DEFORMATIONAL HISTORY OF THE DELHI ROCKS AROUND BILIAWAS, CENTRAL RAJASTHAN

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Around Biliawas (25° 53′ : 74° 14′) at the northern extremity of the Udaipur District in Central Rajasthan, the Precambrian metasediments belonging to the Delhi system of rocks (Heron 1953) have been affected by at least three deformational episodes (F_1—F_3), the second episode being the most intense. Tight to isoclinal earliest folds (F_1), varying in orientation from upright to inclined (Fleuty 1964) with axial trend varying between NNE and WNW have been superposed by tight, upright NS trending structures of second generation (F_2). F_3-structures are essentially upright EW trending broad warps, usually associated with conjugate kinks. Type 1 interference pattern (Ramsay 1962) is noticeable on a medium scale around Motala where large to medium sized F_2 and F_3 structures interfere. Eyed folds, dome and basin structures resulting from such interference are ubiquitous on minor scale also. F_2 folds often display complex geometry-curvilinear hinges, doubly plunging axes, antiforms turning into synforms when traced along axial traces—due to inhomogeneous flattening which appears to have played a significant role during the evolution of F_2 folds. These complexities are unrelated to F_3 folding episode.

INTRODUCTION

An area about 23 kms. sq. in extent around the village Biliawas (25° 53′: 74°14′) in Udaipur district (a quarter of the area falls in Bhilwara district) of Central Rajasthan, comprising dominantly calcareous, sub-ordinately pelitic or semipelitic and rarely psammitic sediments belonging to the Delhi system of rocks (Heron 1953) and regionally metamorphosed upto garnet grade, was lithologically and structurally mapped on a scale of 1 : 15,840. The area has suffered a complex deformational history and three distinct structures have been recognised. The intensity of second deformational movement and accompanying metamorphism (F_2) is the most severe and occasionally it entirely obliterates the traces of early structures (F_1). At the western margin of the area, the structural pattern is dominated by phases of intense folding during F_2 and F_3 movements producing a medium to large scale interference pattern of Type 1 (Ramsay 1962). Type 3 interference pattern (Ramsay 1962) is also noticeable but on a minor scale. A near type 3 interference pattern is suggested by the outcrops south of Biliawas and around Ruparel (Fig. 1). In the central part of the area, F_2 folding is dominant but dies out eastwards. The folds of different generations are localised in separate domains. F_1 folds are ubiquitous at the eastern margin, F_2 in central part and F_3 folds are restricted to the western margin of the area. F_2 folds exhibit complex geometry such as curvilinear hinges, doubly plunging axes,

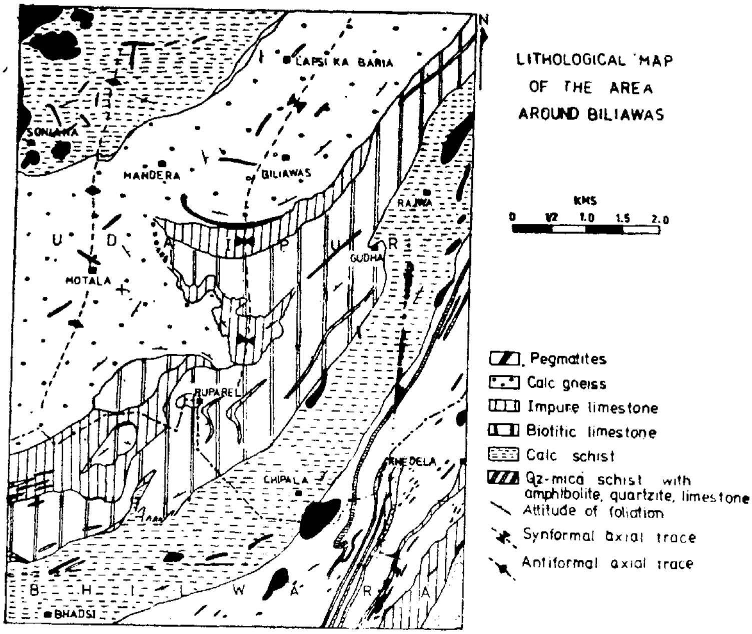

FIG. 1

antiforms turning along the axial traces into synforms (Ramsay 1962, Brown *et al.* 1970) even in areas free from the effect of F_3-folding. This is due to the inhomogeneity of flattening strain which probably played a vital role during the evolution of F_2 structures. In isolated single layers the amount of flattening is a function of the competency of the rock undergoing it, in a multilayer system, it is the composite property of the complex that determines the amount of flattening (Cobbold *et al.* 1971). In less competent isolated layers, such as those of pegmatite and aplite, the strain is taken up by considerable layer-parallel shortening while in relatively more competent ones, it is taken up mainly by buckling with only a little amount of layer parallel shortening (Hudleston 1973). The development of axial plane schistosity in the cores of major F_2 folds, and its place taken by a crenulation cleavage (Knill 1960; and Rickard 1961) in the limb regions of these folds suggests that micas recrystallised at the climax of F_2 deformational movement and that the metamorphic temperatures reached their highest just about the time the F_2-fold development had reached completion (Roday 1975, Ph.D. thesis* *unpublished*). Folds of each generation show variable styles but the variability is more pronounced in F_2-folds. The change in style is a function of the anisotropy of the multilayer seqences involved in buckling.

GEOLOGIC SET-UP

Heron (1953, Pl. 37) mapped a persistent conglomerate band at the base of the Delhis, but field evidence provides no definite support for Heron's view, as fai as the

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*Structure and tectonics of the Precambrian rocks around Badnore, Central Rajasthan, India.

present area is concerned. The so-called conglomerate appears rather to be a highly sheared quartzite, indeed, the shearing is so intense, it has an obliterated bedding in the rock to a considerable extent. All the metasediments have gradational contacts between them without any recognisable unconformity and Heron's division of the Delhi system into a lower Alwar and an upper Ajabgarh series does not appear to be quite convincing. Numerous thin bands of sheared quartzite within quartz-mica schist, increasing in thickness and quantity until the main horizon is reached, speak for this and make Heron's stratigraphic picture of the region questionable. The stratigraphic younging direction cannot be unequivocally established because of intense metamorphism and folding. However, the general sequence of different lithologies given by Heron seems to be acceptable. In this paper, most of Heron's terms for various rock types have been maintained.

The main lithologic units are quartz-mica schist, calc schist, biotitic limestone, impure limestone and calc gneiss, appearing successively in that order westwards. The contact between quartz-mica schist and calc schist is mostly obscured by a swarm of pegmatite veins and bosses. Biotitic limestone is not a homogeneous limestone in which biotite occurs disseminated as the name suggests but a banded rock consisting of biotite rich calcareous and biotite rich psammitic layers. Impure limestone is invariably siliceous, hard and slabby and gives rise to crescent shaped bold ridges (Fig. 1) where affected by major F_2 folds. It often pinches out along the strike Biotitic and impure limestones are succeeded by huge pile of calc gneisses which maintain a uniform width along the strike. Both biotitic limestone and calc gneiss often display differential weathering.

Extensive pegmatite activity has occurred in the area, more particularly along the contact of quartz-mica schist with calc schist. They range in size fromthin veins and stringers to thick veins and bosses. Large pegmatite bosses have emplaced calc schist around Soniana (Fig. 1) and one of these dated by Holmes (1955) gave an age of 735 million years. Mostly, they follow the foliation planes in country rocks and their emplacement appears to be guided by the structure and lithology. Three distinct generations of pegmatites occur, as mentioned in the author's earlier paper (Roday 1976).

