GEOMETRICAL ANALYSIS OF BOUDINS FROM THE PRECAMBRIAN TERRAIN AROUND BADNORE, CENTRAL RAJASTHAN AND SOME GENETIC IMPLICATIONS OF THEIR BUCKLING BY LATER STRAINS

by PRAKASH P. RODAY, *Department of Applied Geology, University of Saugar, Sagar*-470003

(Communicated by Professor W. D. West, F.N.A.)

(*Received 13 June 1977; after revision 15 October 1977*)

Geometrical analysis of boudins formed during an early phase of progressive deformation from the Precambrian terrain around Badnore in Central Rajasthan, by a method evolved by the author is presented. Using this method, the relative competence of the three main lithologies involved in boudinage has been determined and geometrical shapes of pegmatitic boudins have been shown to be related to their mineralogy. The diverse orientation of axial surfaces and axes of later folds is suggested to be due to the varying response of variably oriented surfaces to the constantly changing incremental principal strains during progressive deformation. The rotation of early boudins about later fold axes is suggested to be similar to the history of a layer, first undergoing stretching but later contraction, owing to the change in the orientation of incremental principal strains.

INTRODUCTION

DURING progressive deformation by a combination of pure and simple shear involving complex paths taken by deforming particles (Ramberg 1975), the increments of strain are added to the deforming body at infinitesimal intervals (Flinn 1962) and at any stage, if sufficient evidence is available, it is possible to determine the orientation of incremental strain ellipsoid (Ramsay 1967 *b*) and to make an estimate of the quantity of strain added (Durney & Ramsay 1971). Whether a layer (or layers) involved in deformation would respond by buckling or stretching depends upon its orientation with reference to that of the incremental strain ellipsoid (Ramsay 1967 *a*).

Ramsay (1967 *a*) discussed the response of layering oriented variably with reference to the incremental strain ellipse at any given stage during progressive deformation by rotational strain. A condition of plane strain and pure shear is rather unlikely to have occurred in naturally deformed geologic bodies and most strain increments must have had a rotational component (Ramsay 1969; Ramsay & Graham 1970). Ramsay (1967 *a*; pp. 111-120, Figs. 3-56) distinguished four distinct zones on the basis of relationship between finite and infinitesimal strains at any stage during progressive deformation, and stated that within each of these zones, the layer has a different deformational history. If the orientation of layering lies within zone 1, the expanded layers begin to contract, a situation identical with the geological condition of boudins beginning to fold. In zones 2 and 4, the expanded layers further expand and contracted layers further contract respectively, the geologic conditions being separation of already developed boudins and tightening and amplification of folds.

In zone 3, the contracted layers begin to expand or natural folds begin to unfold, or more realistically, disrupt by boudinage. A layering lying parallel to the lines (or surfaces) of no incremental longitudinal strain (with $e=0$) does not undergo any deformation and its length remains unchanged during and after the deformation. But only slight change in the orientation of incremental strains may cause it to buckle or stretch. In the account that follows, the formation of a set of late folds in the Badnore area is suggested to be the result of the varying response of variably oriented surfaces to the changing axes of incremental principal strains during progressive deformation (very likely to be the concluding phase): the boudins related to early strains are analysed and finally the structures resulting from the history of layers in zone 1, viz., the buckling of stretched layers (boudins) are described and their genesis discussed.

STRUCTURES FROM THE BADNORE AREA

Most of the observations made, and described and analysed in this paper are from a rather small area around Badnore (25 51'N: 74 17'E) in the Bhilwara district of Central Rajasthan. The area around this village comprises the metasediments belonging to the Banded Gneissic Complex Group (Gupta 1934: and Heron 1953), regionally metamorphosed upto staurolite grade in general, and extensively migmatised. The migmatites grade into a granitic body eastwards, outside the eastern limit of the area shown on the map (Fig. 1). The granitic body was thought by Gupta (1934)

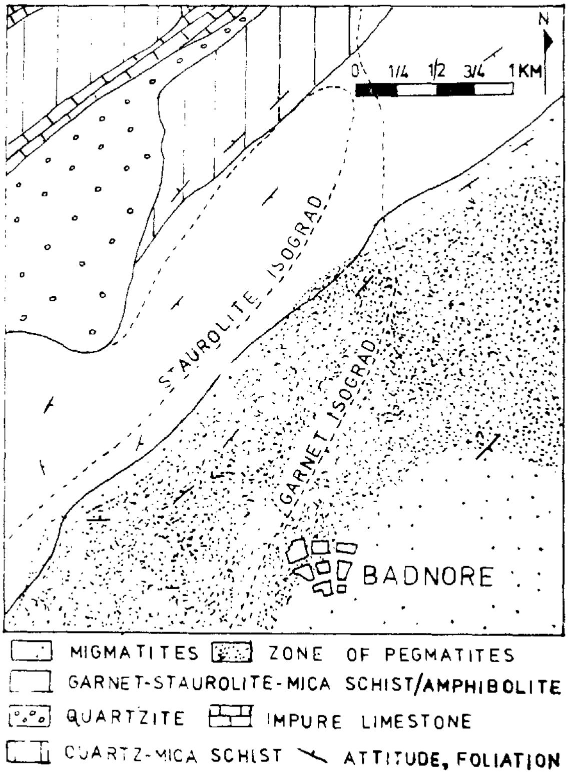

FIG. 1. Lithological Map of the area around Badnore.

