d).

The coalescence of neighbouring fold axes, en echelon patterns as described by Campbell (1958),

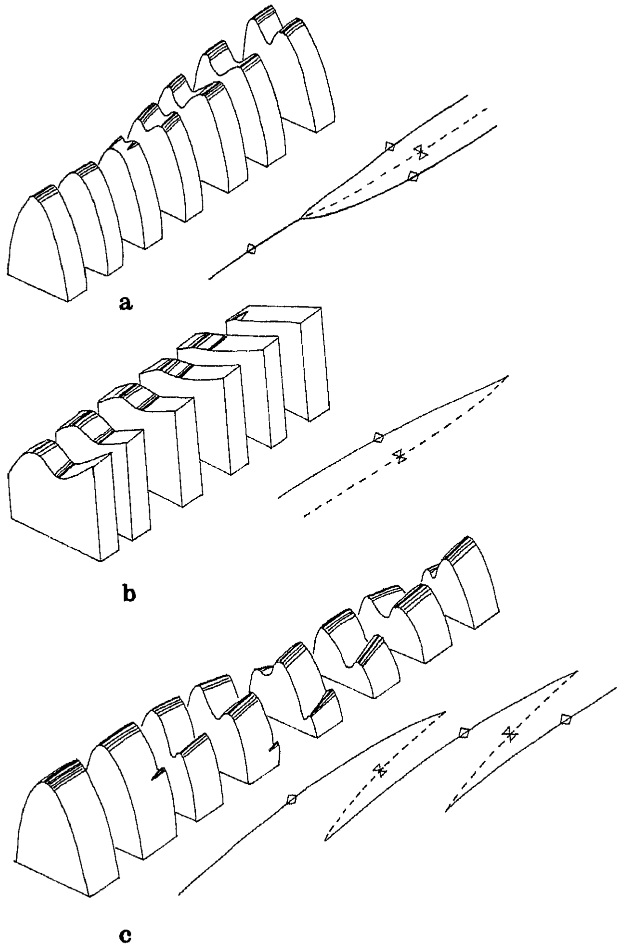

Figure 4. Block diagram and plan view of (a) branching pattern, (b) convergent pattern, and (c) en echelon pattern of fold axes.

and several other complex patterns have been observed. These have been classified into three basic types.

- **Branching pattern:** In this pattern the fold axis branches into two (figure 4a). Near the point of branching the two axes are at an angle to one another but further away they become nearly parallel. A synform may or may not lie between the two branches of an antiform and vice versa. The two branches of a fold may reunite after a certain distance. Where this happens in a branched antiform with an intervening synform the resultant structure is an elongated basin (figure 5a). Similarly an elongated dome may lie between two branches of a synform. A parent fold may set out branches at several successive points (figure 5b); at places one branched set may lie nested within another branched set (figure 5c). The branch of an antiform may form the intervening fold within a neighbouring synform branched in the opposite sense (figure 5d).
- **Converging pattern:** Here the axis of an antiform joins with that of a neighbouring synform

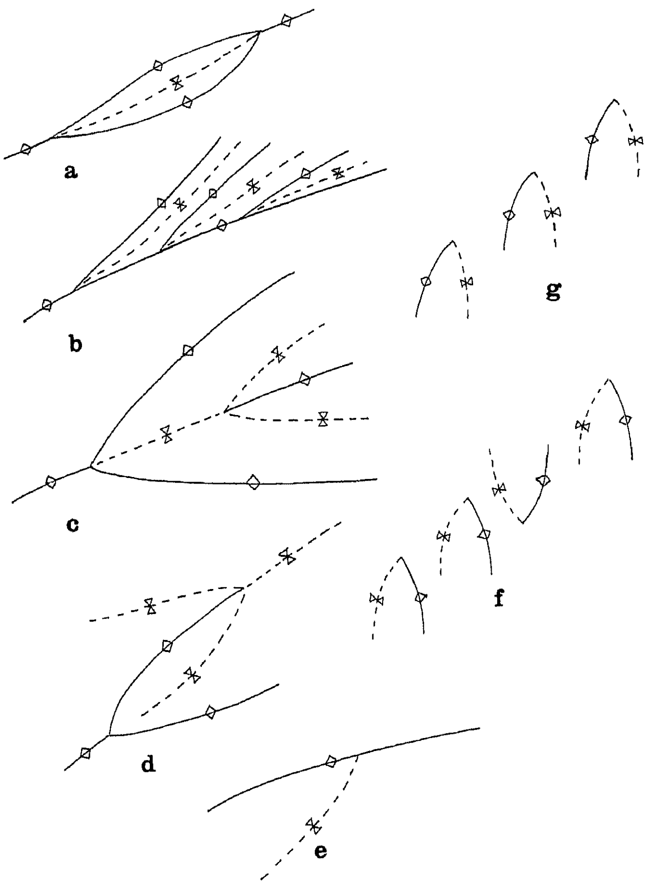

Figure 5. Plan view showing variations in different patterns of fold axes; (**a, b, c, d**): branching patterns; (**e, f, g**): converging patterns.

(figure 4b). The fold pair may die out at the point of convergence or one of them may continue beyond (figure 5e). A number of converging pairs may be arranged in one line or in a dextral or sinistral en echelon manner (figure 5f). Two neighbouring converging pairs may converge in the same or in opposite directions (figure 5g). Where the axes of a pair of folds converge at both ends the pattern has been described as pod folds by Campbell (1958).

- **Zigzag en echelon pattern:** This pattern has been described by Campbell (1958). Here the axes of neighbouring folds are arranged in an en echelon manner and the antiformal axes are joined together by synformal axes and vice versa (figure 4c). The en echelon arrangement may be dextral or sinistral.

Varieties of combinations of these three basic patterns occur in the area. Some of the commonly observed combinations are shown in figure 6. Figure 7 shows the pattern in a single hand specimen and illustrates how complex the pattern may be when considered in details. In all these types the fold axes are necessarily curved showing plunge culminations and depressions. In some folds sharp swings of fold axis occur and a subsidiary fold may branch out from such points of curvature (figures 7, 8a).

Plunge culminations and depressions have given rise to elongated domes and basins on the bedding surface (figures 3a, b). At places the domes and basins have very irregular patterns and no definite axis can be recognized (figure 3c). The domes and basins cannot be considered to be due to interference of two different fold phases as there is no regular pattern of distribution of the points of culmination and depression (cf. Ramsay and Huber 1983, p. 66). They are products of a single deformation episode (Ramsay 1967; Borradaile 1972; Ghosh *et al* 1995). In the three dimensional strain, structures developed on the bedding surface will depend on the orientation of the surface with reference to the principal axes of strain and on the nature of the strain ellipse section on the bedding plane (Ramsay 1967). In the constrictional type of deformation, if the bedding surface is suitably oriented there would be shortening along both axes of the sectional strain ellipse. If the shortening in one direction is appreciably in excess of the shortening in the other, elongated domes and basins would result and one dominant set of fold axis, albeit curved, may be recognized. If, however, the shortening in the two principal directions are nearly equal, irregular domes and basins without any definite fold axes would be formed. In the present area the first type (figures 3b, c) is more common.