STRUCTURE

(a) *Folding Movements*

Three distinct folding movements, here designated F_1, F_2 and F_3 have affected the rocks in the area. Minor folds related to each movement are abundant in the area under study.

(*i*) *F_1 folds* — These are generally plunging inclined (Fleuty 1964) with axial surfaces trending NNE or NE and axes plunging NNW or SSE at varied angles; or upright with axial surfaces trending NNE and axes plunging at steep or moderate angles to NNE or SSW with all variations of orientation in between. They are isoclinal in style or nearly so and in areas least affected by later deformational movements or in psammitic bands relatively less affected by F_2 or F_3 episodes, they have usually NW or SE plunging axes. It is therefore reasonable to assume that their present orientation is the result of the impress of later deformations. They have enormously thickened hinges and attenuated limbs, small interlimb angle and high amplitude-wavelength ratio (Table I). These folds are concentric in origin, modified

TABLE 1

Comparative study of folds of different generations

	F_1	F_2	F_3
1. Orientation	Inclined to upright Rarely reclined	Essentially upright but plunging inclined in the hinges of major F_3 folds	Essentially upright, associated with conjugate kinks
2. Form	Isoclinal or nearly so	Open or close but sometimes tight to isoclinal	Broad open warps.
3. Interlimb Angle	0—20°	Variable from 20° - 140°. Variability due to the competency of the rock types.	90°-160°
4. Amplitude/wavelength Ratio	10 : 1 to 3 : 1	3 : 1 to 1 : 2	1 : 3
5. Axial trend	Variable between NNE and WNW	Essentially NS but swinging between NNE and NNW	EW, the trend becomes WNW or WSW because of conjugate nature.
6. Axial surface trend	NNE	NS	EW
7. Axial surface Dip	Moderate to steep	Sub-vertical	Sub-vertical
8. Frequency of minor folds	Sparingly developed	Abundant	Abundant
9. Major folds	Present but difficult to map	Well developed	More or less well developed.
10. Geometry	Flattened parallel (Sub-class 1C, Ramsay, 1967)	Flattened parallel, varying between sub-class 1C and Class 2, Ramsay 1967	Flattened parallel (sub-class IC, Ramsay 1967)
11. Cleavage	Incipient strain slip cleavage.	Axial plane schistosity or crenulation cleavage	Fracture and crenulation cleavage.
12. Linear structures	Quartzo-feldspathic striping, elongation of micas, biotite feldspar knots, preferred orientation of hornblende	Crenulations, microlithons, cleavage mullions, bedding/cleavage intersection lineation, quartz rods, boudins, biotite-feldspar-quartz knots	Crenulations, bedding/cleavage and cleavage/cleavage intersection lineation

subsequently by enormous amount of compressive strain. This is evidenced by the reversal of curvature around hinges, disharmonic nature etc. The geometric studies (Roday 1974) reveal that they are of the sub-class IC type (Ramsay 1967). F_1 linear structures have diverse trends and variable plunge amounts owing to their rotation about later fold axes. The regional schistosity curves sympathetically around the hinges of these folds. Major folds of this generation do occur but difficult to identify because of the isocinal nature of these folds with extremely narrow hinges and more or less complete obliteration of small scale sedimentary structures due to regional metamorphism. In general, minor F_1-folds are restricted to the eastern part of the area. As regional schistosity is pre-F_1-folding, it is found deformed in all the deformational events. An incipient strain-slip cleavage (Bonney 1886) appears to have developed during F_1-folding movement.

Various linear structures are developed during F_1 episode. Hinges of minor F_1 folds form a prominent lineation of this generation with their widespread development in the eastern part. In quartz-mica schist, quartzofeldspathic lits form a prominent lineation. Besides these, elongation of micas in pelitic varieties, biotite-feldspar knots in quartz-mica schist, preferred orientation of hornblende in amphibolites are other mineral lineations formed during F_1 episode. Predominant quartzofeldspathic stripping in quartz-mica schist suggests that the metamorphic conditions during F_1-folding were of the grade of amphibolite facies. Minor F_1-folds are usually large in size, relatively speaking, in psammitic rocks (Pl. I, Fig. 1) in contrast to semipelitic or pelitic varieties.

(ii) F_2-folds — These are essentially upright (Fleuty 1964) with subvertical axial surfaces trending approximately NS and axes plunging at subhorizontal or gentle angles to N or S. The attitude of the axes of F_2-folds, however depends upon the attitude of the already folded surfaces on which F_2-folds are developed since F_2 axes lie at the lines of intersection of axial planes of F_2-folds with already folded surfaces (Ramsay 1960). Some variation in the amount of plunge of F_2 linear structures is, however, due to inhomogeneous flattening. Sometimes these folds are open to close, at other times quite tight and at still other times almost isoclinal resembling F_1-folds in form and style (Table I). Thus their interlimb angles are extremely variable and depend upon the competency of the rock undergoing deformation.

It is commonly observed in the field that F_1-folds with steep or moderate plunge occur in the limbs of outcrop scale F_2-folds. The hinges of minor F_2-folds, on the other hand, show recumbent to reclined F_2-folds, whether F_1-folds are recumbent or reclined depends upon the plunge of F_2 axis. Minor F_2-folds are abundant in calc gneiss and biotitic limestone groups but rare in other lithologies. (These folds are also parallel, modified by flattening, as evidenced by the reversal of curvature around hinges (Pl. I. Fig. 2), disharmonic nature (Pl. II Fig. 3) and the disappearance of folds toward the margins of the zone of contact strain (Pl. II, Fig. 1). The geometric studies (Roday 1974) reveal that these folds are also of sub-class IC type of Ramsay (1967).

A prominent cleavage, here termed S_2 to distinguish it from the regional schistosity S_1 and bedding S_1, is developed parallel to the axial surfaces of F_2-folds and it often shows considerable fanning, especially in open to close folds. In calc schist

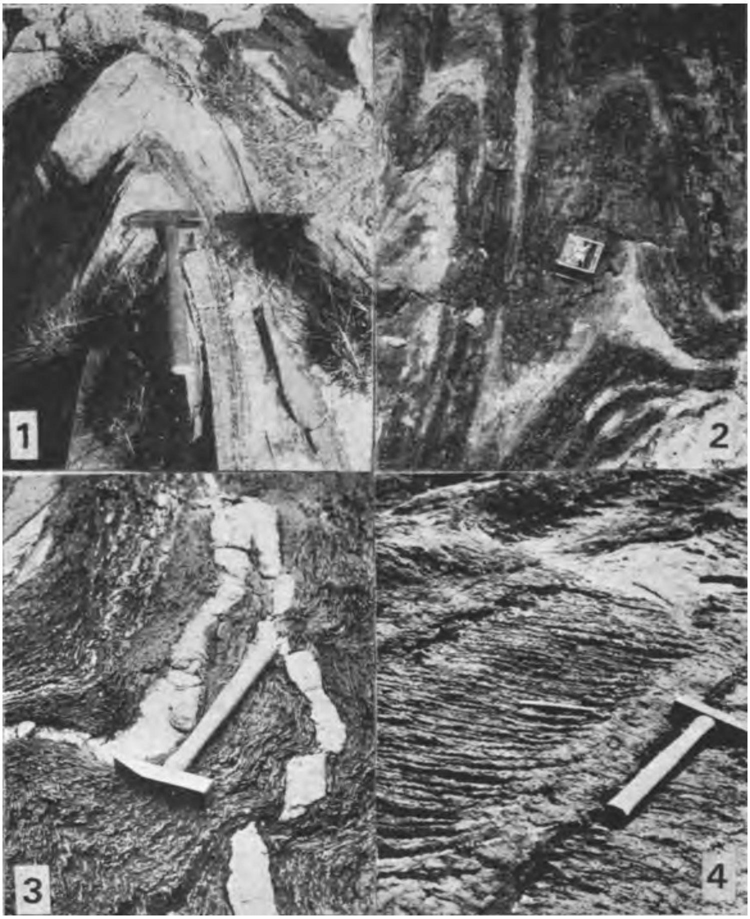

Plate I

1. Tight to isoclinal F_1-fold in a quartzite band southeast of Rajwa.
2. F_2-folds in biotitic limestone near Gudha showing reversal of curvature around hinges.
3. F_2-fold in quartz mica schist, just outside the eastern limits of the area. Note the fracturing of eastern limb and crenulations related to F_3.
4. S_3 cleavage cutting across the banding in calc gneiss at a large angle near Mandera.

