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Successive development of plane noncylindrical folds in progressive deformation

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Abstract—In the history of superposed deformations of the iron formations at the western border of the Kolar Gold Field in S India, an important event was the successive growth of broadly coaxial plane noncylindrical folds in course of a progressive deformation concomitant with development of ductile mesoscopic shear zones. The noncylindrical folds were initiated as active folds by the creation of a buckling instability at successive stages on newly developed foliation surfaces. The nucleation of noncylindrical folds and the subsequent axial-plane folding of the tightened mature folds are explained by the mechanical inhomogeneity of the rocks and the heterogeneous character of strain. The correlation between increasing tightness and increasing noncylindricity of the folds indicates that the initial curvatures of hinge lines were accentuated by an extension parallel to the subhorizontal stretching lineation. From the patterns of deformed lineations over folds of varying tightnesses, it is concluded that the passive accentuation of hinge-line curvatures was mostly achieved when the folds had already become isoclinal or very tight.

INTRODUCTION

Although plane noncylindrical folds have received a large amount of attention in recent years, certain aspects of their origin are still rather obscure. The difficulty of explaining such structures is especially felt when their hinge lines are strongly curved and the folds are isoclinal or very tight. In the extreme case when the hinge line is isoclinally bent, the fold has the appearance of a somewhat flattened sheath. In recent years several authors (Carreras *et al.* 1977, Quinquis *et al.* 1978, Ramsay 1980, Cobbold & Quinquis 1980) have explained similar structures by an accentuation of initially curved hinge lines in course of progressive simple shear deformations. A major problem associated with this theory is to explain the initial waviness of the hinges. Moreover, as pointed out by Treagus & Treagus (1981) a model of active folding being completely replaced at a mature stage by a purely passive mode of evolution is unrealistic. Hence, where the noncylindrical folds have been initiated by a buckling instability in a layered stack of competent and incompetent units, the problem is the extent to which the fold geometry was modified by passive accentuation of initial curvatures of the folding surfaces.

In most areas, the plane or weakly non-plane, strongly noncylindrical folds occur in association with other types of folds, and the deformation history is complicated by the development of successive generations of folds, lineations, cleavages and shear surfaces. There are very few regions where the longitudinal directions of the folds are sufficiently well-exposed to reveal the exact geometry of the curved hinge lines; there are fewer areas where the successive phases of plane noncylindrical folding are so well-preserved that a coherent history of their geometrical evolution can be worked out without gross oversimplification. One such area is in the western border of the Kolar Gold Field (Bruce Foote 1882, Smeeth 1899, Viswanatha & Ramakrishna 1981) in S India, between Madge's Corner and Dodbetta (Fig. 1).

The following discussion about the origin of plane noncylindrical folds is based on field studies of mesoscopic structures in this region where the nearly continuous outcrops of thinly banded iron formation show a profusion of mesoscopic folds with large expanses of

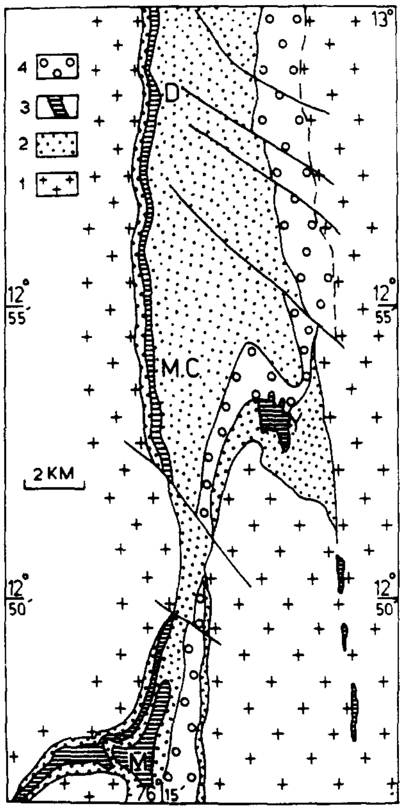


Fig. 1. Geological map of the Kolar Gold Field, modified after Viswanatha & Ramakrishnan 1981. D, Dodbetta; Y, Yerrakonda; MC, Madge's Corner; M, Mallappakonda. 1, Peninsula gneiss; 2, Metabasic rocks; 3, Iron-formation; 4, Arkose, conglomerate, and volcanics.