Strain heterogeneity in a single phase of deformation is an important factor causing variations in the

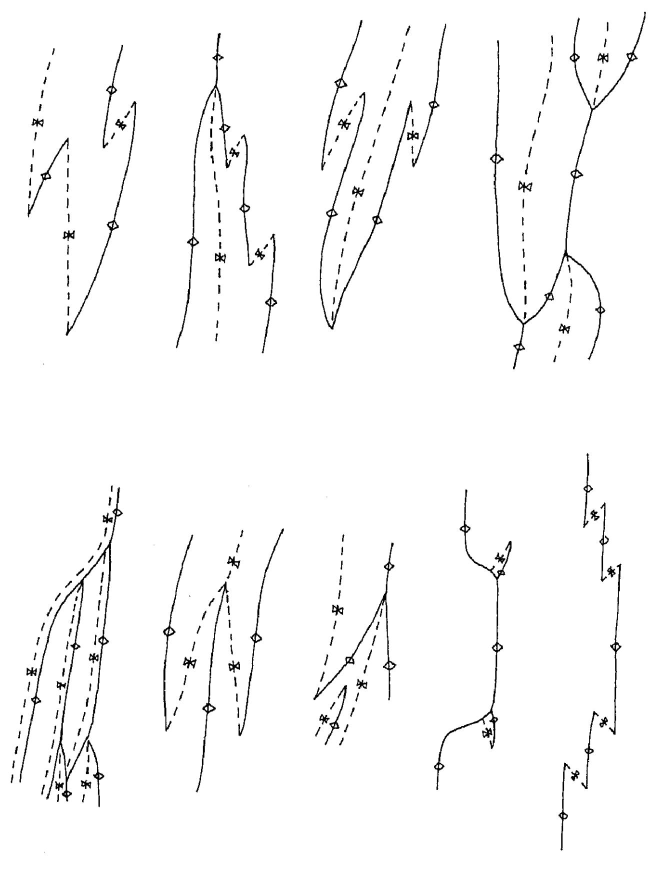

Figure 6. Combinations of different patterns of fold axes.

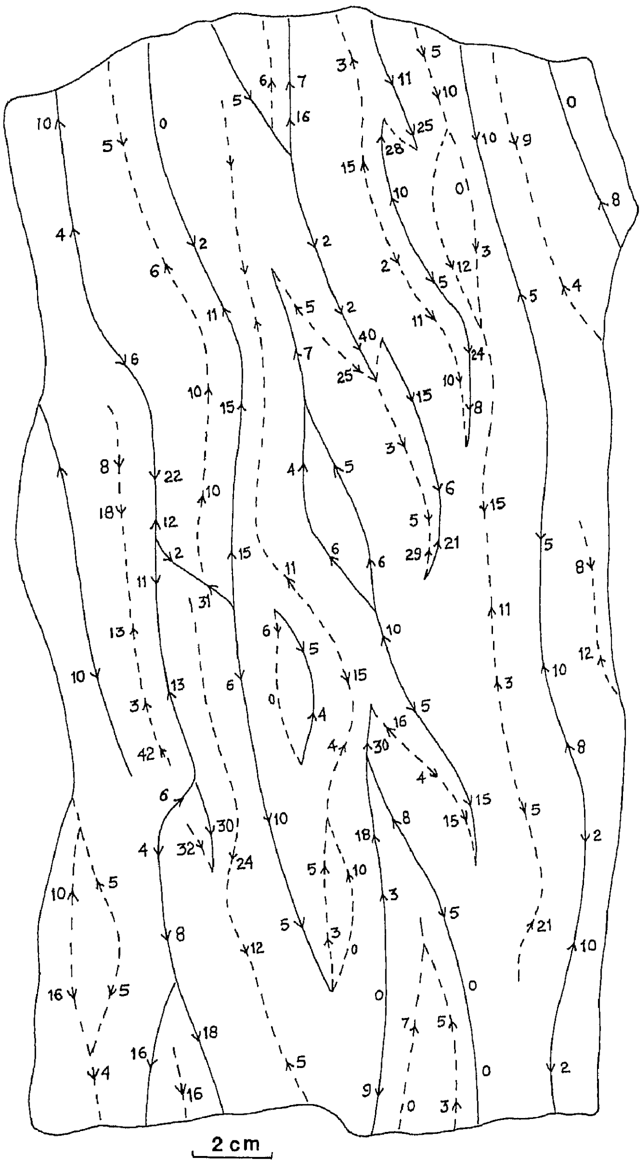

Figure 7. Plan view showing the complex pattern of fold axes in a specimen. The numbers denote the inclination of fold axes keeping the mean enveloping surface horizontal.

Figure 8. (**a**) Nonplane curvature of fold axis in a minor fold.

Figure 8. (**b**) Fine crinkles parallel to the axis of open minor folds.

Figure 8. (**c**) Fine ribbing on limb oblique to the axis of larger fold. Pencil parallel to fold axis, arrow parallel to oblique ribbing.

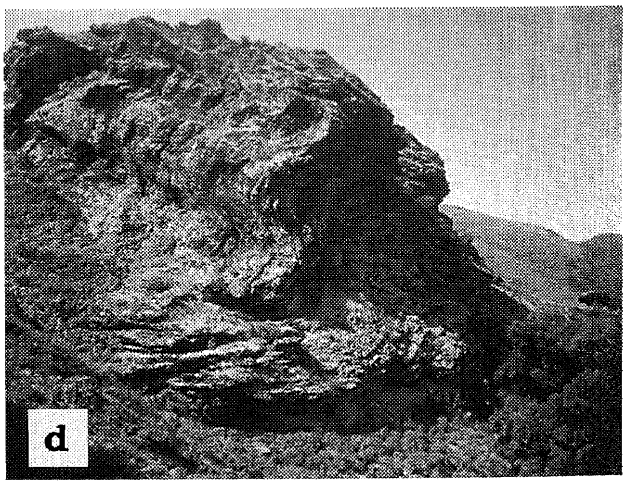

Figure 8. (**d**) Large recumbent fold near Dattatreyapitha.

attitude of the fold axes. Willis (1894) and Johnson (1972) have shown that in a layered medium buckle folding is initiated at a site where there is a slight original irregularity on the bedding plane. If on a plane surface such an irregularity is present at one point, the fold would be initiated at that point, but the influence of this initial perturbation would decrease away from it. As a result, in the final fold form the amplitude would be maximum at this point and it would gradually decrease in both directions away from it. As deformation progresses the fold grows in amplitude and also in longitudinal extent along the fold axis. If the initial surface has several such points of irregularity distributed over it, individual folds would be initiated at different points. As the folds grow along the fold axis the linking between adjacent growing folds would cause a complex pattern of variation of fold axes. Dubey and Cobbold (1977) in experiments with model materials have shown that during the growth of a fold it propagates by increasing the length of its hinge line. The neighbouring fold complexes spread towards one another and their mutual linkages give rise to a variety of patterns. The pattern is fundamentally controlled by the phase difference between the approaching complexes. If these are in phase, antiform directly links with antiform and synform with synform. If they are out of phase they cannot link directly but may link obliquely giving rise to curved hinge lines (figures 7, 8a). Branching patterns are formed when the two fold complexes approaching each other have different wave lengths (figure 10d of Dubey and Cobbold 1977).