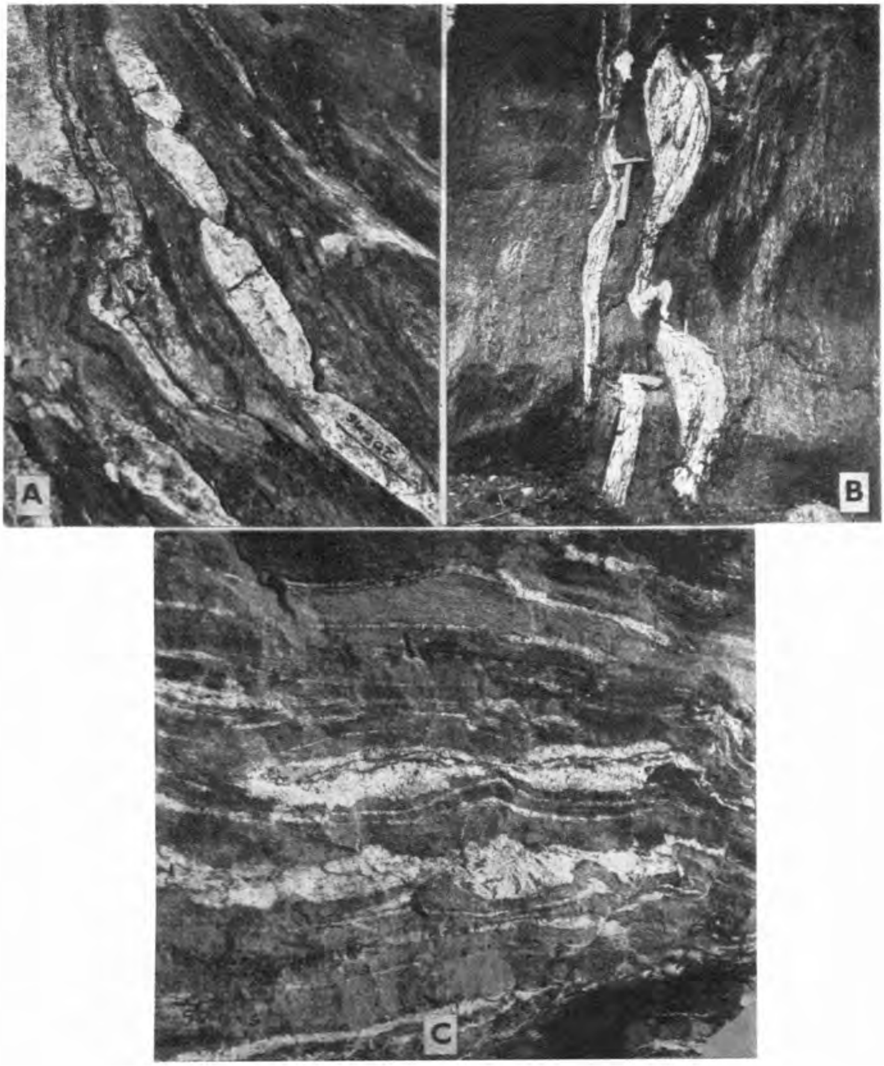

PLATE I. A. Pegmatitic boudins arranged *en echelon* outside the western limits of the area shown in Fig. 1.

B. Aplitic boudins in garnet-staurolite-mica schist west of Badnore affected by later strains. The approximate *monotropic* type 1 and near *monotropic* type 2 symmetry in upper and lower boudins is only attributable to later strains.

C. Pegmatitic pinch and swell structures immediately west of Badnore.

to be intrusive in character; however, field evidence does not provide any support for Gupta's views. Westwards, the migmatites grade, rather sharply into a garnet-staurolite-mica schist/amphibolite horizon, and the latter is profusely emplaced by aplite (Heron 1953) along the regional foliation. Quartz veins of different generations, as well as basic dikes—now metamorphosed—are abundant and help unravel the otherwise intricate tectonic events, very meaningfully. Nearly all the rocks have suffered large scale pegmatite emplacement; the zone rich in pegmatites is demarcated in Fig. 1. The pegmatite emplacement initiated well before the early fold movements started but continued during the entire deformational event (Roday 1976). The pegmatites consist of quartz and potash feldspar, sometimes interwoven to form a graphic network and muscovite which occurs in the form of segregations rather than being evenly distributed. Biotite occurs only subordinately. All the pegmatites are characteristically devoid of tourmaline as observed by Heron (1953). The plagioclase is absent in these pegmatites. A large number of pegmatites have been involved in boudinage, producing pinch and swell structures (Plate I C) or well-separated boudins (Plate I A).

All the structures recognisable in the area have been grouped into two distinct categories—early and late. Both are suggested to have been produced during a single period of progressive deformation with probably only a little time gap between them, or none at all, as adduced by the study of growth of porphyroblasts of garnet, staurolite etc. (Roday 1975; Ph.D. thesis—*unpublished*).

The early structures are essentially isoclinal folds and have two distinct orientations; (i) Reclined (Fleuty 1964), with a WNW to NW axial trend and axial surface trending approximately NE; and (ii) Upright (Fleuty 1964) with axial surfaces and axes both trending NE. The axial surfaces of these folds are almost always subvertical. Upright folds are of two types. Type 1 structures have a subhorizontal plunge whereas type 2 folds have moderately or steeply plunging axes. Both upright and reclined folds are here regarded as early structures. But it appears that the early reclined folds were brought into a disposition of type 2 upright folds by rotation about type 1 upright folds, the latter are therefore later but the time gap was probably too short. The regional foliation curves around the hinges of minor early folds and no

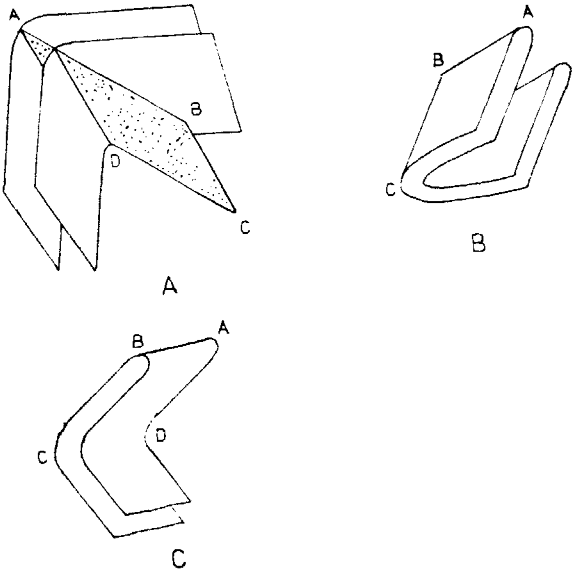

FIG. 2. Late folds and their effect on early folds. A. The geometry of a typical late fold. B. Rotation of an early reclined fold about the axis of a later fold. C. Rotation of an early type 1 upright fold about the axis of a later fold.

distinct cleavage appears to have been developed during the evolution of these folds.

The late structures are broad open folds, symmetrical or asymmetrical, with a large interlimb angle and having a very variable attitude of axial surfaces and axes. These folds are usually recumbent to reclined (Sutton 1960; and Turner & Weiss 1963) with a large angle between the trends of their axial surfaces and axes. Folds of such geometry have been reported from other parts of Rajasthan, and especially from the type area of Aravalli rocks around Udaipur (Roy *et al.* 1971) and from the area between Ajmer and Srinagar (Bhargava 1972; Ph.D. thesis, University of Saugar—*unpublished*). The late folds have been diagrammatically shown in Fig. 2 A; their relationship with early reclined and type 1 upright folds is illustrated in Figs 2 B and 2 C. In Fig. 3, the attitude of the axial surfaces and axes of some late minor folds measured in the area are shown, and the variability of the attitude of two important fold entities could be clearly noticed. The axial surfaces and axes of these