it is developed in the form of a fracture cleavage (Agron 1950 in Cosgrove 1976—Pl. III, Fig. 3) but in pelitic schists and in rocks displaying high degree of anisotropy, it is developed in the form of a crenulation cleavage (Knill 1960; and Rickard 1961). At places, it occurs in the form of a well developed axial plane schistosity. It is interesting to note that in the cores of major F_2-folds, and especially in the one around Biliawas, a prominent axial plane schistosity is developed but its place is taken by a crenulation cleavage or simply microbuckles in the limb areas, east and west of Biliawas (Fig. 2), suggesting the recrystallisation of micas about the time the F_2-folding accelerated. Along the axial surfaces of crenulations or "microbuckles", second generation micas are developed and these steadily increase in quantity towards the

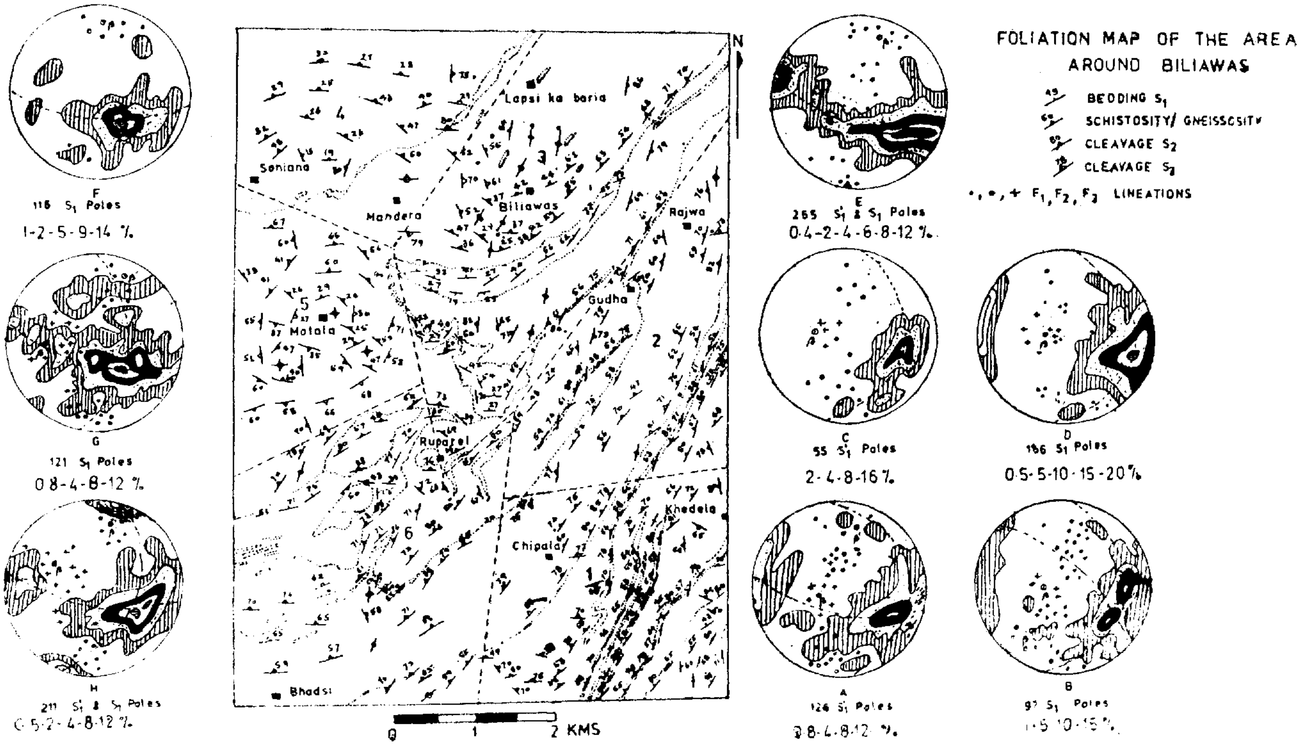
FOLIATION MAP OF THE AREA
AROUND BILIAWAS
BEDDING S_1
SCHISTOSITY/ GNEISSOSITY
CLEAVAGE S_2
CLEAVAGE S_3
F_1, F_2, F_3 LINEATIONS
N
Lapsi ka baria
Soniana
Mandera
Biliawas
Rajwa
Gudha
Motala
Rupaje!
Khedela
Chipala
Bhadsi
1
2
3
4
5
6
0
1
2 KMS
F
116 S_1 Poles
1-2-5-9-14 %
G
121 S_1 Poles
0.8-4-8-12 %
H
211 S_1 & S_1 Poles
0.5-2-4-8-12 %
E
265 S_1 & S_1 Poles
0.4-2-4-6-8-12 %
C
55 S_1 Poles
2-4-8-16 %
D
186 S_1 Poles
0.5-5-10-15-20 %
A
126 S_1 Poles
0.8-4-8-12 %
B
97 S_1 Poles
1-5-10-15 %