The role of inhomogeneity in the formation of noncylindrical folds has also been discussed by Rhodes and Gayer (1977). They invoked a mechanism of formation of buckle folds by layer parallel shear where the cohesion between the layers is variable. They suggested that in case of linear, but not infinitely linear, inhomogeneities which lie perpendicular to the shear direction, the buckle folds would inherit the same degree of nonlinearity. Where, however, the inhomogeneities approximate to points, the degree of noncylindricity would depend on the stiffness (ratio of thickness to ductility) of the layer. In a layer with a low stiffness, a developing fold would be propagated in the direction of its hinge line for a short distance compared to layers with high stiffness. As a result, folds in layers of low stiffness would show a greater degree of curvature.

In a study of noncylindrical folds from Norway Ramsay and Sturt (1973) concluded on the basis of recurring similarity in style and range of axial orientation that the noncylindricity is a primary phenomenon and not a consequence of refolding. They observed that the axial curvature is dependent on the angle between the mean attitude of layering and the axial surface, the axial curvature and noncylindricity being more common where this angle is small. However, in contrast to the observations of Ramsay and Sturt (1973), in the Bababudan hills axial curvature and noncylindricity are common even where the axial surface makes a high angle with the mean layering (figures 3d, 7). We are of the opinion that in the banded ferruginous quartzite initial irregularities on the bedding surface and the interference of progressively growing folds played the dominant role in the development of noncylindrical folds with curved fold axes. The fold styles point to a deformation environment (low P-T) where strong rheological contrasts existed between different layers (Chadwick *et al* 1985b). It is postulated that under such conditions minor initial inhomogeneities exerted a greater influence on the resultant buckle folds. This is different from deformation in a higher metamorphic grade where passive folding would be dominant. We suggest that noncylindrical folds with high axial curvature are likely to be more common in situations where rocks have high overall viscosity and strong viscosity contrast; buckling would dominate over flattening in such situations.

2.3 *Minor structures and progressive deformation*

As pointed out by Chadwick *et al* (1985b), though there is considerable variation in the orientation of the folds no consistent superimposition relation of temporally distinct phases of folding is decipherable. Certain geometrical features observed in the area indicate that the structures formed at different stages of progressive deformation. Where folds of different scales occur together variable relations between their axes are observed. A fine ribbing, which is caused by minute crinkles on the bedding plane is at places parallel to the axes of the associated larger folds (figure 8b). Such parallelism is generally observed where the larger folds are of the nature of gentle to open undulations. In other instances the ribbing is oblique to the axes on the limbs of the larger folds (figure 8c). The acute angle between the lineation and the fold axis opens in the same direction on the two limbs so that the ribbing pattern on the unrolled surface is similar to an acute chevron nearly symmetrical about the fold axis (figure 9a). On the hinge zone the ribbing is usually parallel to the fold axis. Such a pattern cannot be

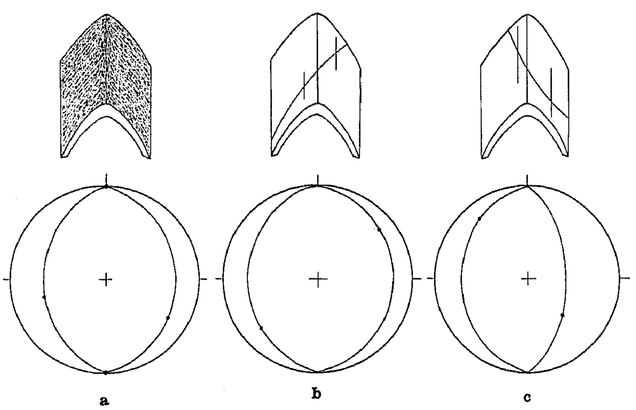

Figure 9. Patterns of oblique lineations on minor folds; (**a**). lineation showing chevron pattern on unrolled surface; (**b**). Lineation bent by fold, angle between lineation and fold axis same on two limbs; (**c**). lineation bent by fold, angle between lineation and fold axis different on two limbs.

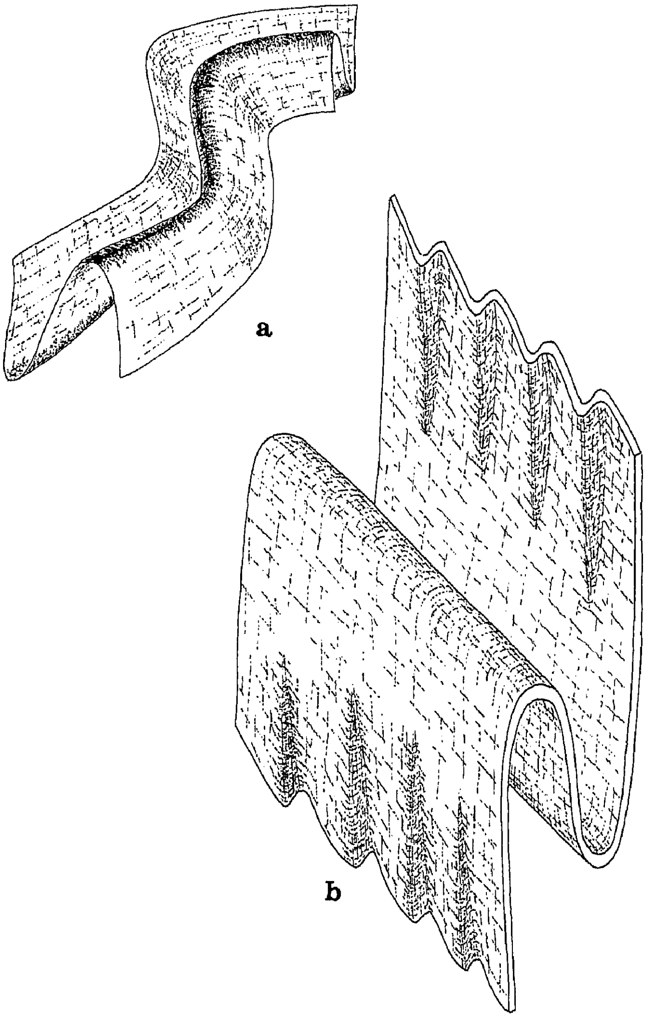

Figure 10. (a). Nearly nonplunging E-W trending folds bent by folds with N-S axial plane; (b). Folds with oblique axes on limbs of isoclinal folds.

explained as due to flexural refolding of an earlier lineation.

Near Kavikalgundi tight to nearly isoclinal folds having gently plunging axes are common. These have a sinistral shape in cross section when viewed from the east and are congruous with respect to the Bababudan synform. On the long limbs of these folds smaller open folds with moderately plunging axes are present which are also congruous to the major synform (figure 10b). These die out towards the hinge of the larger fold and no refolding relation between the two sets are present. The pattern is similar to the modified second (2b) mode of superposed buckling in multilayers described by Ghosh *et al* (1993).