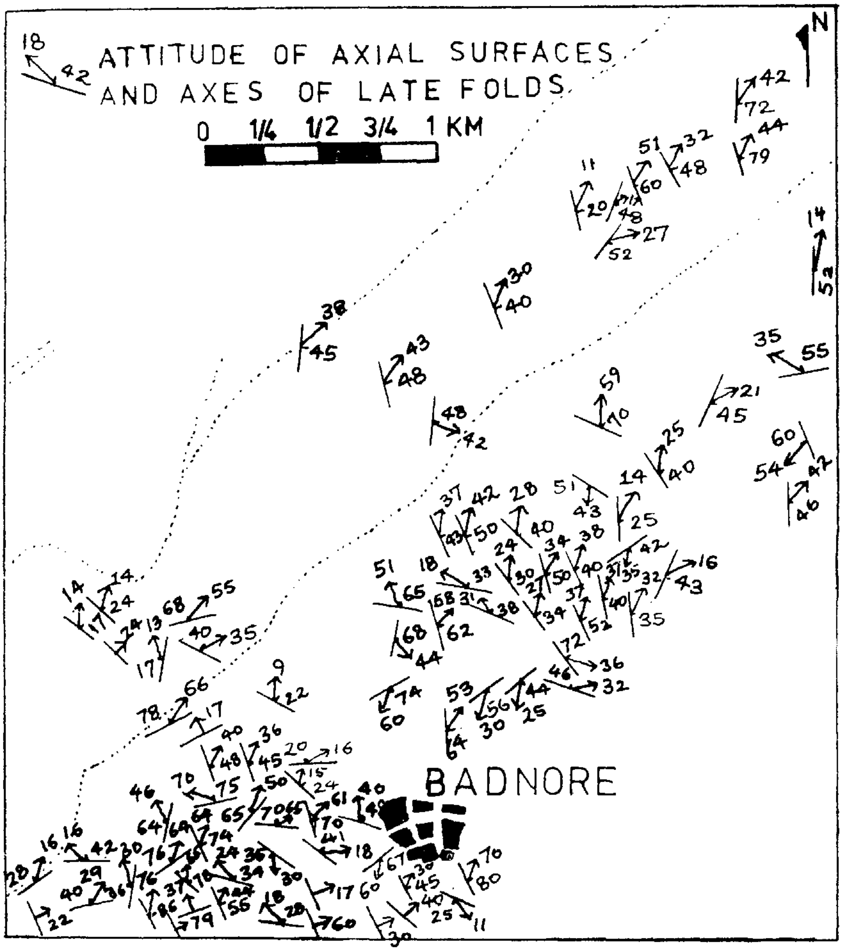

FIG. 3 Map showing the attitude of axial surfaces and axes of some late minor folds in the area around Badnore. Note that though considerable variability is noticed, majority of the axial planes trend NW or NNW.

folds are subhorizontal, gentle or moderately dipping. Though the axial surfaces display variable orientation with their trend changing from EW to NS, a majority of them trend in NW or NNW direction. The axes depict a relatively more uniform trend, between NE and east suggesting that the principal extension direction did not undergo any appreciable change in orientation during progressive deformation.

The rotation of early structures (minor folds, boudins and stretching lineation) about the axes of later folds is noticed at many places in the field. A feeble crenulation cleavage (Knill 1960; and Rickard 1961) is developed parallel to the axial surfaces of these folds. Crenulations or microbuckles is the only recognisable lineation associated with later folds. No major folds related to later deformation are noticed and these appear to be developed only on outcrop scale.

In areas of polyphase folding, the variability of the attitude of axes of later folds is generally ascribed to the variability of orientation of surfaces already folded by early folds and on which later folds are superposed (Ramsay 1960). In the present area, the variability of the attitude of both axes and axial surfaces of later folds occurs not of the axes only), and as axial surfaces do not appear to be affected by any later deformation in the immediate environs, this feature is not attributable to the general rule quoted. The formation of both early and late structures appears to be due to the two distinct phases of the same progressive deformation, the variability of orientation of axes and axial surfaces of superposed later structures appears to be due to the change in the orientation of incremental principal strains. Several directions of folding probably originated due to the variable response of variably oriented surfaces to the constantly changing principal incremental strains.

BOUDINS AND THEIR GEOMETRICAL ANALYSIS

(i) *General Description and Observations*—Boudinage (Lohest 1909) results from stretching in the direction of layering (Wegmann 1932) or nearly so: or compressive forces normal or nearly normal to layering (Quirke 1928), of a competent layer enclosed in a relatively less competent matrix. Cloos (1947), Ramberg (1955, 1959) and Rast (1956) have done some excellent work on the morphology, development and mathematical theory of the formation of boudins. The boudins (or pinch and swell structures) found in the area considered in the present paper are related to early phases of progressive deformation and have invariably been rotated during the later phase, especially in the immediate vicinity and west of Badnore. The boudins in the eastern part, related to early reclined folds are relatively less affected or unaffected.

Most of the boudins analysed in the present study belong to the phase that produced early upright folds of type 1 category. Some boudins related to type 2 upright folds were also considered.

Boudins are more abundant in three lithologies: Psammites, aplites and pegmatites. In reality, they are developed in almost all lithologies as they develop whenever the orientation of the layer to undergo stretching lies in the desired direction and a sufficient competence contrast between the layer and matrix exists.

A majority of the boudins are found in pegmatites, some in aplites and only a few in psammites. Boudins in psammites include those in quartzites and quartz veins with their frequency falling in that order. This distribution of boudins in three lithologies only reflects the relative abundance of one lithology over the other. In the analysis presented here, 73 boudins were considered; 34 of these were pegmatic, 22 aplitic and the remaining 17 psammitic. The sampling in psammites and pegmatites was restricted to the eastern and east-central parts of the area where boudins have not been affected by later strains. Aplitic boudins are mostly developed in the northwestern part of the area and were carefully sampled. The number of samples in each of the lithologies was based on their relative abudance. Considering the small extent of the area covered, the polyphase deformational history and the lack of availability of ideal profile sections, the number of boudins analysed is not inadequate.

Only psammitic boudins in quartzites were treated for geometrical analysis and those in quartz veins were disregarded, owing to their having been affected by later strains. Besides, boudins in quartz veins have sometimes very irregular shapes owing to the tendency of quartz to undergo fracturing under small strains.

The geometry of boudins was studied in a section normal to the fold axes or normal to boudin line (de Sitter 1956, 1958) and such a section is herein referred to as the *ac* section. The boudins developing normal to fold axes or at various angle to fold axes (Sanderson 1974) were not considered in the present analysis and only boudins developed parallel to fold axes ($k \geqslant 1$; see Sanderson 1974) were considered. The *ac* section would therefore correspond with the YZ section of the finite (or incremental) strain ellipsoid. The basis for this statement is the theoretical prediction that fold axes rotate towards X-axis of the finite strain ellipsoid during progressive deformation (Flinn 1962). The possibility that a YZ section may not necessarily correspond with the profile section of a fold under certain conditions is here ignored. Since the boudins formed in the area are suggested to have been developed during a progressive deformation, the *ac* section corresponds with the YZ section of the incremental strain ellipsoid at a certain stage. All the measurements have been made in two dimensions only, in the *ac* section of the boudins.

The morphology of boudins in different lithologies is markedly different. Psammitic boudins are rectangular in outline with little gap between the separated segments suggesting their formation by taking only small strains (Ramsay 1967*a*) and relatively quickly. This suggests a large competence contrast between psammite and enclosing matrix. Where individual boudins have been appreciably separated by immediately added strains, the matrix material has flown into the gaps, which are not filled in by any crystallised matter, suggesting that no voids formed during the deformation and that the latter was volume conserving (Ramberg 1955; and Ramsay 1967*a*).

Boudins in pegmatites and aplites are occasionally arranged *en echelon* (Plate IA, Plate IIIB) suggesting development of shear strain, or rotation subsequent to formation of boudins (Plate IIIB), i. e., pure shear followed by rigid body rotation (Nadai 1963). This pattern was not observed in psammitic boudinaged layers. Sigmoidal boudins suggesting development of shear strain (Fig. 4F) were mostly observed in pegmatites (Plate IIIA) and rarely in aplites (Plate IB).