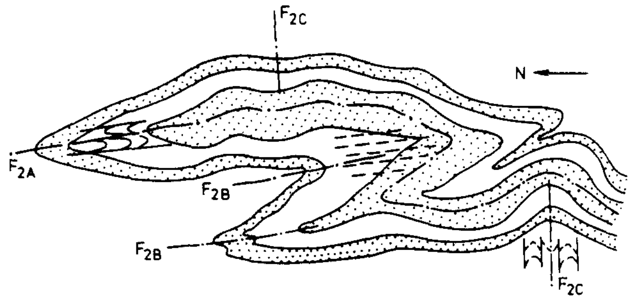


Fig. 2. Geometrical relations among F_2 folds. The folds are broadly coaxial with subvertical fold hinges. The axial traces of F_{2A} and F_{2B} are N–S, and those of F_{2C} are close to E–W. In incompetent units there are crenulation cleavages axial planar to F_{2A} and F_{2B}. The cleavage parallel to axial surface of F_{2C} is weakly developed.

exposed hinges. Here, critical evidence concerning the contemporaneity of shearing and folding and about the successive generations of noncylindrical folds is uncommonly well-preserved.

SUCCESSIVE DEVELOPMENT OF PLANE NONCYLINDRICAL FOLDS

From overprinting relations as observed on the mesoscopic scale, the folds in the iron formation between Madge's Corner and Dodbetta can be classified into three broad groups. The folds of the first group (F_1) are usually strictly isoclinal and are parallel to a N–S trending subhorizontal mineral lineation (L_1). The lineation and the axial surfaces of the F_1-folds are folded by the second group of folds (F_2) with N–S striking subvertical axial surfaces and with a steep generalized attitude of their curved fold hinges. The axial surfaces of the F_2-folds have been folded by a third group of folds (F_3) consisting of a system of open domes and basins or irregular open non-plane noncylindrical folds. Our main concern here is with the F_2 group of folds which, when unaffected by a later deformation, are mostly plane noncylindrical and are also the most dominant folds on the mesoscopic scale.

The F_2 group consists of three generations (F_{2A}, F_{2B} and F_{2C}) of folds. For the convenience of description the geometrical relations among them are shown in Figs. 2 and 3. The reason for their inclusion in a single group is to emphasize a certain community of characters; the folds are broadly coaxial, the folds of each generation are essentially plane noncylindrical and all the three generations of folds are broadly synchronous with a progressive shearing movement.

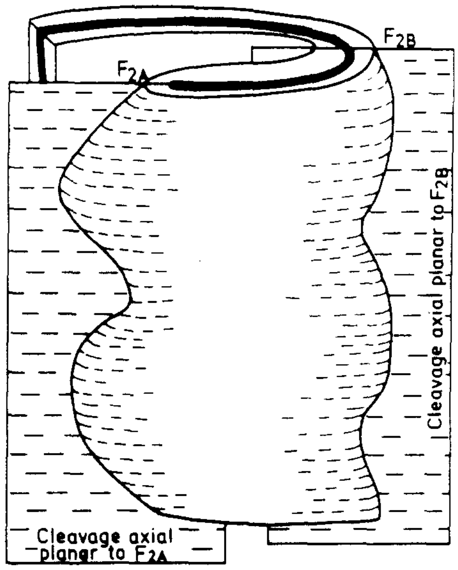


Fig. 3. Broad coaxiality of noncylindrical F_{2A} and F_{2B}. The general orientation of both fold groups is steep, but the earlier hinge is more arcuate. Hence the two folds are parallel only where they are parallel to their general orientation. Both folds deform a subhorizontal lineation; however, there are newly developed subhorizontal lineations on their respective axial-planar crenulation cleavages.