All the above features may be explained as due to the formation of the larger and smaller folds at different stages of progressive deformation. If we start with a planar bedding inclined to the principal strain axes, during progressive deformation it would rotate towards the XY plane. If buckle folds are initiated at any particular stage of deformation their axes would be parallel to the direction of maximum elongation at that instant (Flinn 1962; Ramsay 1967). With increasing deformation the folds get tighter and at the same time the plane as a whole (the enveloping surface) rotates towards the XY plane. The fold axes that develop at a later stage on different parts of the already folded bedding will be controlled by the orientation of the respective part of bedding with respect to the principal axes. These, in general, will not be parallel to the earlier formed axes. Thus the axes of smaller folds developed later on the limbs of a larger fold would show systematic divergence from the axis of the latter, and neighbouring folds developed at different instants of progressive deformation may have differently oriented axes. In such progressive deformation if the two limbs of the earlier formed fold are symmetrically oriented with respect to a principal plane of the strain ellipsoid, the pattern of the later formed fold axes would be of the chevron type (figures 8c, 9a). It also follows from the above discussion that where the larger fold is of the nature of gentle undulation, that is, where the limbs do not deviate much from the initial attitude of bedding the divergence between the earlier and later formed axes would be small (figure 8b).

In the examples described above the smaller folds are interpreted to have developed at a later stage on different parts of earlier larger folds. The reverse relationship is also found. At places a set of minor crinkles are bent by a larger fold having a slightly oblique axis. Here the larger fold obviously developed later than the smaller folds. However, orientationwise the folds cannot be grouped into two distinct populations of early and late age.

On some minor folds a lineation defined by fibrous amphibole is seen to go over the fold hinge in the manner of deformed lineation. The angle between the lineation and the fold axis may or may not remain constant (figures 9b, c). The significance of this lineation remains uncertain. There is no separate planar fabric or minor fold related to this lineation, and its orientation falls within the general scatter of the axes of the minor folds. It is, hence, unlikely that it represents a distinctly different deformational episode. Probably it records the direction of stretching on the bedding surface at an earlier stage of deformation. Folds with oblique axes originated at a later stage when the attitude of bedding with respect to the principal axes of strain had changed, and the lineation was bent by such folds.

At several places overturned, asymmetrical folds with gently inclined axial planes are seen (figures 11a, 12a, b). On their normal limbs minor folds are present some of which are less tight, nearly symmetrical and have steep dipping axial planes; the overturned limbs are devoid of minor folds. This variation can also be explained as being the result of progressive deformation. A bedding plane which is not parallel to one of the

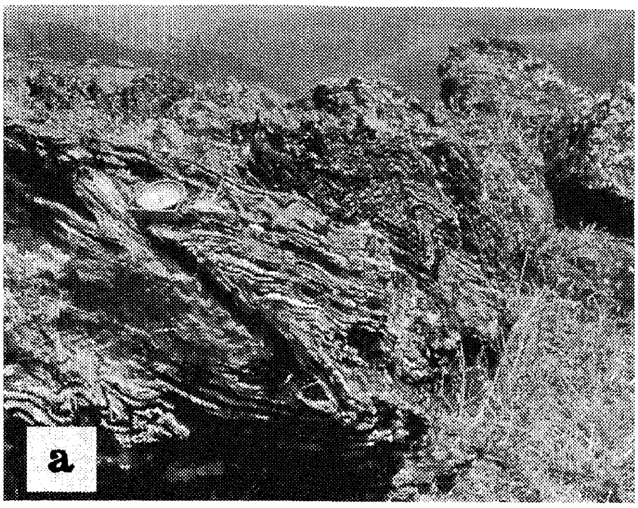

Figure 11. (**a**). Overturned mesoscopic folds, smaller folds on gently dipping normal limb are upright, nearly symmetrical and have larger interlimb angle.

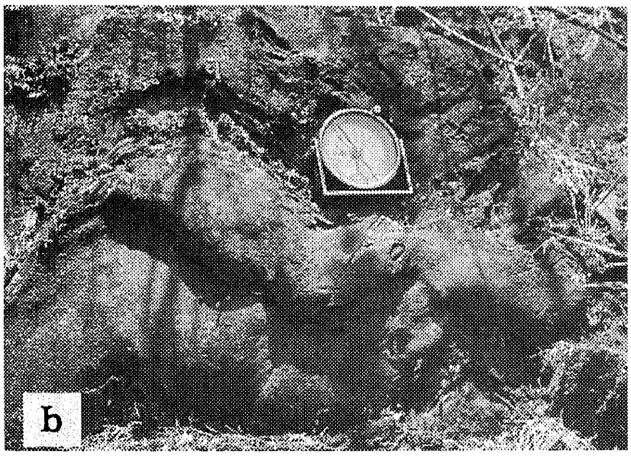

Figure 11. (**b**). Hinges of E-W folds bent by N-S folds.

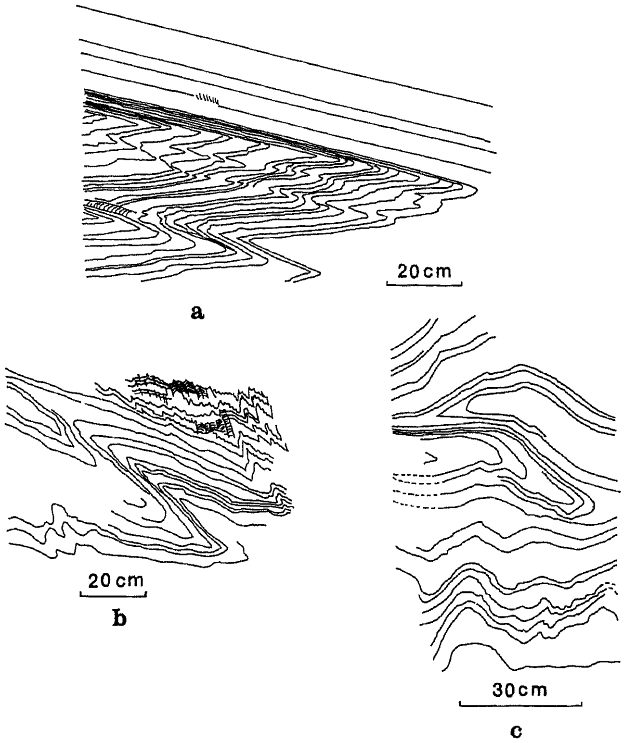

Figure 12. (**a**). Overturned minor folds, smaller folds are present only on gently dipping normal limb; (**b**). Overturned minor fold with more open, symmetrical, upright smaller folds on normal limb; (**c**) coaxially refolded minor folds. All sketches are drawn from photographs.

principal planes will rotate with progressive deformation and a layer parallel shear would act on such planes. This shear would impart an asymmetrical shape to the folds developed on such planes (Ramberg 1963). In such asymmetrical folds the long limbs may continue to lie within the domain of shortening while the short limb might rotate into the domain of elongation. As a result the smaller folds would continue to develop only on the long limbs at later stages of deformation while the short limbs would remain planar or be even boudinaged. When buckle folds are initiated their axial planes are likely to be almost perpendicular to bedding (Flinn 1962; Ramberg 1963). Therefore, the smaller folds that develop at later stages would retain their perpendicularity while those that formed earlier would rotate to an inclined position. Hence we may infer that open symmetrical folds with steep axial planes on the normal limbs of larger overturned asymmetrical folds (figures 11a, 12b) developed at a later stage, while asymmetrical smaller folds on the normal limbs (figure 12a) developed earlier and were rotated more.