The amount of gap between individual boudins is a measure of the strain suffered by the rock. Gaps are usually less in boudins with low l/d ratios (see later part of this paper) but high in boudins with high l/d ratios. The gaps are narrow in psammites, moderate in aplites but variable in pegmatites.

Boudins are entirely separated in psammitic layers suggesting brittle deformation but usually joined by thin necks in pegmatites (Plate IC) and aplites (Plate IB) suggesting

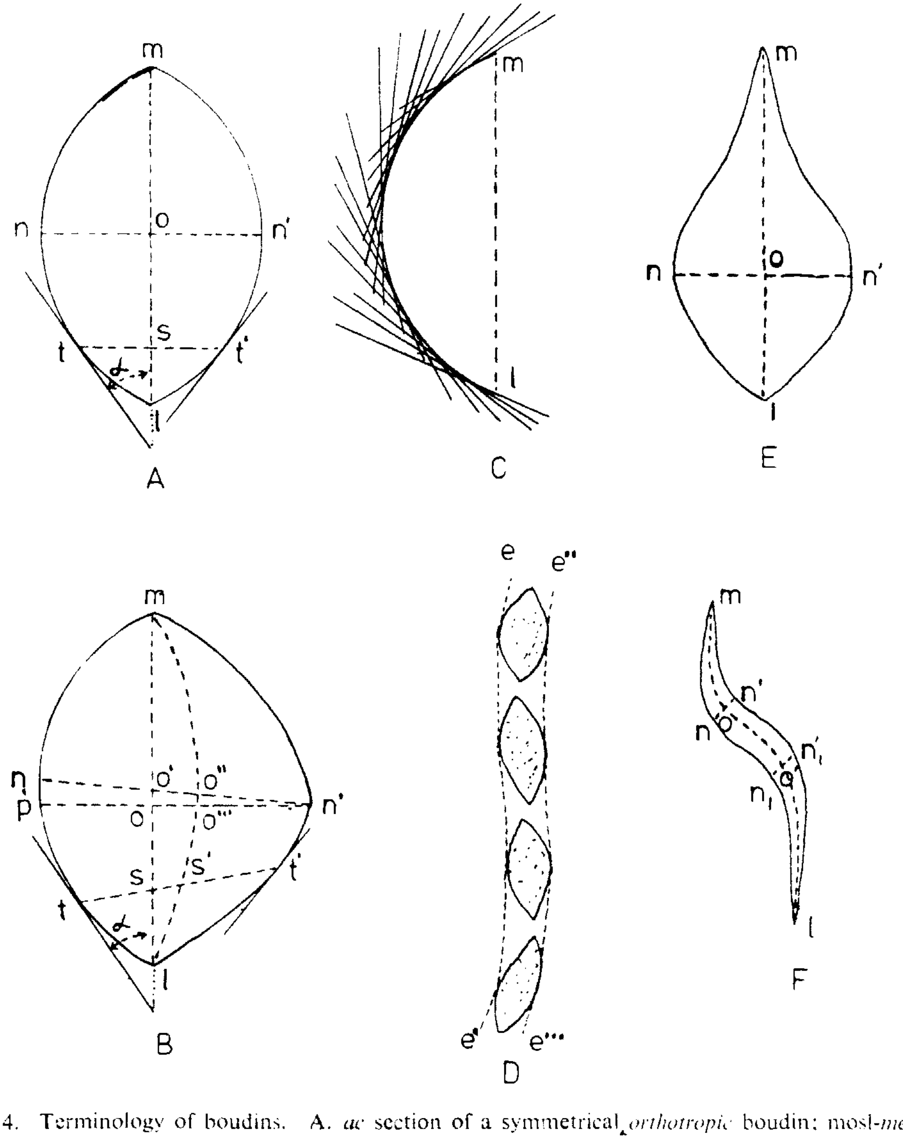

FIG. 4. Terminology of boudins. A. *ac* section of a symmetrical *orthotropic* boudin: mosl-*median line*. non'-normal to *median line*, n & n'-*neutral point*. m & l-*end points*. tst'-*tie line*, α-*internal angle*; mosl and non' also represent *length* and *breadth* respectively. B. *ac* section of an asymmetrical *monotropic* type 2 boudin; mo'osl-*median line* and *length*, mo"o"'s' l-*median arc line*, n-& n' *neutral points*, m & l-*end points*, no0"'n'-normal to *median line* and *breadth*, tss't'-*tie line*, α-*internal angle*. C. Diagrammatic representation of the construction of a series of tangents for various values of α on one margin of a boudin in *ac* section; ml is the *median line*. D. *Enveloping lines* of a chain of boudins, represented by ee' and e"e"'. E. *Monotropic* type 1 boudin in *ac* section. m & l-*end points*, n & n'-*neutral points*, mol-*median line*, non'-normal to *median line*. mol and non' are also *length* and *breadth* respectively. F. A sigmoidal (*tritropic*) boudin in *ac* section. moo'l-*median arc line*. n,n' n₁, n₁'-*neutral points*, non' and n₁o'n₁'-normals to *median arc line*.

ductile flow. The necks are of variable length, the length being greater on the average in pegmatites. Pinch and swell structures (Plate IC) which are boudins joined by necks of more or less uniform length throughout, with swelling and pinching occuring at more or less uniform interval, indicating low competence contrast are better developed in pegmatites and aplites but especially so in the former. They are found in some psammitic bands as well, which are very thin and are enclosed in a matrix of semipelitic to psammitic composition suggesting low competence contrast.

(ii) *Terminology of Boudins* — Certain terms used in the geometrical analysis have to be defined before the analysis is attempted. The cross section or profile section of the boudin normal to the related fold axis is here called an *ac* section, the *a* and *c* in it being respectively the directions of principal extension and principal shortening. The two ends of a boudin in *a* direction are referred to as the *end points* (e. g., *m* and *l* in Fig. 4). In other words, an *end point* is the point of intersection of the *boudin line* with the *ac* section of the boudin.

A straight or shortest line that joins two *end points* is referred to as the *median line* (Fig. 4A, *mosl*; Fig. 4B, *mo′ osl;* Fig. 4C, *ml* etc.). In other words, a *median line* is the trace on *ac* section of a plane containing both *boudin lines* of a single boudin. A *median arc line,* to be clearly distinguished from the *median line* is the straight or sinuous line that divides a boudin into two parts as symmetrically as possible, so that the area of one half is equal to the other (Fig. 4B, *mo″ o″ ′ s′ l*). In other words, a *mediun arc line* is the trace on *ac* section of a planar or curviplanar surface that divides a three-dimensional boudin as symmetrically as possible, so that the volume of one half is equal to the other (as long as strain is homegeneous and folding cylindroidal).

The angle subtended by the median line and any tangent drawn on either margin of the boudin in *ac* section is referred to as α the *internal angle* and is denoted by (Fig. 4, A & B). In *orthotropic* and *monotropic* type 1 boudins (see later part of this paper) the *median line* coincides with the *median arc line ;* the *internal angle,* α, is the same on either side of the *median line* for successive uniform increments of length along it. In *monotropic* type 2 and *tritropic* boudins (see later part of this paper), *median line* has a different position from the *median arc line;* the value of *internal angle,* α, for successive uniform increments of length along the *median line,* is markedly different on two sides of it. The points at which the curvature of the margins of a boudin changes (or the points of maximum curvature at which the value of *internal angle* is zero) are called neutral points (e.g., *n* and *n′* in Fig. 4).