FIG 2

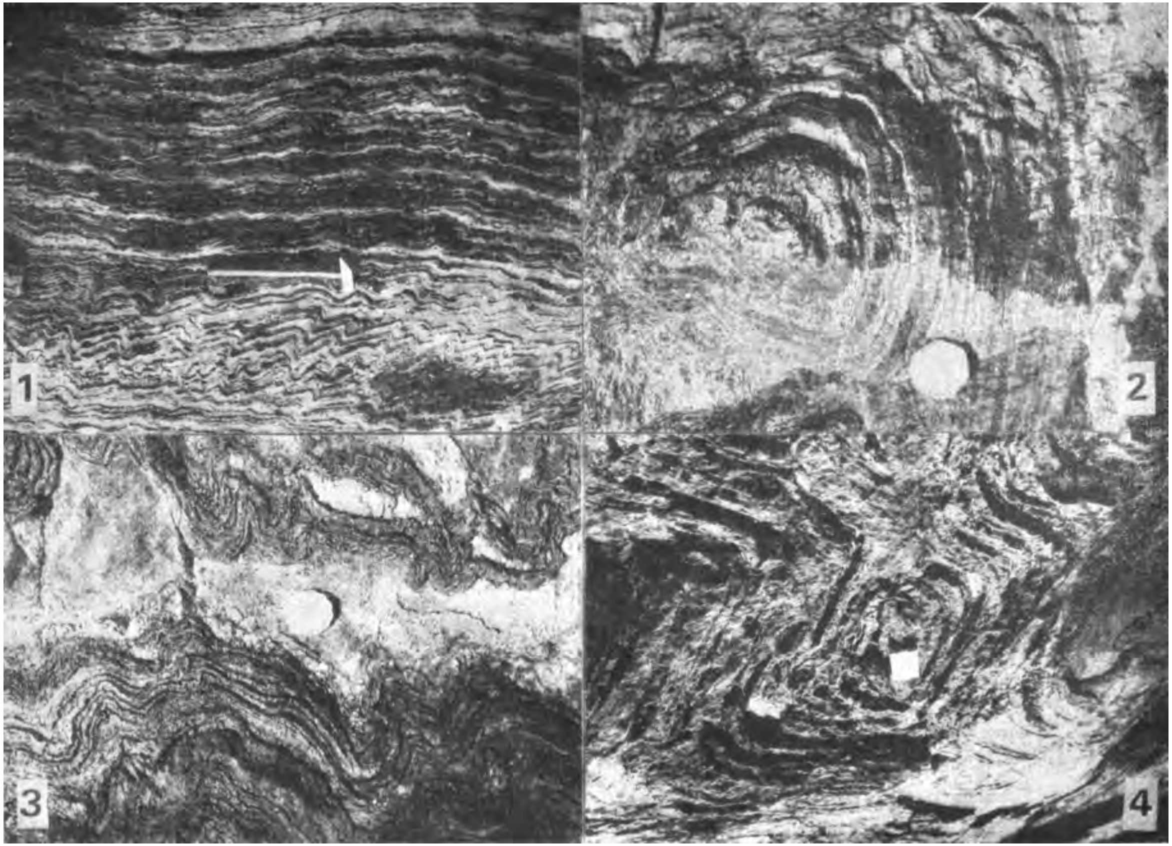

Plate II

1. Asymmetric F_2 buckles dying out towards the boundaries of the zone of contact strain southwest of Biliawas.
2. An eyed fold in biotitic limestone formed due to the differential flattening of an F_2-fold.
3. Disharmonic F_2-folds in biotitic limestone near Chipala, infiltrated by pegmatite.
4. An eyed fold formed by the interference of F_2 and F_3 minor folds near Motala.

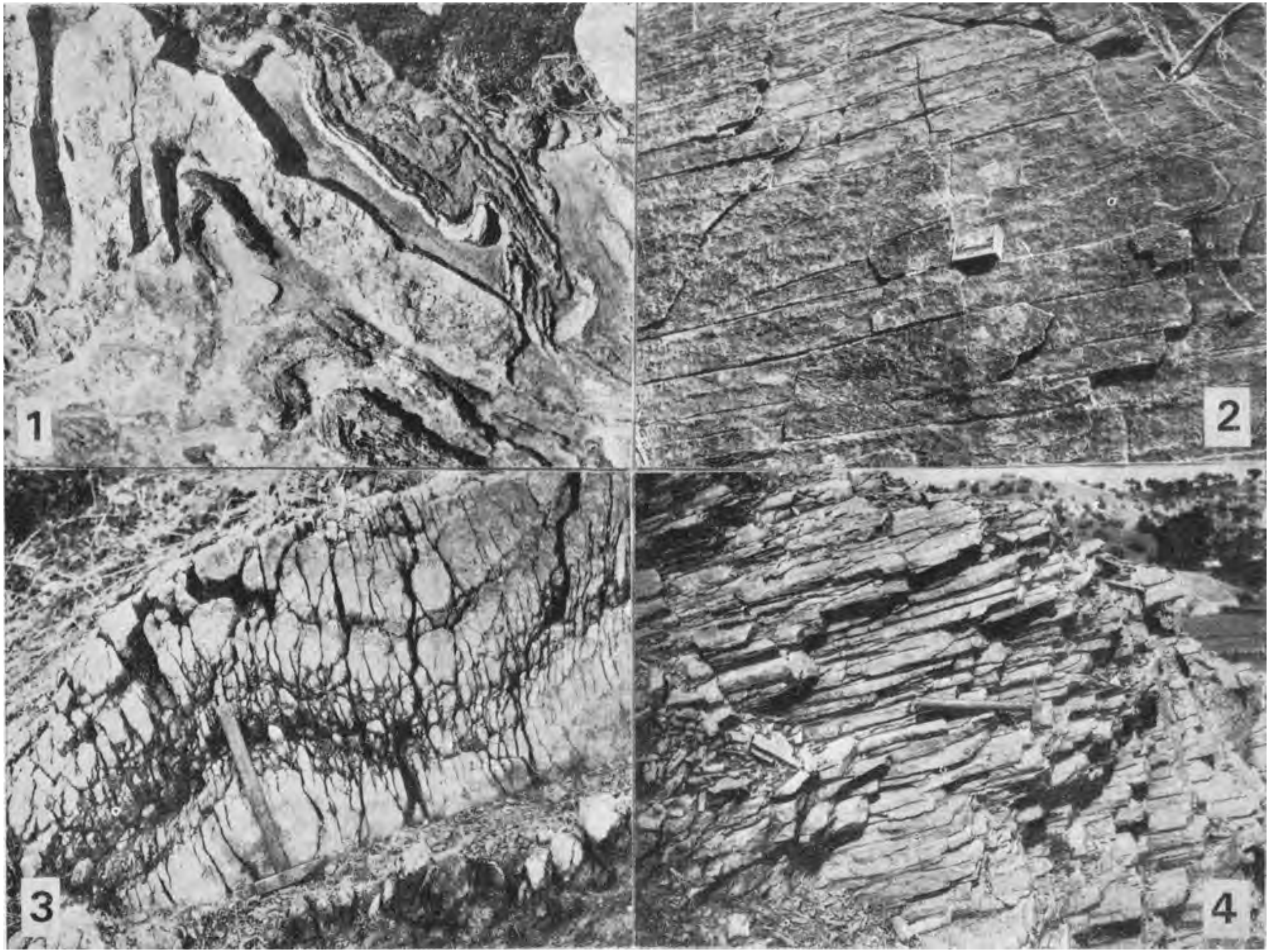

Plate III

1. Plunging inclined F_2-fold traced by pegmatite layer in calc gneiss east of Motala. 2. Traces of S_2 cleavage on S_1 calc gneissic surface southeast of Biliawas. 3. Broad open F_2-fold in calc schist near Bhadsi showing fracture cleavage. Note cleavage mullions near the hammer handle. Cleavage does not show much fanning as the fold is gentle. 4. S_1 S_2 cleavage mullions in calc schist near Soniana.

cores of major F_2-folds. At places in calc gneisses, this cleavage is so prominently developed that earlier bedding (S'_1) and gneissosity (S''_1) are not recognisable.