Another interesting feature resulting from progressive deformation is observed southeast of Mulaingiri. In this region the asymmetrical folds are generally sinistral and congruous with the Bababudan synform. Here, on a macroscopic second order sinistral fold smaller folds remain sinistral on both long and short limbs, though congruous folds on the short limb should have been dextral. It is interpreted that the smaller sinistral folds formed at an earlier stage and the larger fold formed later, but the general strain pattern on the limb of the first order major synform remained the same, so that the larger fold also assumed a sinistral shape, but it rotated the earlier formed smaller sinistral folds.

Coaxially refolded minor folds are seen at places (figure 12c). In these examples the axial planes of the 'later' folds are subparallel to those of the dominant set of folds in the southeastern Bababudans. The 'earlier' folds may belong to a different phase of deformation. However, no such large scale interference pattern is seen and the coaxial refolding may result from continued deformation during a single phase (Chadwick *et al* 1985b).

2.4 *Superposed deformation*

In spite of considerable local variability there is a statistical parallelism in the orientation of the axes and axial planes of minor folds. This, together with a unity of the style of folds and the rarity of consistent refolding relationship, has led the authors to conclude that the dominant set of minor folds belong to a single phase of deformation, though, as discussed earlier, structures formed at an earlier stage have been deformed by those formed at a later stage.

Definite evidence of superposition of a later set is seen in a few exposures. In an exposure north of Dattatreyapitha the axes and axial planes of the dominant set are bent by later folds having nearly N-S trending axial planes (figures 10a, 11b). Near Jensurigudda dome and basin patterns have been produced by the interference of WNW-ESE and NE-SW trending folds. Folds with steep axial planes having N-S to NE-SW strike are observed on the southern slopes of Mulaingiri. These may belong to a later episode of deformation, but clear evidence of their superposition on the main WNW-ESE trending set is lacking. In the greenschist and talc-tremolite schist below the banded iron-formation on the southern slopes of Mulaingiri nearly N-S trending crenulation cleavage is present. Folds related to this cleavage have refolded earlier folds with axial plane schistosity.

3. Macroscopic structural pattern

The major structure in the area is a synformal bend clearly indicated by the swing in the general trend of bedding from E-W and NE-SW in the southern part to N-S in the northern part (figure 13). Topographically this is manifested by the change in the trend of the main escarpment which is everywhere parallel to the regional strike of the bedding.

In the southern part of the area from Mulaingiri to Manikyadhara Falls the regional strike varies from E-W to NE-SW. Higher order folds, macroscopic as well as mesoscopic, are mostly sinistral and congruous with the main synformal bend. North of Manikyadhara Falls and beyond Dattatreyapitha the regional strike becomes N-S. Higher order folds in this part are either symmetrical or dextral though a few sinistral folds are also seen. The general dip of bedding is everywhere inwards defining the major synformal bend in the southeastern corner of the Bababudan 'horseshoe'. Though the regional plunge of the axis of this synform is gentle towards WNW to NW, individual smaller folds are often doubly plunging. At the core of this fold, in the Attigundi-Jensurigudda region the presence of a series of smaller but mappable antiforms and synforms obscures the regional change in strike (figure 16). This represents the zone of crumpling in the core of the larger structure.

Between Manikyadhara and Dattatreyapitha there is a lateral westward shift of the exposure of the main ferruginous quartzite (figure 13) caused by an E-W trending fault. Such rupturing near the zone of sharp bending of competent strata has frequently been observed in the minor folds of the area. Stress concentration in the hinge region of the major synformal bend has probably caused this rupturing.

An interesting structural feature is the presence of small to fairly large nearly recumbent to gently inclined reclined folds (figures 8d, 12a) in the exposures between Manikyadhara and Dattatreyapitha. These folds have gently dipping normal limbs and steep or overturned short limbs. Their axial planes make a low angle with the regional bedding and their axes plunge WNW parallel to those of the dominant set of minor folds. Their shape is indicative of sinistral layer parallel shear. These may belong to an earlier phase of coaxial folding, or they might have been formed during the early stage of the main deformational episode. In the latter event they were rotated during the formation of the major synformal bend due to layer parallel shear consequent on large scale buckling. Drury *et al* (1984) mentioned about the presence of recumbent folds at high levels in the Bababudan belt, though no details were given. They referred to these as early folds.

3.1 *Orientation pattern and structural geometry*

For geometrical analysis the area in figure 13 has been subdivided into twenty sectors (figure 16). Figures 14 and 15 show the trend maps of the axes and axial planes of minor folds. The equal area projection diagrams are given in figure 16; table 1 enumerates the structural data in the different sectors.

A significant feature which emerges out of the geometrical analysis is the frequent noncylindrical nature of folding. In nearly half of the sectors a small circle fits the distribution of bedding plane (S_0) poles. This is the pattern of circular conical folding. The axis of the cone is designated as χ and its position is located by the geometrical construction given by Tischer (1963). The conical distribution pattern is consistent with the observation that individual folds often die out in the direction of fold axis. In other sectors the distribution of the bedding plane poles can be fitted to a great circle and a unique β can be located. Sector 6 shows no definite great circle or small circle pattern (figure 16f). This and the slight deviation from a perfect great circle in some other sectors (2, 3, 18, 20, figures 16b, c, u, y) are either due to variations in the attitudes of the axes of individual folds or due to difference in axial attitudes of neighbouring folds within a sector.

It appears from figures 13, and 16, and from table 1 that in those sectors which contain several well exposed macroscopic folds the patterns are conical while in the sectors with dominantly planar bedding the patterns are cylindrical. For a better understanding of the geometry of structures in conical