The position of the *median arc line* on the *ac* section of a boudin is fixed in the following manner. A series of tangents (e.g., as in Fig. 4C) for successively decreasing values of α upto the *neutral point,* followed by successively increasing values at a uniform interval (of say 5°) are constructed on either margin of a boudin. Two points, each on opposite margin for which the value of α is the same are joined by a straight line called a *tie line* (e.g., *tst′* in Fig. 4A; *tss′t′* in Fig. 4B). The *tie line* is divided into two equal parts so that the position of a median point (e. g., *s* and *s′* in Fig. 4) on it is established. A series of such *tie lines* could be drawn on the *ac* section of the boudin at uniform interval of α and the positions of a series of median points on each one of them could be fixed. Upto a certain point, the median points indicate decreasing values for α; followed by successive increasing values. The line, which is sinuous, is described when all median points are joined together. This is the *median arc line.*

In ideally sigmoidally boudins, the *median arc line* is also sigmoidal (Fig 4F, *ml*). The degree of curvature at various points on the *median arc line* is a mean of the degrees of curvature on two margins of a boudin. The margins of a boudin are the traces on *ac* section of the boundaries of a three-dimensional boudin.

The *length* of a boudin in *ac* section is the length of the *median line* and is denoted by l. The *breadth* of a boudin in *ac* section is the length of the longest normal to *median line* and is denoted by d. In *orthotropic* and *monotropic* boudins (see later part of this paper), this normal passes through both the neutral points. In *tritropic* boudins with sigmoidal shape (see later part of this paper) usually two such normals are present (Fig. 4F). In *orthotropic* and *monotropic* type 2 boudins, the normal passes exactly half way down the length of the *median line*.

The *enveloping line* of the boudins is the line that joins successive points of change in curvature on two margins of a series of boudins. Each series or chain therefore has a pair of *enveloping lines* (e.g., e, e', e'', and e''' in Fig. 4D). An *enveloping line* could be considered as the trace on *ac* section of a corresponding *enveloping surface* of a three-dimensional boudin. If the folding is cylindroidal, the *enveloping surface* corresponds with the boundaries of a folded and boudinaged layer and *enveloping line* is therefore a standard curve, capable of being defined by a mathematical expression. In non-cylindroidal folds, this line is more complex and is difficult as a whole to quantify mathematically. Yet it consists of several segments, each of which is capable of being assigned a mathematical expression.

While studying the geometry of boudins, no distinction is made between clearly separated segments and pinch and swell structures. In the latter, the *median line* continues uninterrupted along the chain of swells and pinches and it is hard to determine the positions of *end points*. For geometrical analysis, the position of each *end point* is fixed by drawing a normal to *median line* at the points where α is maximum, which is usually in the pinched area. The intersection of the *median line* with this normal running across the pinched area is the position of the *end point*. If the pinched area is a considerably long neck, the position of an *end point* within it is usually fixed at a central point in the neck so that the swells on either side lie equidistant from it. So pinches are considered non-existent for analytical purpose, and the whole series of pinches and swells is, in fact, considered to be a chain of swells. *En echelon* or sigmoidal boudins which suggested development of shear strain were disregarded from the present analysis.

(iii) *A Symmetry Concept for Boudins* — All boudins are prismatic (with certain exceptions) in three dimensions. Boudins which develop when the layer is parallel to XY plane of finite (or infinitesimal) strain ellipsoid with $k=0$ (Sanderson 1974) do not have a prismatic form but this condition is unlikely to occur during progressive deformation. Irregular boudinage may result from increase in volume during progressive deformation (Ramsay 1967*a*). Further the boudins may not have a prismatic form if the boudin axes keep rotating during progressive deformation (Flinn 1962).

Since most boudins have a prismatic form or an orthorhombic symmetry, a symmetry concept for boudins in *ac* section is here introduced to distinguish different prismatic boudins from one another. Three distinct symmetry forms of boudins have been suggested which embrace nearly all forms of boudins. These are designated as *orthotropic, monotropic* and *tritropic.*

An *orthotropic* symmetry is one in which a boudin in *ac* section shows a distinct bilateral symmetry with refrerence to both, the *median line* and the normal to *median line* passing through the *neutral points* (Fig 4A).

A *monotropic* symmetry is one in which a boudin in *ac* section shows a distinct bilateral symmetry with reference to either the *median line* or the normal to *median line* through the *neutral points*. The former is referred to as the type 1 *monotropic* symmetry, while the latter as the type 2 *monotropic* symmetry (Figs. 4E and 4B respectively). In type 1 *monotropic* symmetry, the normal usually lies nearer to one of the *end points*. In type 2 *monotropic* symmetry, the normal lies exactly half way down the length of the *median line* (Fig. 4B).

A *tritropic* symmetry is one in which neither the *median line* nor the normal to it have any symmetry about them. The *tritropic* symmetry generally embraces some irregular forms of boudins and also the sigmoidal boudins (Fig. 4F).

Most psammitic boudins have an *orthotropic* symmetry; majority of pegmatitic and aplitic boudins show *monotropic*, some *orthotropic* and only a few a *tritropic* symmetry. Sometimes in a chain of pegmatitic boudins, all symmetry types are noticed. The most interesting feature is the change in symmetry in adjacent chains of boudins. It is noticed that in one chain the symmetry is distinctly *orthotropic* but in the adjacent chain, it is predominently *monotropic*. This appears to be related to the slight difference in composition between adjacent layers. While one layer, probably relatively more homogeneous undergoes uniform stretching producing *orthotropic* symmetry, the one adjacent to it, probably heterogeneous, undergoes non-uniform stretching producing a *monotropic* symmetry. The type of symmetry shown by boudins therefore appears to be related to the heterogeneity of composition of the layer undergoing stretching.

(iv) *Geometrical Analysis of Boudins* — For geometrical analysis, boudins were photographed in the field in a section normal to *b*. For some boudins of reasonably small size (with *d* upto 5 cms.), oriented specimens were collected, cut normal to *b*, polished and then photographed. The photographs were accurately traced and the measurements of various parameters were made on them. The data from each photograph were extrapolated to natural dimension taking the scale of photograph into consideration and the natural dimensions were rather considered in the analysis than the dimensions on photographs.

(a) *l/d* Ratios

The *l/d* ratios for boudins in *ac* section bring out the shape characteristics in two directions *a* and *c*. Both *l* and *d* were measured in the *ac* section. For all boudins analysed (73), the values of *d* were plotted against those of *l*. Fig. 5 is such a plot. The data on boudins in psammites is shown by + symbol, those in aplites by open circles and those in pegmatites by heavy dots. The variation in *l/d* with variation in lithology could be distinctly noticed. The plots for each lithology appear to be concentrated in well-defined zones and there is a systematic variation in *l/d* with lithological variation. The ratios are highest in pegmatites, intermediate in aplites and low in psammites (Fig. 5). The ratio varies between 4 and 2 for pegmatitic boudins, between 1.5 and 1.3 for aplitic boudins and between 1.2 and 0.85 for psammitic boudins. The variation within the same lithology may be attributed, as shown later, to the slight variation in lithological composition. Majority of the pegmatitic boudins have a ratio of 3. Some aplitic boudins have enormous ratios (Plate IIIB). For some boudins in psammites, the values of *d* exceed those of *l*.