The F_{2A} folds invariably occur on the transposed foliation of the F_1-deformation. They are isoclinal or tight, and in spite of their strong variation in plunge (Fig. 4), ranging from subhorizontal to subvertical, the generalized attitude of the curved fold-hinges is steep in most places (Fig. 3). Parallel to the hinges of these F_{2A} folds there is a lineation L_2 marked by puckers grooves-and-ridges, fold mullions and intersection of foliations. On the whole the F_{2A} folds are strongly noncylindrical (Fig. 5a) with planar or gently undulating axial surfaces. Although in extreme cases the single hinge of a fold may bend through an angle of 90° on either side, the folds do not have the tubular shape of typical sheath folds. The hinge lines of the folds are smoothly curved in the form of a more or less regular series of waves or as a series of discontinuous half-waves slightly offset in en échelon fashion. These hinge-line wavelengths are greater for larger folds of thicker units. The F_{2A} folds have transposed the earlier foliation, and within the schistose incompetent layers a crenulation cleavage has developed

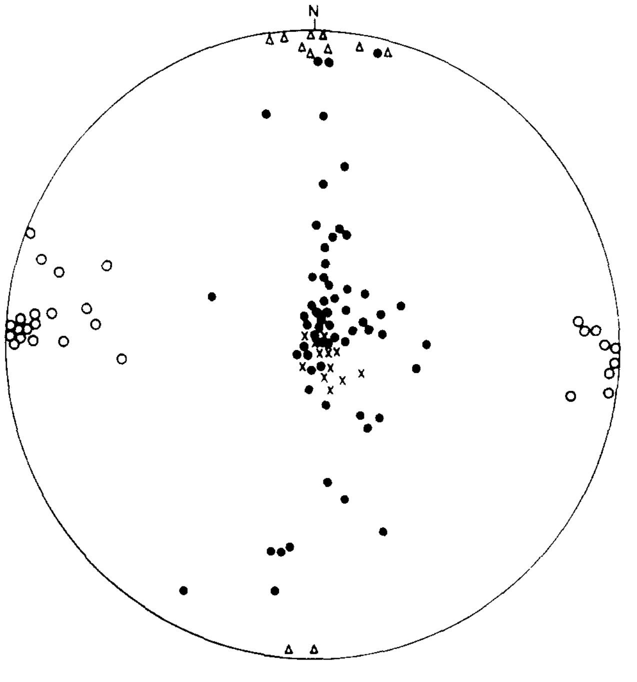


Fig. 4. Equal area projection of structural elements of F_2 folds in the iron formation between Dodbetta and Madge's Corner. Dots, fold axes of F_{2A} and F_{2B}; open circles, poles of axial planes of F_{2A} and F_{2B}; crosses, fold axes of F_{2C}; open triangles, axial planes of F_{2C}.