Although F_2-folds are essentially upright, they have been rendered into plunging inclined orientation (Fleuty 1964) because of the effect of F_3-folding (Pl. III, Fig. 1). This orientation is usually displayed by open to close folds. Usually where F_3-folds are superposed on F_2 folds, the result is the formation of domes and basins or eyed folds. This orientation is, therefore, very unusual and is probably due to the superposition of F_3-folds on F_2-folds which are developed in the hinge regions of earlier F_1-folds and where they have steep to subvertical plunge. Fig. 3 shows attitude of axial surfaces of minor F_2-folds in the demarcated area in which minor F_3-folds are also developed. EW girdle in inset stereogram suggests fanning but two NS girdles indicate rotation about F_3 axis. Southwest of Biliawas, the axial surfaces of F_2

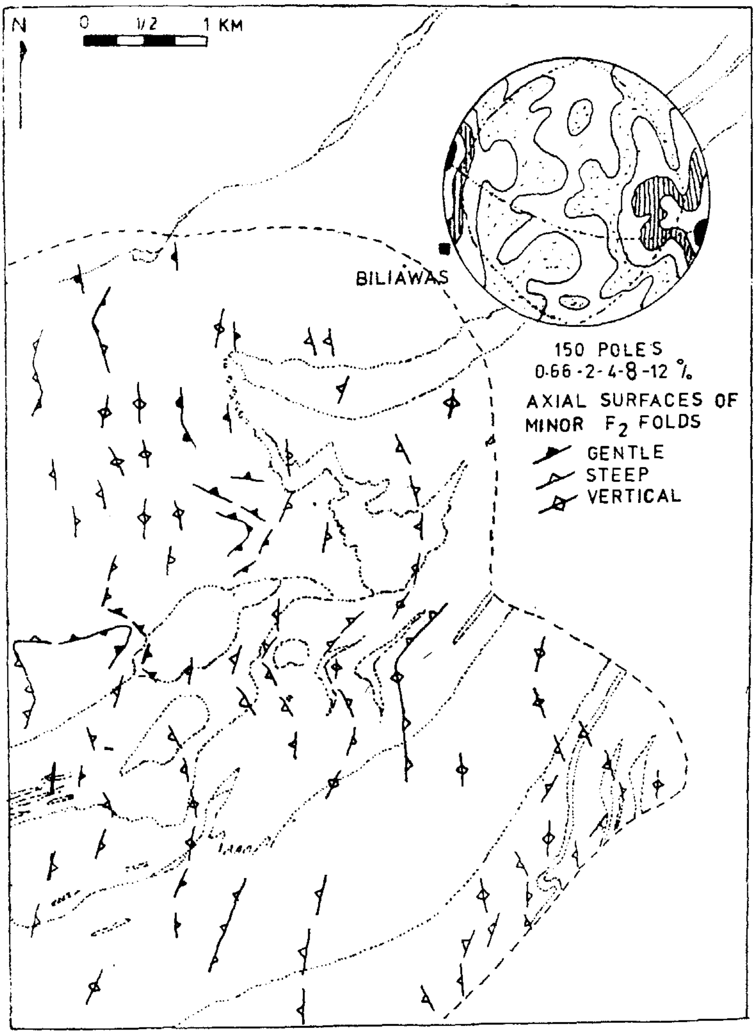

FIG. 3

minor folds trend NW or WNW but their axes plunge gently or moderately to ENE, E or ESE (Fig. 4), probably in the hinge zones of possible medium to large scale F_3-folds. This remarkable change in the trend of F_2 axes can only be explained as a result of the impress of F_3-folding. This orientation of F_2 folds being in the hinge zones of F_1-folds is substantiated by the large scale interference between F_1- and F_2-folds brought out by the pattern of limestone outcrops.

Various linear structures are developed during F_2 episode. Apart from the axes of minor folds, crenulations or microbuckles are widespread, more particularly in pelitic schists or rocks of high anisotropy. Kinks related to this generation are not found, owing to stress being higher than optimum (Cosgrove 1976). Structures resembling microlithons (de Sitter 1954), or more appropriately termed mesolithons, are usually formed due to non-affine slip along discrete S_2 planes. Excellent cleavage mullions are formed (Pl. III, Figs. 3 & 4), especially in calc schist and calc gneiss, where S_1 and S_2 intersect and are more or less equally developed. The commonest F_2 lineation noticed in calc gneiss is the trace of S_2 cleavage on S_2 surface (Pl. III, Fig. 2). Quartz rods are ubiquitously developed in psammitic formations. Boudins related to F_2 movement and often arranged as an echelon, are common throughout the area, especially in pegmatitic and psammitic bands. If the contrast between the layer undergoing stretching and enclosing host is not appreciable, pinch and swell structures form in preference to boudins. Whether boudins or pinch and swell structures would form also depends upon the disposition of original layering with reference to the maximum principal compressive stress (Cobbold *et al.* 1971). Predominant mineral

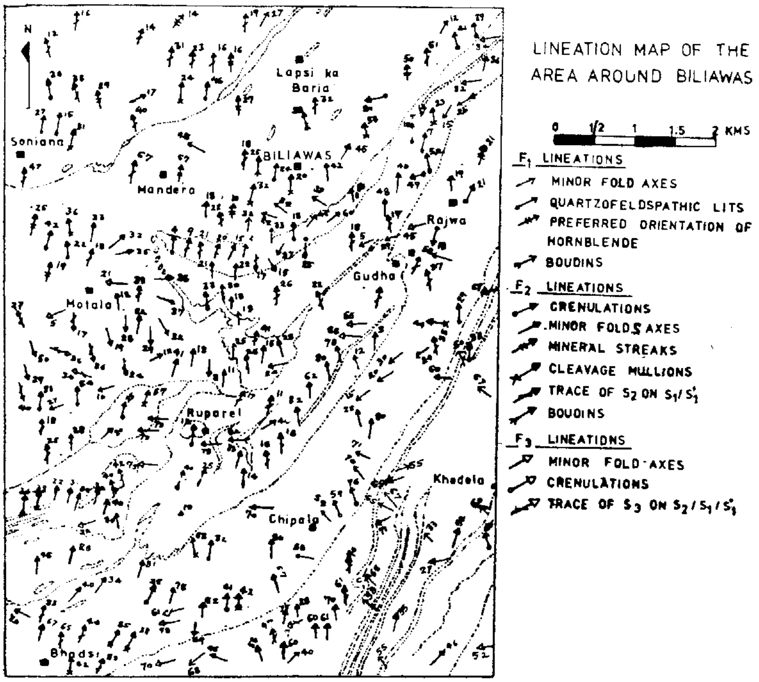

FIG. 4

lineation formed during this event is the elongate knots of quartz biotite and foldspar in calc gneiss.

(*iii*) *F_3-Folds* — These are essentially upright (Fleuty 1964) with subvertical axial surfaces and axes having an approximate EW trend. In suitable lithologies such as layered or thinly laminated and continuously anisotropic materials, they are associated with conjugate kinks which often give rise to a box pattern. Field observations on the stages of formation of a kink band suggest them to be reverse types in which the kinked zone did not undergo thinning until late in the history of its development (Cosgrove 1976). Mostly developed on minor but sub-ordinately on medium and large scales, they are generally broad open warps with large interlimb angle and small amplitude-wavelength ratio (Table I). A feeble axial plane crenulation cleavage (Knill 1960; and Rickard 1961), here termed S_3, is locally developed during this episode in suitable rock types. The effect of this folding on the early linear structures is clearly noticed in the area (Fig. 4). Sometimes F_2 axes are bent without F_2 axial surfaces being folded resulting into type 1 interference pattern (Ramsay 1962); at other times, both axial surfaces and axes of F_2.- folds are folded, causing F_2 lineations to swing between NNE & NNW. At still other times, F_2-folds are rendered into plunging inclined orientation, as described earlier. F_1 lineations obliquely curved about F_2 axes, move apart from each other due to overprinting of F_3 structures.

Apart from the minor fold axes, crenulations or microbuckles in pelitic schists are prominent. The intersection lineation where S_3 cleavage cuts the already folded surfaces (Plate I, Fig. 4) is common in calc gneisses. Minor F_3 folds are usually larger in quartzites and calc schists than in other lithologies. That these folds also occur on a major or at least on medium to large scale is supported by the presence of several medium to large sized domes and basins around Motala, formed due to their interference with major F_2-folds.