Histograms depicting variation of *l*/*d* in three lithologies are also shown in Fig. 5. The ratios are plotted against the number of boudins analysed. Majority of

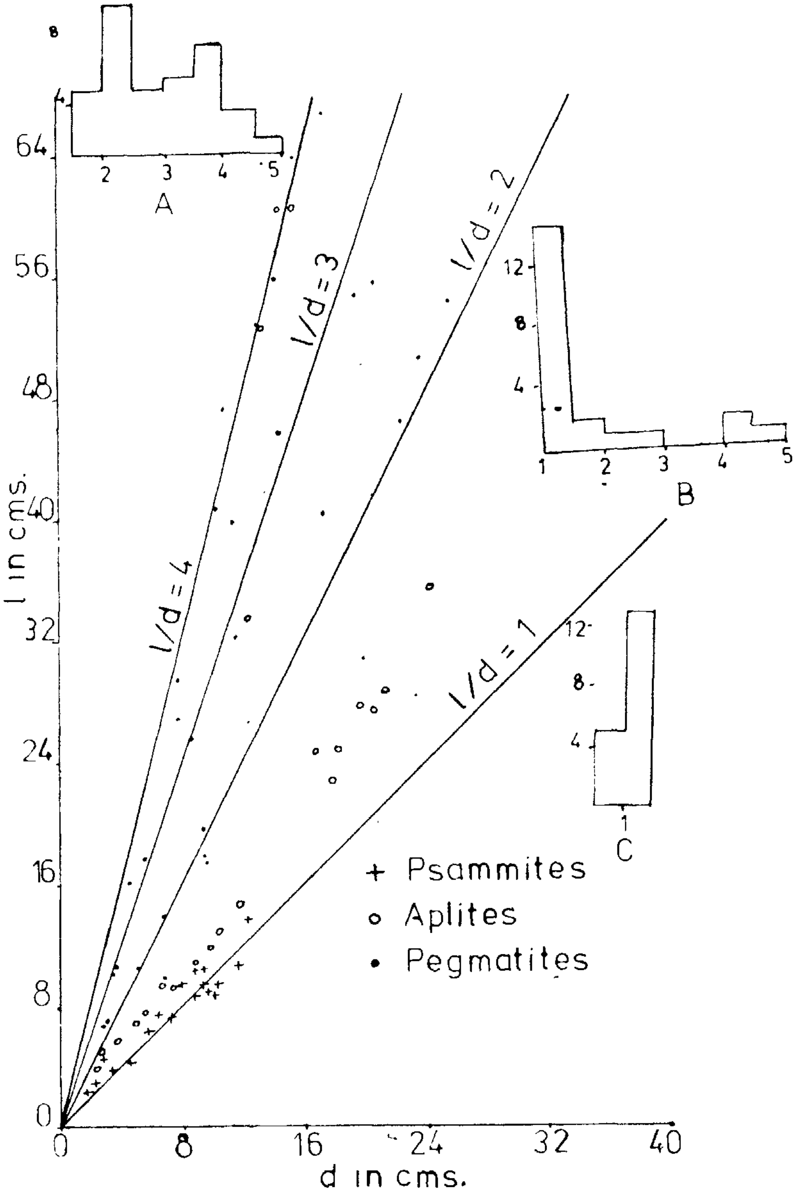

FIG. 5. Graphical representation of the variability of l/d in boudins of different lithologies. Crosses-psammites, circles-aplites, dots-pegmatites. Inset histograms depict *l*/*d* variation in boudins of the same lithology. A-34 boudins in pegmatites, B. 22 boudins in aplites, C. 17 boudins in psammites. Abscissa represents the *l*/*d* while ordinate the number of boudins analysed.

pegmatitic boudins have high ratios; majority of psammitic boudins have low ratios.

In case of all boudins analysed, the host rock is nearly of the same composition, i.e., a semipelite. No appreciable variation in the composition of the host rock is encountered across the area. The *l/d* of boudins directly reflects the competence contrast between layer and matrix, low ratio suggesting high contrast and a high ratio a low contrast. In other words the relationship between the two is inverse. If μ_1, μ_2, μ_3 and μ_4 be the viscosities of the psammite, aplite, pegmatite and semipelitic host respectively, then according to above deductions, μ_1/μ_4 is greater than μ_2/μ_4 is greater than μ_3/μ_4. In other words, $\mu_1/\mu_4 > \mu_2/\mu_4 > \mu_3/\mu_4$. It must be emphasized that the competence contrast between aplites and host is close to the one between pegmatites and host than between psammites and host as supported by the absence of any brittle failure in aplites.

As the host rock is the same everywhere, or since its composition does not vary appreciably across the area, the *l/d* for boudins in three lithologies not only indicates the competence contrast between the layer and matrix but the relative competence of the individual lithologies as well. Therefore, it may be concluded that $\mu_1 > \mu_2 > \mu_3$. Or in other words, relative competence is of the order psammite > Aplite > Pegmatite.

(b) Variation of Internal Angle :

The value of *internal angle* systematically changes on each margin of the boudin. α reaches zero at the *neutral point*. The variation of α on one margin may be the same (as in *orthotropic* and *monotropic* type 1 boudins) as on the other or α may vary at different rates on the two margins of a boudin (as in *monotropic* type 2 and *tritropic* boudins). The variation can be expressed with reference to a fixed distance along the *median line*. In *orthotropic* and *monotropic* type 1 boudins (Fig. 6, A & B) the variation can be represented by a single curve, drawn for various values of α against fixed increments of length along the *median line*. For *monotropic* type 2 and several *tritropic* boudins (Fig. 6C) two curves will be necessary to describe the shape change. In tritropic boudins, however, the *median arc line* will have to be considered in place of the *median line*.

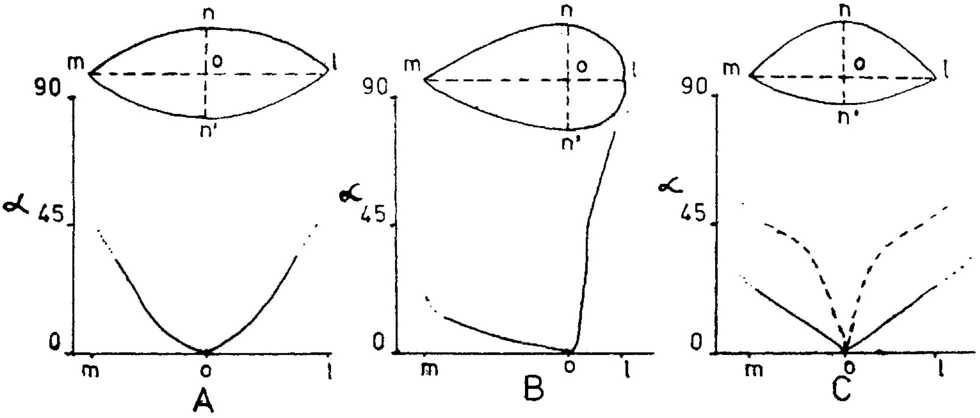

FIG. 6. Graphical representation of rate of change of α with distance along the *median line* in *Orthotropic*(A), *monotropic* type 1(B) and *monotropic* type 2 (C) boudins. *mol-median line*, non'-normal to *median line*, *n* & *n'-neutral points*, *m* & *l end points*.