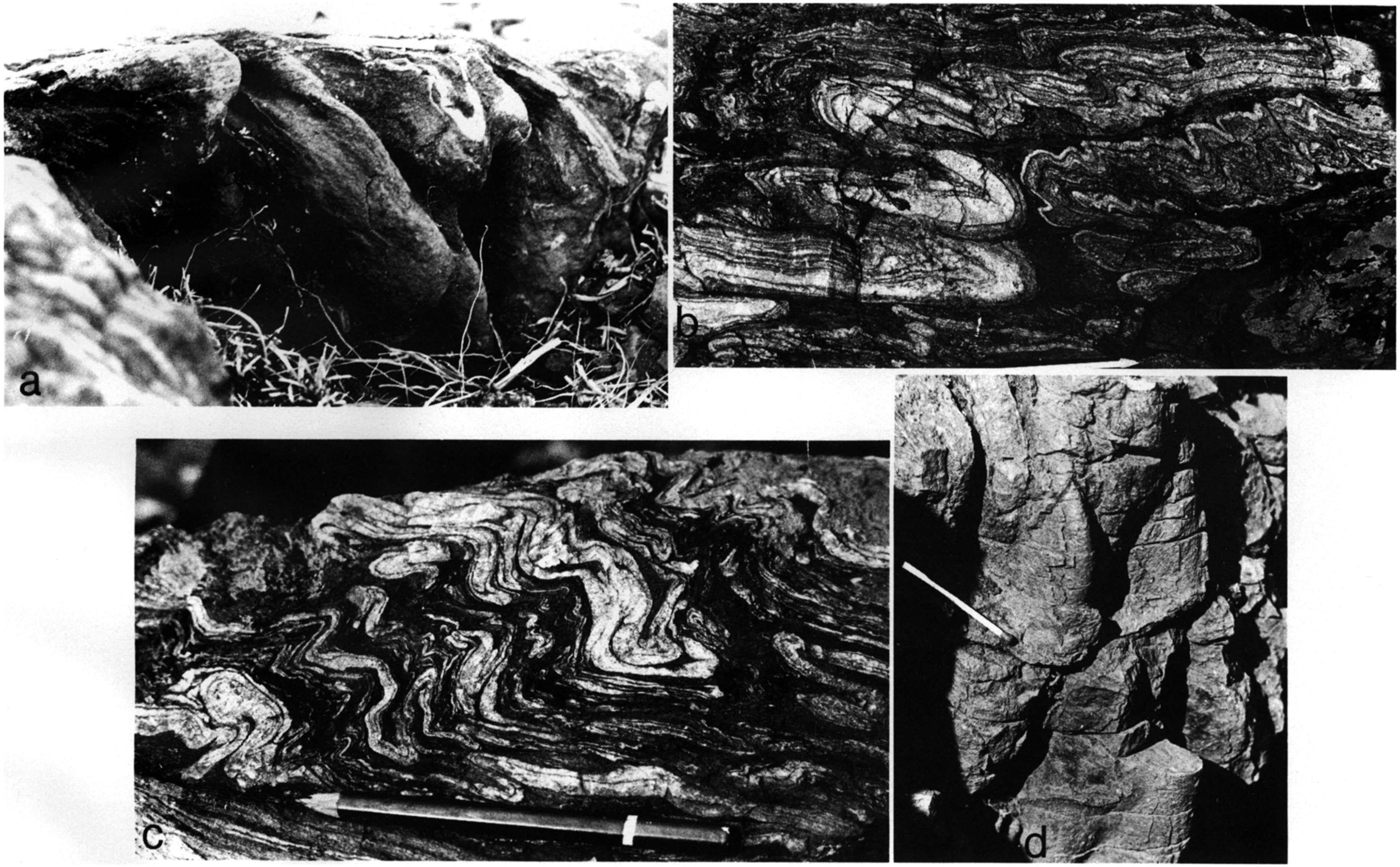
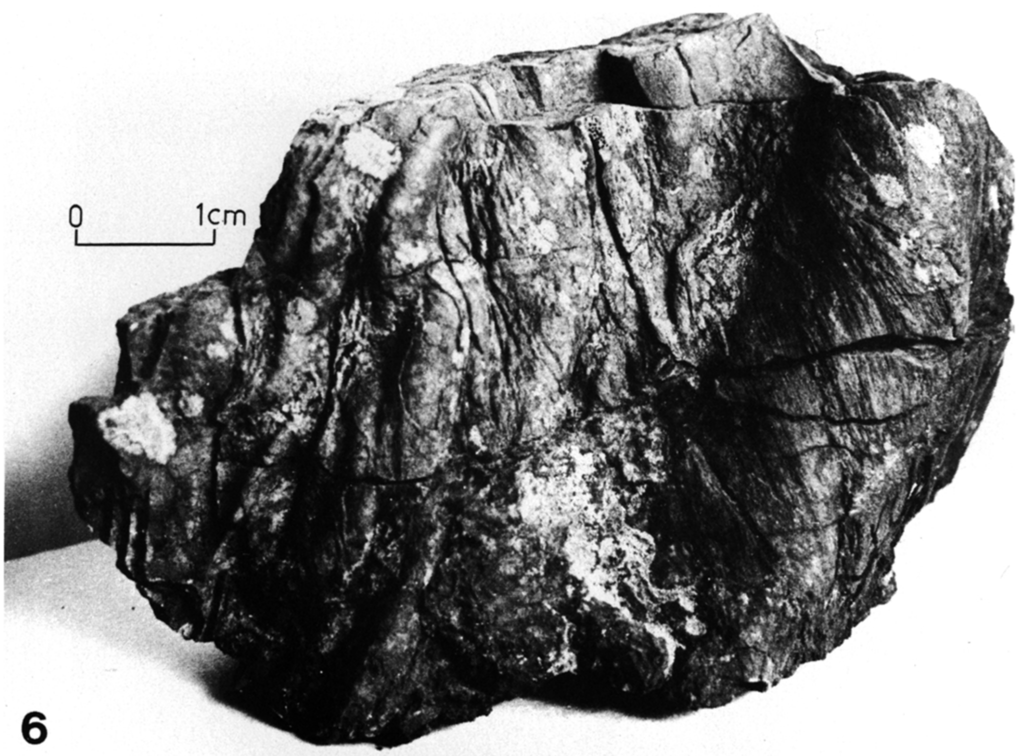


Fig. 5. (a) Plane noncylindrical F_{2A} folds. Note merging of fold hinges. The general orientation of the fold is vertical. Matchstick is parallel to axial trace and match-head points towards S. (b) Disharmonic F_{2B} folds. Horizontal section. Pencil points approximately northward. (c) Hock-shaped interference of steeply plunging F_{2A} and F_{2B} folds. Subhorizontal section. Pencil points towards S. (d) Steeply plunging hinges of F_{2B} with folded subhorizontal lineation L_1. Match-head points southward.