(b) *Geometry of F_2 folds*

Both major and minor F_2-folds exhibit varying form and style in different rock types. Folds are broad, open in calc schist (Plate III, Fig. 3), close to tight in calc gneiss (Pl. III, Fig. 1) but nearly isoclinal in biotitic limestones (Pl. I, Fig. 2). Near isoclinal F_2-folds can be identified from F_1-folds by the distinclty developed axial plane cleavage in the former.

Chevron style folds are usually noticed in biotitic limestone and calc gneiss owing to layered habit of these rock types. They display slight departures from the ideal, mainly manifested in slight increase of competent layer thickness at hinge owing to flattening subsequent to locking. Chevron folds in biotitic limestone display greater shortening across the layering than those in calc gneisses mainly due to the higher proportion of competent material in calc gneiss together with higher viscosity value of incompetent material (Roday, *unpublished*).

Most minor F_2-folds display variation in style and this appears to be a definite lithological control. The parameter interlimb angle describes the degree of tightness of a fold and therefore interlimb angles of several minor F_2-folds were recorded in the field from naturally available profile section exposures and on profile section photographs of such folds taken in the field or of specimens collected in the field. For folds in each lithology, separate histograms were prepared to represent the interlimb angle variation. Figs. 5A-E are a series of histograms depicting interlimb angle variation in biotitic limestone, calc gneiss, quartz-mica schist, calc schist and impure limestone. The histograms reveal an extraordinarily steady and uniform interlimb angle variation between various lithologies. The interlimb angles are least in biotitic limestone but maximum in calc schist. This is a definite lithologic control and it would be too incorrect to attribute this to the finite strain variability across the area, especially since the area covered is small.

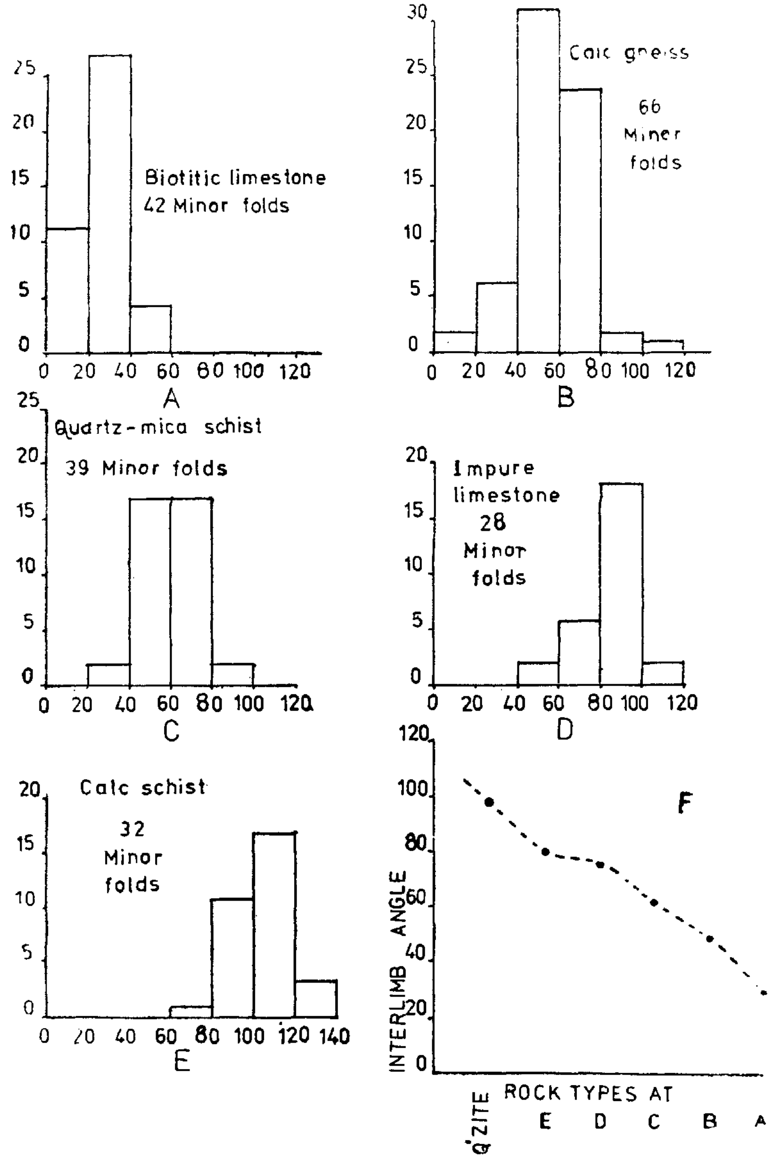

FIG. 5. Interlimb angle variation in rock types.
A-E Abscissa - Interlimb angle Ordinate Number of folds

The response of a multilayer system to buckling depends upon the composite behaviour of the system (Cobbold *et al.* 1971) rather than on the properties of individual layers. Folds form in layered rocks in preference to massive ones as the buckling instabilities necessary to initiate folding can only form in layered rocks (Biot 1965). In the present area, biotitic limestones are very finely laminated whereas calc gneisses are very coarsely banded. The present deduction is that folds are relatively close or tight in rocks which are layered and finely laminated (e.g., biotitic limestones), close in medium banded (e.g., calc gneisses) but broad and open in coarsely banded (e.g., calc schist) or massive (e.g., limpure lmestones) rocks. In case of isolated single folded layers it is the viscosity contrast between the layer and matrix that determines the degree of tightness which depends upon the degree of amplification of the dominant wavelength (Biot 1957). Fig. 5F is the plot of mean interlimb angles in various lithologies. The curve is uniformly sloping with only a little break at one stage. This figure conclusively sums up what has been said above.

Major folds of second generation also display variation in style as deduced from their wavelength in structural map (Fig. 2). Major F_2-folds are close in calc gneiss, tight to isoclinal in biotitic limestone but open in calc schist. For example, in the neighbourhood of Biliawas village, a major F_2 synform is noticed. The wavelength of this major synform (Fig. 2) is about half a km. at Biliawas, the limb dips are moderate to steep, suggesting the degree of tightness of this fold. This fold becomes open in siliceous limestone (crescent shaped outcrop south of Biliawas, Fig. 1) south of Biliawas but tightens again in biotitic limestone horizon in the heart of Biliawas Reserved Forest just northeast of Ruparel, bearing numerous parasitic folds on its hinge and limbs. The fold dies out when traced southwards into calc schist formation west of Chipala (Fig. 2). So is the case with a series of antiforms and synforms in calc gneiss further west, which die out or become open when traced into calc schist formation towards north and south.

A large number of F_2 minor folds exhibit complex geometry even in areas free from the effect of F_3-folding. They often have curvilinear hinges and display plunge variation with depth in large outcrop sized fold '*s*'. Another interesting feature noticed on minor scale is the turning of an antiformal structure into a synformal one when traced along the axial trace of a fold (Ramsay 1962; and Brown *et al.* 1970). Doubly plunging axes are quite common and give rise to eyed folds (de Sitter 1956; Ramsay 1962, p. 473; Nicholson 1963; and Wunderlinch 1963). Though the hinges are doubly plunging or curvilinear, limbs are straight and do not show curvature or fracturing which suggests that thse features have not resulted as a consequence of the effect of F_3-folding. Eyed folds show folding only in one cross section unlike the eyed folds formed by fold inerference (Ramsay 1962) in which folding is seen in two cross sections. Pl. II, Fig. 2 is the photograph of such an eyed fold. Murty and Pahuja (1976) also noted such complex geometry in minor folds from the area between Bhim and Todgarh. They attributed the origin of such non-cylindrical structures to differential flattening in *'ab'* plane. The author also believes that these features form due to intense inhomogeneous flattening and his views are in accord with those of Murty and Pahuja (1976).