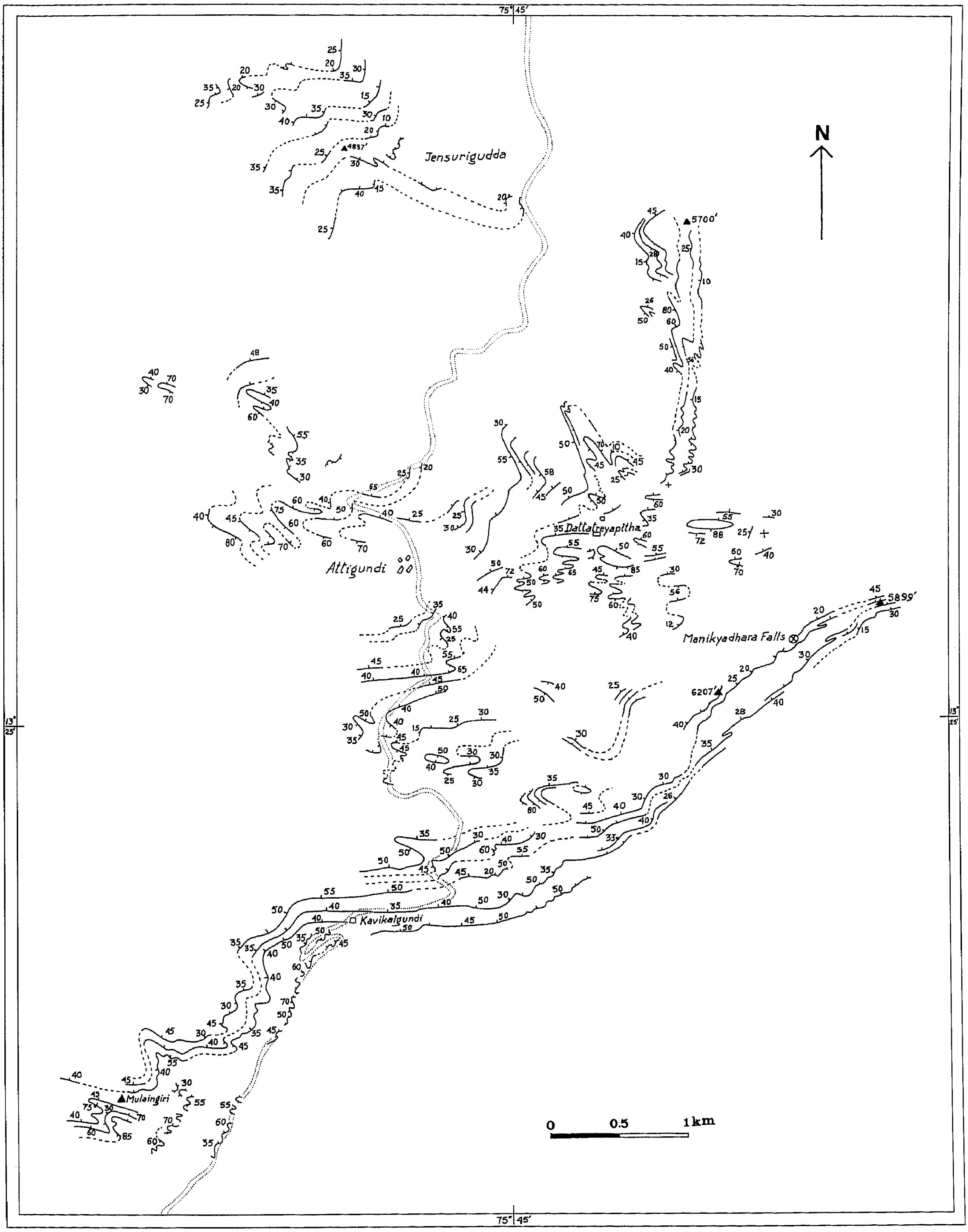

Figure 13. Map showing generalized orientation of bedding.

Figure 14. Map showing generalized orientation of axial planes of minor folds.

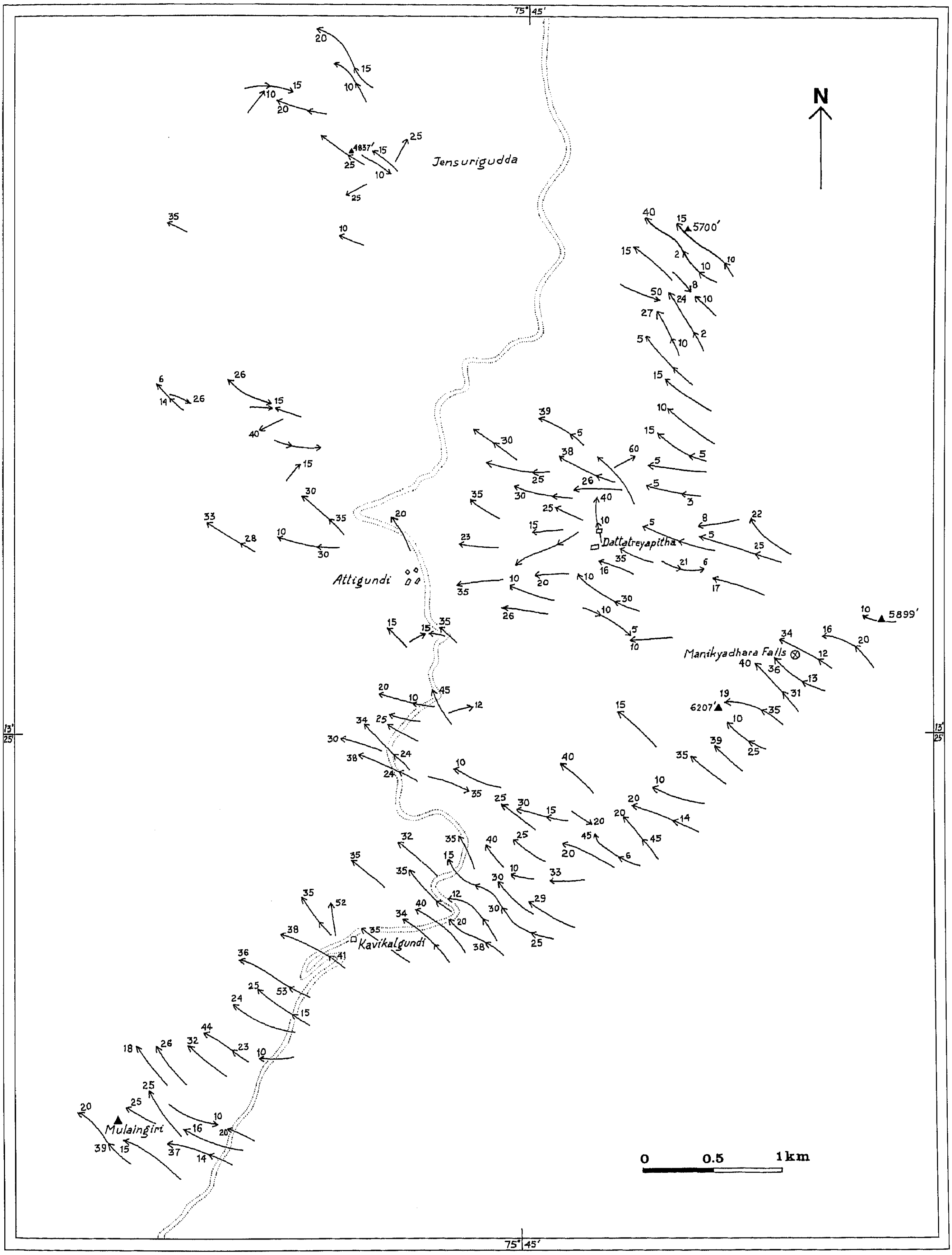

Figure 15. Map showing generalized orientation of minor fold axes.