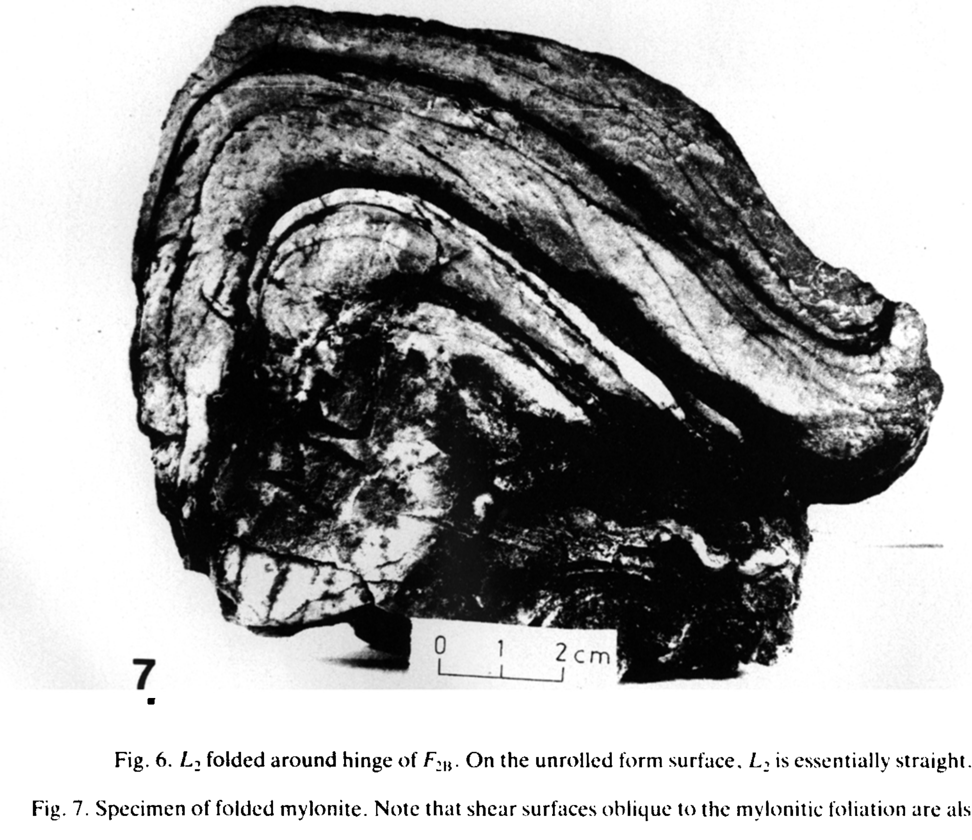


Fig. 6. L_2 folded around hinge of F_{2B}. On the unrolled form surface, L_2 is essentially straight.

Fig. 7. Specimen of folded mylonite. Note that shear surfaces oblique to the mylonitic foliation are also folded.

parallel to their axial surfaces. Over the F_{2A} hinges the subhorizontal lineation L_1 is always seen folded. For folds with strongly curved hinges the angle between L_1 and the fold-hinge is approximately a right angle where the pitch of the fold axis on the axial surface is about 90°. This angle decreases with decrease in the pitch of the fold-hinge, and where the hinge assumes a locally subhorizontal position the hinge and L_1 become approximately parallel.