The complex geometry described above is frequently noticed on minor scale in

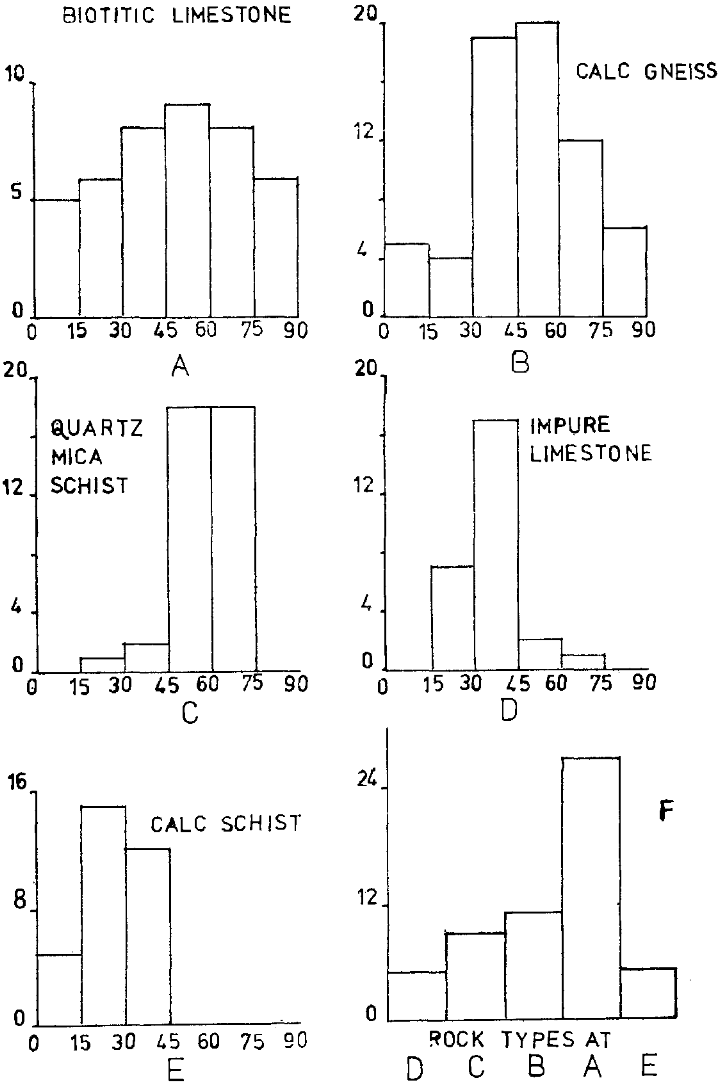

FIG. 6 Plunge variation in F_2 - folds in different lithologies.
A—E Abscissa—Amount of plunge Ordinate—Number of folds

biotitic limestone and to some extent in calc gneisses and little or none at all in other lithologies. Fig. 6 represents a series of histograms depicting plunge variation of F_2 lineations in different lithologies. It will be noticed that the variation is more pronounced in biotitic limestone and calc gneiss. Little variation is seen in other lithologies. This suggests that the rocks mobility is in determining the amount of plunge variation. Less competent lithologies usually suffer greater shortening. Biotitic limestone and calc gneiss appear to be more susceptible to this than the rest. Differential flattening may have been introduced rather early in the stages of fold development.

(c) *Interference of folds*

Ramsay (1962) has discussed at length different types of outcrop patterns which develop owing to the interference of two sets of folds. For the mappable outcrop pattern to be formed, it is necessary that both fold sets must develop on large scale. If the scale of one folding is highly contrasting with the other, the outcrop pattern remains simple. Interference patterns have been described by various workers (de Sitter 1952; Tobisch 1966; Naha & Chaudhuri 1968; and Roy 1972). Type 1 and type 3 patterns are recognisable in the area under study both on major and minor scales, the former due to the interference between F_2 and F_3 folds and the latter due to that between F_1 and F_2-folds. Type 1 pattern is formed on a large to medium scale around Motala (Fig. 2) but the outcrop pattern is not produced since one lithology (calc gneiss) has been affected. Type 3 pattern on a large scale is suggested around Biliawas, where F_1 and F_2 linear structures lie subparallel (Fig. 4).

In the present area, major F_2-folds can be fairly easily identified (Fig. 2) but major F_1-folds are difficult to be recognised due to their being isoclinal with very narrow hinge zones and obliteration of small scale sedimentary structures due to the intense metamorphism. But major F_1-folds are hypothesized on the basis of limestone outcrops repeating south of Biliawas (Fig. 1) and regular variation of F_1 linear structures. F_3-folds on major scale are also hypothesized, as a large to medium scale type 1 interference pattern is developed around Motala and further, even in areas where these folds are not observed to be developed on minor scale, the rotation of F_1 and F_2 linear structures is noticed.

(i) *Type 1 Interference Pattern*—To the west of the major F_2 synform at Biliawas occur a series of medium scale F_2 antiforms and synforms which die out into calc schist formation to the north and south (Fig. 2). Large to medium sized domes and basins are formed in the vicinity of Motala due to the overprinting of F_3 on F_2-folds. The structural map (Fig. 2) brings out the attitudinal variation of regional bedding foliation S_1, which becomes horizontal at the tops of domes and bottoms of basins. This interference is also seen on minor scale and eyed folds (Pl. II, Fig. 4) related to this are abundant. The stereoplot of regional schistosity for this domain brings out the presence of two distinct sets of folds lying at large angle to each other.

(ii) *Type 3 Interference Pattern*—The outcrop pattern in Fig. 1 suggests this pattern, where upright to inclined or nearly reclined F_1-folds and upright F_2-folds on large scale interfere. The map of lineations (Fig. 4) shows parallelism between F_1 and F_2 linear structures in this part of the area. This interference can be seen on minor scale also. F_1 linear structures are scarce due to intense F_2-folding and accompanying metamorphism but the outcrop pattern itself is highly suggestive.

(d) *Structural Analysis*

Following the standard practices of structural analysis (McIntyre 1951; and Weiss & McIntyre 1957), the area was divided into six tectonic domains (Fig. 2) in which folding can be considered to be statistically cylindroidal. Lower hemisphere equal area projections (hereafter referred to as the S-pole diagrams) of poles to bedding/bedding foliation were prepared separately for each tectonic domain in support of what has been mentioned above. Equal area projection of poles to S_2

cleavage was prepared for the entire area. Axial surfaces of minor F_1 and F_2-folds were also analysed. Lineations related to F_1 and F_2 movements have been rotated and brought into diverse positions (Clifford *et al.* 1957; and Ramsay 1960) but F_3 lineations show fairly constant trend. It is difficult to unroll the linear elements because of the complexity of folding movements. No separate plots were made for linear structures but these were plotted in the *s*-pole diagrams of individual domains. Not all but only a few lineations representative of the general trend for the domain in question were plotted.