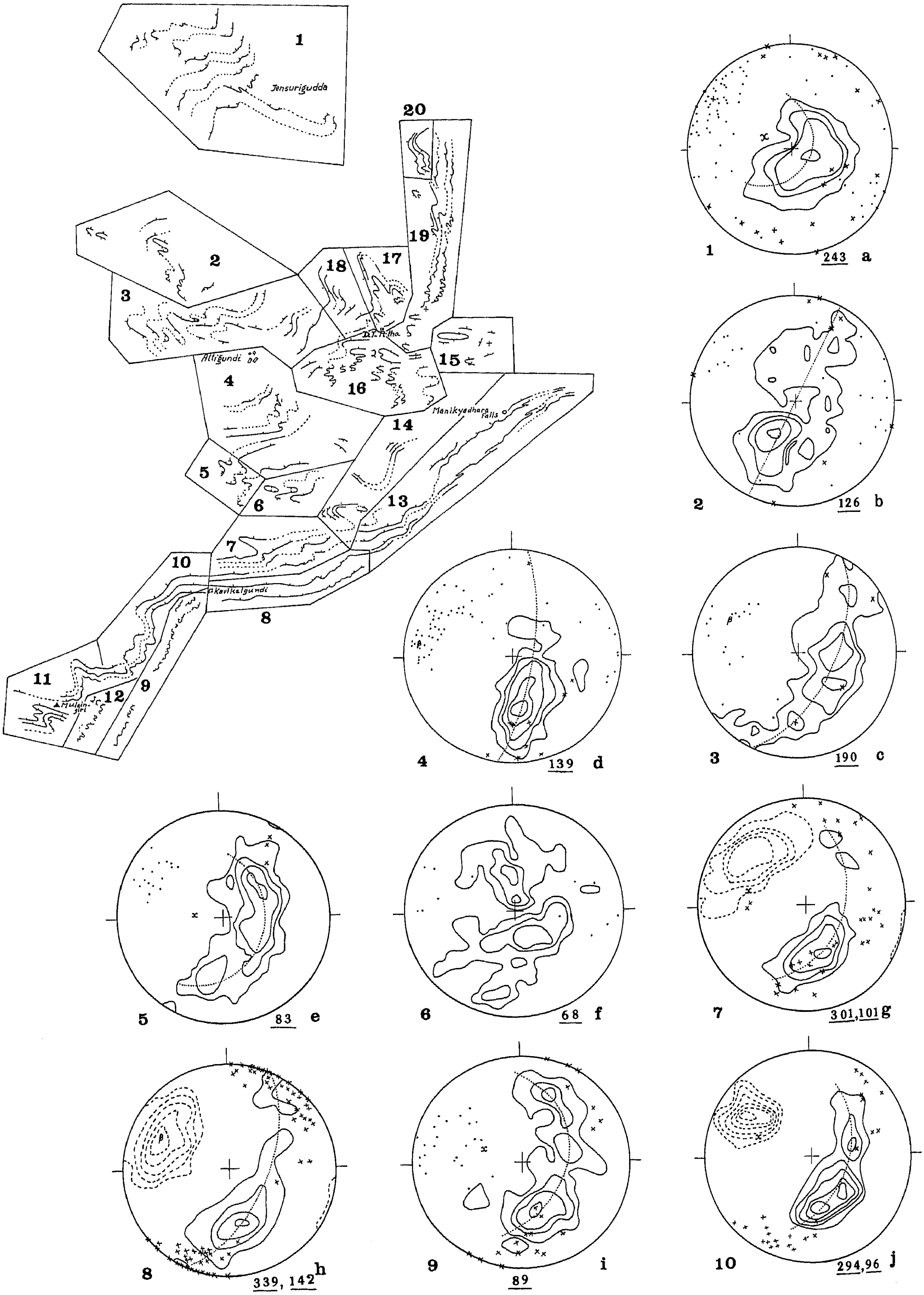

Figure 16. (*Continued*)

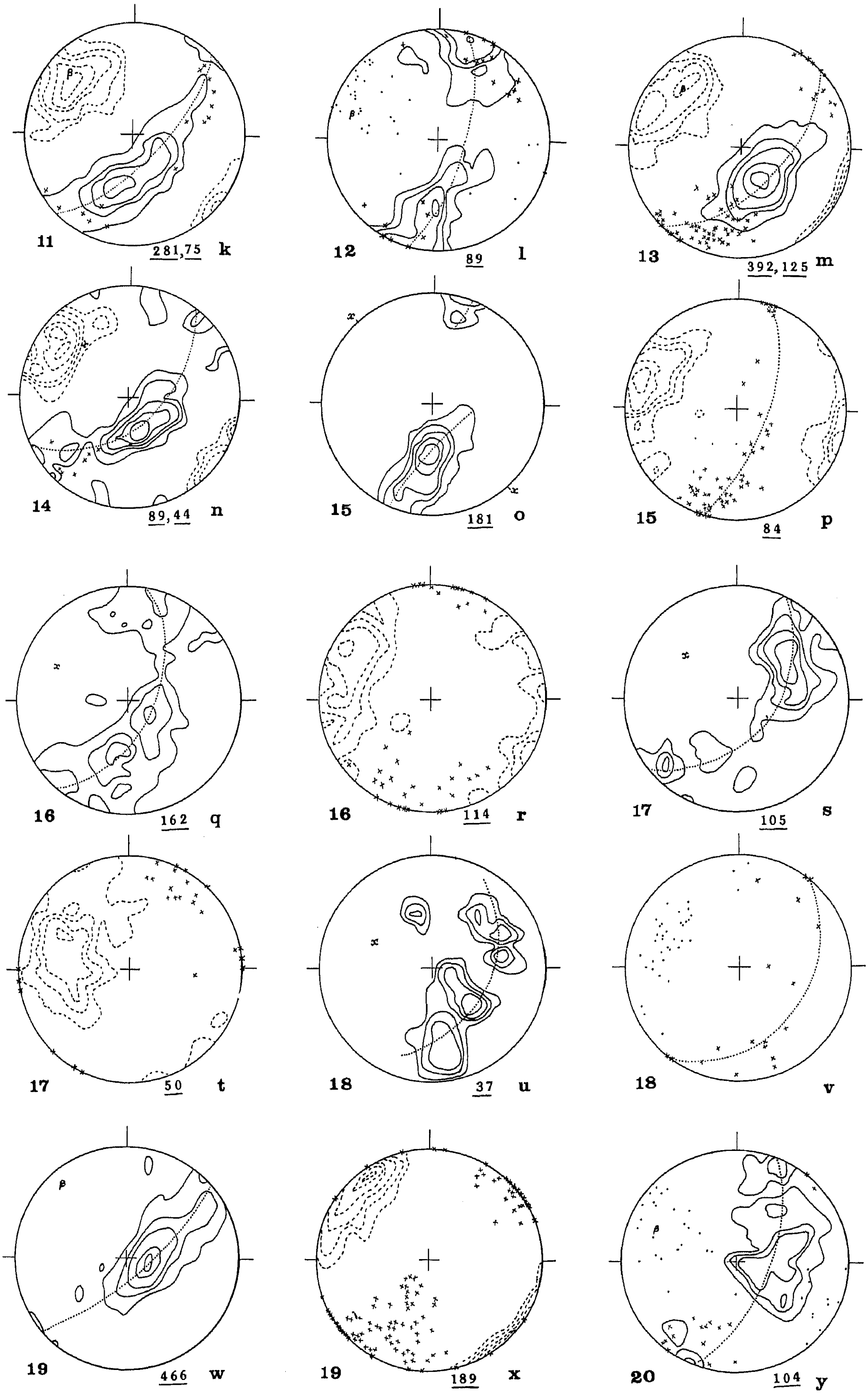

Figure 16. Equal area projection diagrams of structural data in different subareas. Solid contours – bedding, crosses – axial planes, dashed contours or dots – fold axes. Inset shows sector delineation. Bold number in each diagram indicates the sector number. Underlined number indicates the number of measurements for the contoured diagrams. Where there are two such numbers the first number refers to bedding measurements, the second to fold axes. Contours at 1–3–5–10–15% per 1% area.