The strongly asymmetrical F_{2B} folds, either S- or Z-shaped (Fig. 5b), refold the isoclinal F_{2A}, with the axial surfaces of the two systems parallel or at a low angle to each other and with the interference of the two systems producing hook-shaped patterns on the horizontal surface (Fig. 5c). They show a wide range of tightness from open to isoclinal folds. Similar to F_{2A}, the F_{2B} folds also show bifurcations of fold hinges, curving of the hinge lines on planar axial surfaces and the dying out of folds along their lengths. However, the degree of noncylindricity of the folds (Fig. 5d) is generally less than that of F_{2A}. The generalized disposition of the wavy hinge line of F_{2B} is steep (Fig. 4) and is approximately at a right angle to L_1. Consequently the gross orientation of their hinge lines is parallel to that of F_{2A}. In this sense F_{2A} and F_{2B} are broadly coaxial. Yet, since the wavy forms of their hinge lines are neither harmonious nor of the same amplitude, the two hinges are parallel only in certain segments where both assume their common generalized orientation (Fig. 3); elsewhere F_{2A} and L_2 become folded around the hinge of F_{2B} (Fig. 6).

The limbs and axial surfaces of F_{2A} and F_{2B} are deformed by a set of gentle to fairly tight, symmetrical or moderately asymmetrical, plane noncylindrical folds (F_{2C}). These are broadly coaxial with F_{2A} and F_{2B}, although their axial traces are nearly E–W and at high angles to the axial traces of the earlier folds (Figs. 2 and 4). The noncylindricity of F_{2C} is much less than that of either F_{2A} or F_{2B}.

Although the lineation L_1 is folded by all the F_2 folds, a similar N–S trending subhorizontal lineation has newly developed on the crenulation cleavages which occur parallel to the axial surfaces of F_{2A} and F_{2B} (Fig. 3). This single lineation appears to have developed over the periods of growth of F_{2A} and F_{2B}; there is no evidence for two different generations of lineation. From the lineation observations it is concluded that the F_{2A} and F_{2B} folds developed in a single progressive deformation.

The iron formation in the area under consideration shows gently curving inosculating shear surfaces and shear zones which dissect the rocks in long lenticular pieces with dimensions ranging from a few centimetres to a few metres. The lenses which can be seen in both horizontal sections and vertical E–W sections, are closed on all sides and the bounding shear zones of such lozenge shaped pods are noncylindrically curved. However, the microstructures of the rocks do not show any qualitative difference within and outside the ductile shear zones; the mylonitic rocks within the shear zones only show a much greater elongation of porphyroclasts and a smaller size of the matrix grains. Thin sections perpendicular to F_{2A} microfolds from the ductile shear zones often show a folding of the mylonitic foliation over the hinges; in certain cases, however, a true mylonitic foliation is axial planar to the folds on the foliated colour banding. Evidently the axial planar foliations of successive stages within or outside the shear zones, are approximately parallel to the local orientations of the XY planes of the corresponding stages of deformation. In a similar way the subhorizontal lineation in the mylonites is essentially parallel to the one which occurs outside the shear zones and has the same kinematic significance. The discrete shear surfaces and the mylonitic foliation on the ductile shear zones are often themselves folded. In some places the mylonites are intersected by N–S trending steeply dipping newly formed zones of shear with fresh development of a subhorizontal penetrative lineation. Over the hinge zones of the folded shear-zone foliation the deformed lineation occurs at a right angle to the steeply plunging fold axis, and this consistent orthogonal relation must mean that the development of the shear zones and the folding of the mylonitic foliation (Fig. 7) within them represent the different stages of a single progressive deformation. The similarity in style and the broad coaxiality of these folds with folds of the F_2 group lead to the conclusion that the F_2 group of folds was broadly contemporaneous with the shearing movements.

ORIGIN OF PLANE NONCYLINDRICAL FOLDS

The present study leads us to conclude that the initiation of the plane noncylindrical folds could not have taken place in a passive manner by accentuation of small initial irregularities on the bedding or the foliations. This conclusion is reached for the following reasons.

(1) Even the earliest of the F_2 folds developed on a transposed foliation; hence the folds could not have developed by a passive amplification of initial irregularities of a bedding surface.

(2) The individual folds as well as folds of different orders penetrate through a fairly thick stack of foliated layers.

(3) Since the noncylindrical folds continued to be initiated during successive axial-plane folding on successive generations of foliation surfaces, an initial irregularity of a foliation can hardly explain this feature.

(4) The disharmony of the folds (Fig. 5b), their size variation according to the law of competence, development of different orders of folds and the characteristic combination of class 1c and class 3 types (Ramsay 1967) in alternate competent and incompetent units give unmistakable evidence of their initiation as buckle folds; the approximate passive modification of their shapes must have been a later feature.