(i) *Domain I*—This domain is about 3 sq. km. in area, and consists of sheared quartzite, impure limestone, quartz-mica schist and calc schist. Attitudinal variation is noticed (Fig. 2) between Khedela and Chipala, because of the overprinting of F_3-folds. Fig. 2A is the *s*-pole diagram of total bedding in this sector and the spread of low density contours permits drawing a girdle with its axis emerging at β corresponding to F_i axis which is supported by the cluster of F_3 lineations around β. The scatter of F_1 lineations from WNW to NW and SSE to S appears to be the rotation about F_3 axis. A few poles falling at or near the western periphery is due to the development of medium scale F_2-folds in limestone. Another girdle can be drawn with its axis at β'. F_2 lineations, though mainly clustered around this, still show some scatter owing to rotation about F_3 axis. Fig. 2B is the *s*-pole diagram of total bedding foliation in this domain. F_3-folding is suggestive from the split in the maximum and the spread of contours. Two girdles, one nearly NS with axis β and another nearly EW with axis β' can be drawn, the former corresponding to F_3 and the latter to F_2-folding. Major F_2-folding is noticeable south of Chipala, in Fig. 2, figures A and B are quite similar supporting the field observation that bedding and regional foliation are parallel and have behaved as a single planar feature during all deformational events. But girdles are more well defined in Fig. 2B than in Fig. 2A suggesting that folds are relatively more close or tight in pelitic than in psammitic rocks.

(ii) *Domain II*—This domain is 4.5 kms, sq. in areal extent and consists of lithologies, biotitic limestone, calc schist and quartz-mica schist, each covering approximately an equal area. Fig. 2C is the *s*-pole diagram of total bedding in this domain, representing a point maximum which suggests either a homoclinal series, limb of a fold or a series of isoclinal folds. Field observation supports the isoclinal folds F_1 and F_2 lineations show some scatter due to rotation about F_3. Fig. 2D is the *s*-pole diagram of total bedding foliation in this domain. It is similar to Fig. 2C except for a few poles falling on the western periphery due to vertical foliation, the verticality having been brought about the F_3 axis. Foliation dipping steeply to NW becomes vertical and then changes gradually in strike to NW and dips SW owing to the rotation about F_3 axis.

(iii) *Domain III*—This domain covers an area of 5.5 sq. km. and includes impure and biotitic limestones and calc gneiss. *s*-pole diagram of bedding and bedding foliation (Fig. 2E) brings out well-defined girdle with axis β related to F_2 folding. No great effect of F_3 folds is seen. The well-defined girdle suggests F_2 folds to be cylindrical but the map of lineations (Fig. 4) shows a disarray of F_2 lineations and axes. This apparently cylindroidal nature of F_2-folds is suggestive of the isoclinal nature of F_1-folds with very narrow hinge zones. The plunge variations of F_2 axes and lineations may be attributed to : (*a*) development of F_3-folds on earlier folded surfaces (Ramsay 1960), (*b*) the effect of F_3-folding, and (*c*) complex geometry of F_2-folds due to inhomogeneous flattening.

(iv) *Domain IV*—Consisting only of calc schist, this domain covers about 2.5 sq. km. of area. *s*-pole diagram of schistosity (Fig. 2F) brings out a low or gentle F_2-fold, slightly affected by F_3. Minor folds of all generations are rather rare in this sector.

(*v*) *Domain V*—Approximately 1.5 sq. km in area and consisting of calc gneiss, this sector shows interference of F_2 and F_3 on a medium scale *s*-pole diagram of bedding and bedding foliation (Fig. 2G) suggests the interference between two fold sets. Clear girdles are hard to draw as there is considerable interference of F_2 and F_3 structures.

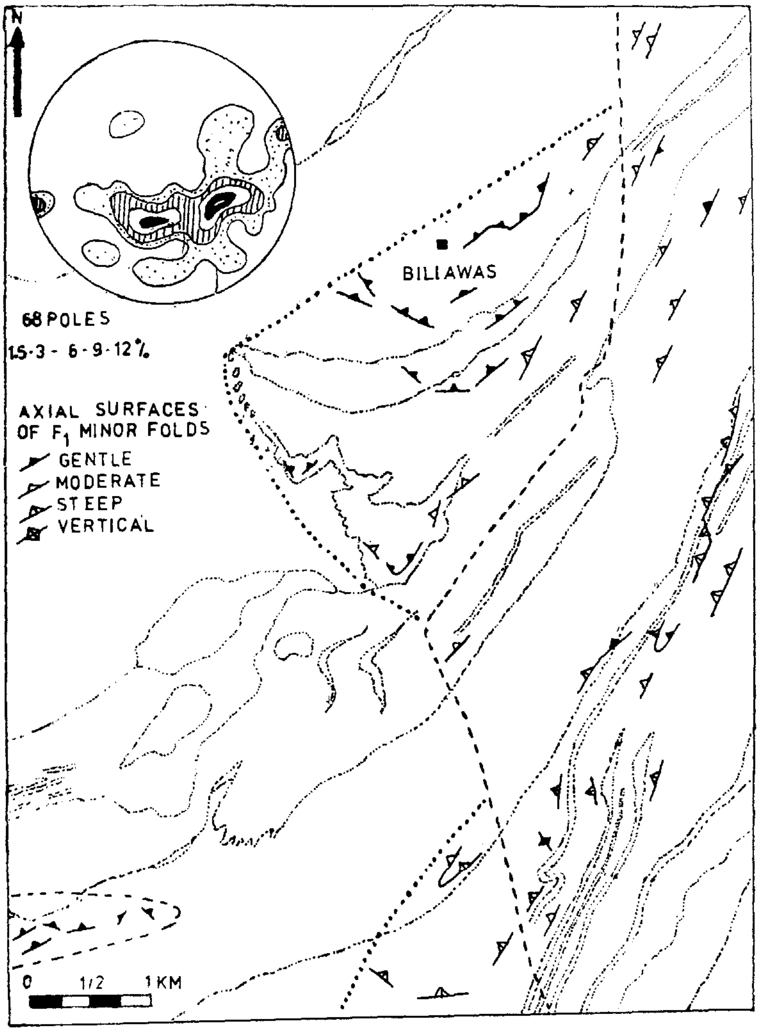

FIG. 7

(vi) *Domain VI*—Approximately 6 sq. km in area and containing calc gneiss, impure and biotitic limestones, the *s*-pole diagram of total bedding and total bedding foliation of this domain (Fig. 2H brings two girdles with axes β and β′ related to F_2 and F_3-folds. The scatter of F_2 lineations in this is comparable to the swing of F_2 axes between NNE and NNW noticed in the map of lineations (Fig. 4).

(vii) *Axial surfaces of minor F_1 and F_2-folds*—The attitude of some minor F_1-folds axial surfaces are shown in Fig. 7. The sector marked by dashed line contains minor F_1-folds but minor F_2-folds are rare. The dotted line demarcates the area of predominent F_2 minor folds with but few F_1 minor folds. The inset *s*-pole diagram of poles to axial planes of F_1-folds with two close maxima and little spread suggests rotation, predominently about F_2 and subordinately about F_3. Rarity of F_1-folds and high intensity of F_2folds forbid drawing clear girdles.

FIG. 8. 309 poles to S_2 cleavage 0.3—3—6—9—18%

Fig. 8 is the *s*-pole diagram of poles to S_2 cleavage in the whole of the area and is clearly indicative of rotation about F_3 axis.

CONCLUSION

Complex deformational history with three different structures is noticed in the Delhi rocks around Biliawas, folds of different generations having developed in localised domains. Major and minor interference patterns as described are being reported for the first time. Second generation folds display complex geometry attributable to inhomogeneity of flattening strain. The change in style of folds is a function of the rheologic properties of isolated single layers, or due to the degree of anisotropy of multilayered materials.

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