The study of a large number of boudins of *monotropic* shape reveals that the rate of change of α with reference to the distance along the *median line* appears to be related to the mineral composition of boudins and is commonly encountered in aplites and pegmatites. The study of numerous such curves constructed shows that the greater difference between degrees of curvature on two margins is noticed if there is considerable variation in the composition of an individual boudin.

Besides the heterogeneity of composition, the variability of rate of change of α on either margin of the boudin is probably attributable to the size of the boudin. The variability is more distinctly noticed in boudins of large size than in small ones. This is probably because large strains are required for stretching of a thick layer and besides, the heterogeneity of mineral composition is more likely to exist in boudins of large size, relative to small ones.

(c) *l/d* ratios in conjunction with triangular diagrams

It has been stated above that the shape or symmetry variation or variation of rate of change of α on two margins is related to the compositional variation within the boudin. Such changes would affect the *l/d* of boudins. To substantiate this, a case study of pegmatitic boudins was carried out, which consists predominently of three mineral components—quartz, feldspar and mica (muscovite). The composition of each boudin was visually estimated using a magnifying glass and plotted in a triangular diagram in terms of three mineral components (Fig. 7). The composition of each boudin is represented by a single point in this diagram. At each point the *l/d* obtained from the previous study was plotted and the diagram contoured. The diagram (Fig. 7) reveals that *l/d* ratios are higher in quartzofeldspathic than in mica-rich boudins. The ratio steadily increases towards 0% mica line. The contours lie nearly parallel to one side of the triangle suggesting that the *l/d* ratios are significantly affected by the percentage of mica alone in the boudin.

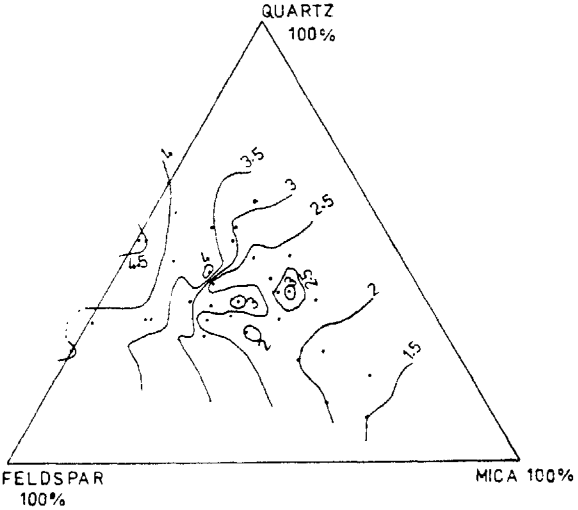

FIG. 7. A triangular diagram representing variation of *l/d* with change in composition of individual pegmatitic boudins. The contours are drawn at 0.5 interval of *l/d*.

The rate of change of α also depends on the compositional variation within the boudin. If a boudin is heterogeneous, a competence difference with regard to response to stresses is created and the competence of one part of the boudin is not the same as other. For example, in a large pegmatitic boudin containing in some part segregations of mica and in other quartz and feldspar, would undergo greater stretching in quartzofeldspathic portion than in the micaceous one. Micas are capable of taking stresses without undergoing strain for a relatively longer period and further, quartz is known to undergo pressure solution even under low grade metamorphic conditions. Micas therefore probably take up stresses and undergo solution rather late during the history of development of boudins. A concentration gradient is probably established between micas and quartz in order to homogenise the boudin but the deformative process probably ends before the process of homogenisation is complete leaving a boudin with compositional variation within it from one point to another. The percentage of mica not only affects the l/d but gives rise to various shapes which are far from regular. Most notable shape, however, is the *monotropic* type 2.

FOLDING OF BOUDINS

Boudins analysed above belong only to early deformational events. The late folds which have diversely oriented axes and axial surfaces usually bring about a rotation of these boudins. As the late folds are diversely oriented, the folded boudins present various relationships with the axes of later folding. Three distinct types of rotation have been observed in the field. These are:

(*i*) Type 1 Rotation: when the axis of later folding lies normal to the plane containing short and intermediate axes of boudins (Plate IB, IIB, IID).

(*ii*) Type 2 Rotation; when the axis of later folding lies normal or nearly normal to the plane containing long and intermediate axes of boudins (Plate IIIC). This rotation is very rarely observed in the field.

(*iii*) Type 3 Rotation; when the axis of later folding lies at a moderate angle to the plane containing short and intermediate axes of boudins (Plates IIA, IIC, IIIB).

It is apparent that in type 1 rotation the long axis of boudin is used as the rotational axis; in type 2, it is the short axis. In type 3 rotation, none of the axes of the boudin is used for rotation, rather the late fold axis has an angular relationship with the three boudin axes. The rarity of type 2 rotation suggests that the boudins did not undergo contraction in the same direction as that of the principal extension.

The variability of rotational axes is obviously due to the variability of orientation of later folds. Rotation of pegmatitic boudins is more commonly noticed than that of the other two. This is because both psammitic and aplitic boudins are developed in areas where late folds are not conspicuously developed. In chains of pegmatitic boudins, the folding of necks of boudins is more commonly noticed (Plate IB) together with change in shape of boudins. Boudins with high l/d behave as an integral part of the layering undergoing buckling (Plate IIC).

Type 1 rotation usually causes convexity or concavity of boudins producing crescent shaped boudins. Type 2 rotation usually produces choccolate tablet structures (Wegmann 1932). Type 3 rotation produces numerous geometrical variations, depending upon the relationship of the rotational axis with the long axis of the boudin.

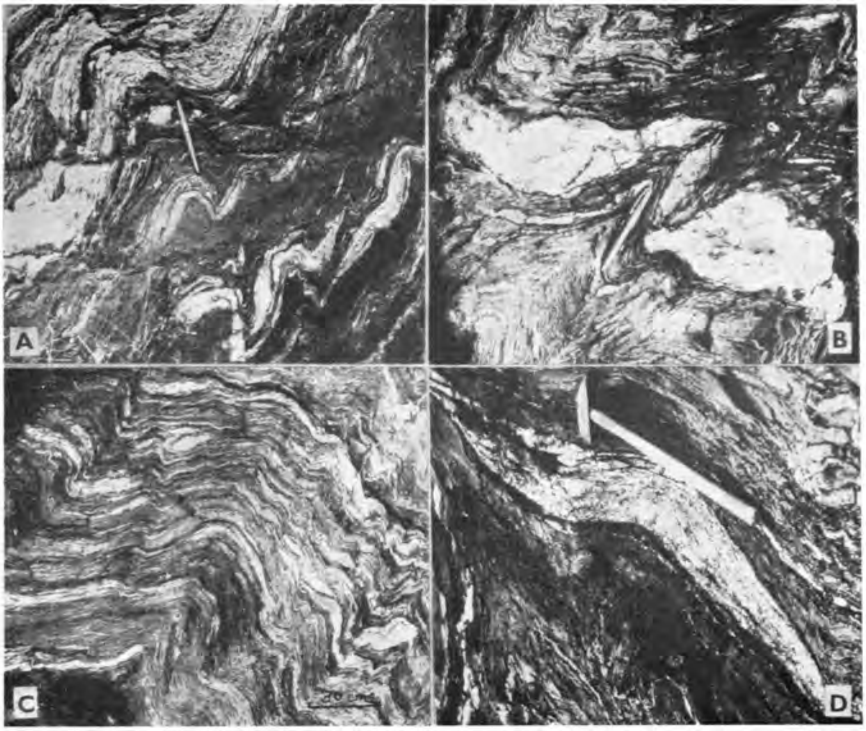

PLATE II. Rotation of early pegmatitic boudins about later fold axes. A & C. Type 3 Rotation *B* & *D*. Type 1 Rotation. West and southwest of Badnore.