From the arguments given above we can conclude that, for the early stages of development of these plane noncylindrical folds, a theory of passive folding is not relevant even as a first approximation. The theory must simultaneously explain both the creation of a buckling instability and the initiation of noncylindricity—repeatedly, for successive axial plane folding. Moreover, in certain places we noticed a rough tendency of the neighbouring wavy hinge lines of the same generation and on the same form surface to have roughly similar wavelengths. This suggests that the initial noncylindricity was not quite irregular.

If the initial noncylindricity of the F_2 group of folds was not inherited essentially from pre-existing undulations, it could have been generated either by an inhomogeneous deformation or because of the mechanical inhomogeneity inherent in the anisotropic rocks. The mechanical inhomogeneity of the rocks is manifested in different scales. From microscopic to mesoscopic domains, the intensity of deformation and hence the fabric of the rocks show a strong spatial variation. Such a variation in fabric is all the more expected when the progressive deformation of the rocks involves boudinage, pinch-and-swell and transposition of foliation. As a result of such inhomogeneity the mechanical property of the rocks would vary both across and along the direction of shearing motion so that the stiffness of the sheeted structure would vary in different segments. Again, as a result of the spatial variation in mechanical property, the inter-layer sliding along a surface would be inhibited or facilitated to different extents in different places. Nucleation of buckle folds would tend to be facilitated in the relatively weaker segments and in segments with greater ease of gliding, and since these properties are likely to vary both along and across the generalized direction of the shearing motion, the initial folds would be discontinuous and noncylindrical. With progressive deformation the hinges will extend lengthwise and merge with one another so that the lengths of the hinge line waves or half-waves will increase. A certain amount of noncylindricity and bifurcation of fold hinges have been recorded in experimentally produced buckle folds in homogeneous competent sheets embedded in softer materials (Ghosh & Ramberg 1968, Dubey & Cobbold 1977). We suggest that the noncylindricity of the mature folds will be more pronounced in mechanically inhomogeneous anisotropic materials. Significantly, for the area under consideration, the hinge-line waves of the same generation and on the same form surfaces are roughly similar in size, and the hinge-line wavelengths are usually larger for larger folds of thicker units. This indicates that, although mechanical inhomogeneities facilitated the nucleation of noncylindrical folds, the scale of inhomogeneity was not a dominating factor in controlling the statistical average of the hinge-line wavelengths of mature folds.

Over the isoclinal or very tight F_2 folds the deformed L_1 is not unrollable; it is strongly curved when the form surface is unrolled over a more or less cylindrical short segment of the fold. On the other hand, when the open or moderately tight F_2 folds, which deform either L_1 or L_2, are unrolled, the lineations remain essentially straight or are gently curved. This indicates that the transition from a dominantly active to a dominantly passive mode of folding occurred only when the folds had become very tight or isoclinal; moreover, only such folds were strongly noncylindrical. Since an external rotation of the hinge lines could not have taken place without making the folds significantly non-plane, we conclude that the accentuation of hinge line curvatures was mostly achieved in an approximately passive manner when the folds had already become isoclinal or very tight.

The broadly coaxial folding of the foliations, the shear zones and the discrete shear surfaces indicate that during the progressive development of the F_2 group of folds, the deformation plan changed in such a way that the axis of rotation or the intermediate axis of strain remained more or less constant (i.e. subvertical) in orientation but the earlier stretching fabric was brought into the compression field. It is well known that a homogeneous shearing motion cannot distort the slip planes themselves. Again, with the rare exception of pulsating strain ellipsoids as described by Ramberg (1975), a steady-state progressive homogeneous deformation cannot cause a shortening of material planes which had once entered an extension field. However, the relative movement between sheets of rocks could have approximated an affine deformation provided the mechanical properties, especially the ease of gliding, was uniform. If the relative movement is impaired to different extents in different places the earlier axial surfaces of the tightened folds can once again be folded. Moreover, in the noncylindrically curved shear zones and within the lozenge-shaped pods bounded by them, the deformation could not have been homogeneous; the magnitude of strain and the orientation of the instantaneous strain axes must have varied from place to place. In such a situation a foliation could have been folded and refolded in progressive deformation as the material points were translated from one strain domain to another.

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