Table 1.

Sector no.	β	χ	Apical angle	Modal fold axis
1.	-	66° → 295°	39°	12° → 305°
2.	0° → 297°	-	-	-
3.	28° → 296°	-	-	-
4.	13° → 278°	-	-	20° → 291°
5.	-	68° → 276°	56°	22° → 299°
6.		No regular pattern		
7.	-	45° → 285°	75°	30° → 310°
8.	30° → 296°	-	-	30° → 292°
9.	-	59° → 290°	65°	30° → 288°
10.	-	47° → 291°	71°	30° → 294°
11.	20° → 313°	-	-	28° → 307°
12.	20° → 285°	-	-	12° → 300°
13.	29° → 314°	-	-	27° → 316°
14.	-	38° → 318°	74°	20° → 306°
15.	-	0° → 317°	66°	12° → 284°
16	-	16° → 295°	78°	12° → 300°
17.	-	40° → 308°	78°	32° → 297°
18.	-	42° → 294°	82°	30° → 290°
19.	15° → 318°	-	-	8° → 325°
20.	25° → 292°	-	-	-

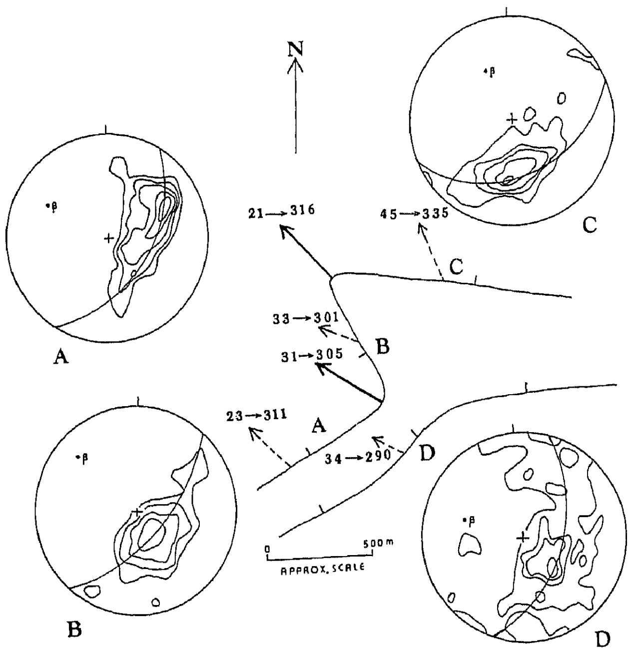

Figure 17. (a). Sketch map of a sinistral fold in Sector 10. Orientation of β in sectors **A, B, C, D** shown by dashed arrows. Bold arrows represent orientation of axis of major synform and antiform determined from the intersection of bedding plane maxima in sectors **A** and **B** and sectors **B** and **C** respectively. Bedding plane patterns in different sectors are shown in equal area projection diagrams. Contours at 1–3–5–10–15% per 1% area.

folding, a part of sector 10, which shows this pattern has been mapped in detail. A large sinistral fold is present in the area (figure 17a). The structural data from the western long limb, the short limb and the eastern long limb (subareas A, B and C respectively) have been plotted in equal area projection diagrams 17b, c and d. Though in each subarea the bedding plane has an overall planar attitude, the presence of higher order folds cause the bedding planes to be scattered along great circles whose poles (β) give the statistical attitudes of the axes of these higher order folds. The axes of minor folds and lineations are either parallel to or make small angles with it. The intersections of the bedding plane maxima in subareas A and B and B and C give average attitudes of the axes of the major synform and antiform respectively of the sinistral pair. The average attitudes of these axes and the S_0 maxima and β in each subarea are shown schematically in figure 17(a). The βS on the limbs are not parallel to the axes of the first order folds but define a chevron pattern similar to that seen on some minor folds (figure 9a). Thus, in domains showing conical distribution of S_0 poles, within smaller areas with overall planar bedding, the patterns may be cylindrical and the axes of the smaller folds in such subareas need not be strictly parallel to the axes of the larger folds within the domain.

The minor fold axes show considerable variation from sector to sector (figures 15, 16). They generally have gentle to moderate plunge towards WNW to NW (table 1). The doubly plunging nature of some minor folds is indicated by ESE to SE plunges observed in some sectors (figures 16a, b, l, y). In some sectors (figures 16d, g) the fold axes show a spread along the S_0 maximum great circle, denoting variation of axes of small folds on essentially planar bedding. In domains with cylindrical folding the minor fold axes maxima are close to β but are not always strictly coincident with it (figures 16c, d, h, i, l, v, y). In domains with conical folding (figures 16a, e, g, j, k, n, p, r, t) the minor fold axes lie close to the zone of intersection of the great circles representing the different S_0 maxima or submaxima. In such domains the minor fold axes are not parallel to the χ axis. The deviation is greater where the apical angle of the cone is small (table 1).

The axial planes of minor folds have WNW-ESE to NW-SE strike and moderate to steep northerly dip. Polyclinal folds are quite common and in some sectors the axial plane poles are distributed along a great circle whose pole does not generally coincide with β or minor fold axis maximum. This indicates that the polyclinal folds are not homoaxial. Axial planes of a distinctly different set are found in some sectors (figures 16a, t, v). Their strike varies from N-S to NE-SW. As discussed earlier these belong to a later episode of deformation.

4. Regional pattern

The strike of the axial planes and the trend of the fold axes in the Bababudan belt are in contrast to the N to NNW trend in most of the other Dharwar schist belts. This throws open the possibility that the folds in the different schist belts may not be contemporaneous.

The Bababudan belt has been thought of as a low strain zone bounded by N-S shear zones on either side (Drury *et al* 1984). Therefore, it is conceivable that the early Dharwar structures are preserved here in a relatively unmodified state. The dominant fold system in the southeastern Bababudans has steep axial planes and gentle WNW to NW plunge. In the northeastern corner of the Bababudan horseshoe also (figure 1) one of the authors (DM) has recorded the presence of folds with similar orientation. Thus, the first order regional structure in the Bababudan ranges appear to be a broad hinged (U-shaped) westerly plunging synform, whose inward dipping limbs are represented by the two E-W arms of the Bababudan horseshoe and whose hinge zone is exposed in the N- S trending ridge of the eastern Bababudans. Within the area studied no earlier regional fold is deciphered, though folds on fairly large to small scales (e.g., the large recumbent to reclined folds near Manikyadhara) might have formed earlier in the same progressive deformation episode. West of the present area, on the southern limb of the Bababudan synform a tight synformal fold (Vodigudda synform) has been mapped by Chadwick *et al* (1985b). They are of the opinion that it is contemporaneous with the Bababudan synform. However, its shape is incongruous with the easterly closure of the latter and the evidence on its chronology is equivocal.

In the present area there is indication of a weak deformational episode responsible for N-S to NE-SW trending axial planes and crenulation cleavage. This may have caused the regional curvature of the axial trace of the Bababudan synform. Chadwick *et al* (1985b) ascribe this curvature to 'synchronous refolding', while Drury *et al* (1984) interpret that this is due to refolding induced by a prominent shear zone west of the Bababudan belt. More structural information from the western Bababudans is needed to resolve this problem.

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