It may also produce *en echelon* pattern (Plate IA). It is probably a rigid body rotation of boudins (Ramberg 1955).

DISCUSSION

The reclined and type 2 upright folds were the first to form in the area, probably as a result of subhorizontal principal compression acting along the layering in NW-SE direction. The upright type 1 structures were formed as a result of such forces and as progressive increments of strain were added without any change in the orientation of the principal stresses, these folds became progressively tight, amplified and finally became isoclinal, thus becoming indistinguishable from type 2 upright folds everywhere in the field except where cases of refolding could be observed. With progressive deformation with principal strains maintaining the same orientation, the axial surfaces of all the structures were brought into parallelism. Thus during the initial stages of progressive deformation, the principal strains appear to have maintained more or less the same orientation.

During later part of the movement which produced reclined to plunging inclined or rarely recumbent open structures, with diverse attitude of axial surfaces and axes, the principal strains appear to have been remarkably rotated; this has resulted in

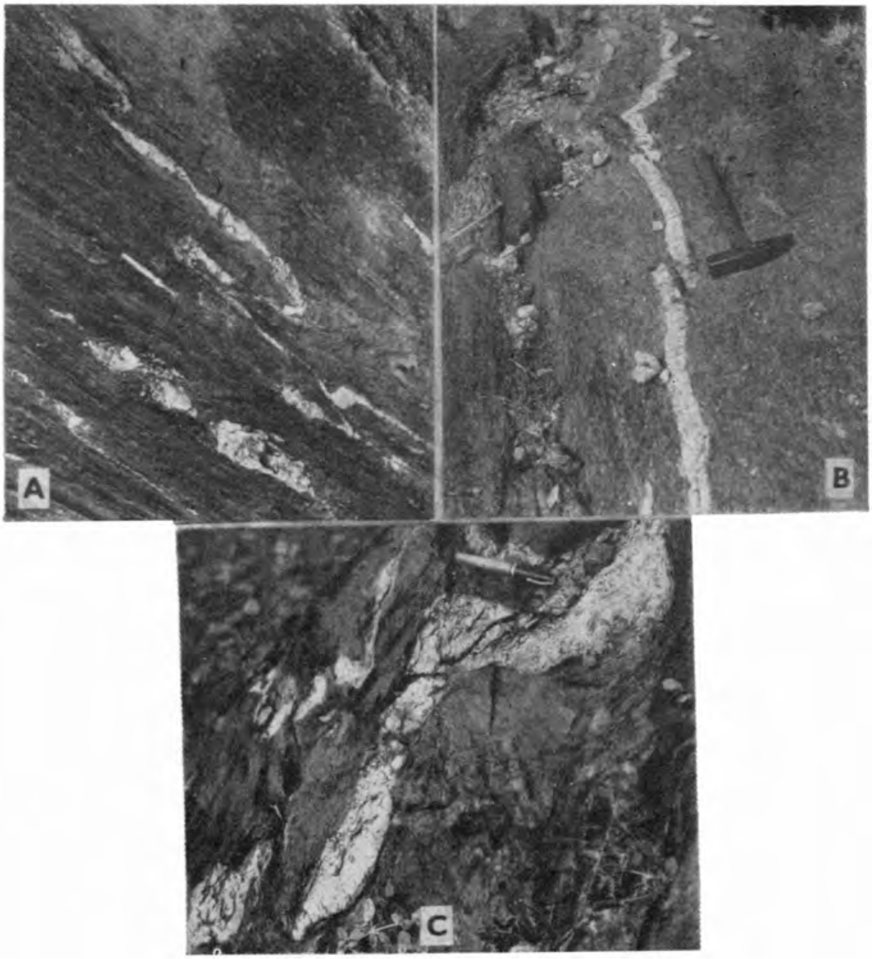

PLATE III. A. Sigmoidal pegmatitic boudins outside the western limits of the area shown on the map (Fig. 1).
B. Elongated aplitic boudins with high *l/d* in garnet-staurolite-mica schist west of Badnore affected by later strains (Type 3 rotation).
C. Pegmatitic boudins outside the western limits of the area shown in Fig. 1, affected by later strains (Type 2 rotation).

gentle or moderately dipping crenulation cleavage trending nearly NW or NNW. This cleavage is very substantially penetrative at places and does not appear to be affected by any later fold movement, at least not in the area considered in the present paper. The variability of trend and dip of crenulation cleavage which bears parallelism with axial surfaces of later folds could be attributed to: (*i*) the impress of later deformation which appears to be nearly absent in the area, (*ii*) the rotation of principal stresses and (*iii*) the varying response of variably oriented layers with reference to the incremental principal strains.

As the axial surfaces of later folds show departures from a mean statistical trend of NW or NNW, but not to any appreciable extent, the stress field may not have rotated to any appreciable degree during the course of progressive deformation.

The variable orientation of axial surfaces and axes could be attributed partly to the variable response of surfaces variably oriented with respect to that of the incremental principal strains of the related ellipsoid. A northeasterly trending form surface, for example, gives rise to gently inclined, open late folds under a principal compression oriented at acute angle to layering but at a high angle to the axes of early folds. The axial surfaces of such folds would trend nearly northwest and axes plunge due about northeast, almost down the dip of the axial surfaces. An EW trending subvertical surface, such as in the hinge zone of an early fold would however, behave in a different manner. A southerly dipping EW surface would produce plunging inclined with axial surfaces trending NE and axes plunging due SE. A northerly dipping EW trending surface would undergo folding to produce asymmetric buckles with axial surfaces trending nearly NS and axes plunging due east. A northwesterly trending subvertical surface would produce asymmetric buckles with axial surface trending nearly EW and axes plunging north or south depending upon whether the original surface was inclined subvertically to the northeast or southwest. The late folds show all these orientations specified as would an examination of the map (Fig. 3) reveal. A part of the variation of the attitude of axes of later folds could be ascribed to the orientation of the already folded surfaces on which later structures are superposed (Ramsay 1960). A moderately dipping and statistically northwesterly trending axial surface of later fold would produce the diversity in trend and plunge of the axes of later folds in the hinge zones and limb regions of early folds.

From the above discussion it appears that the orientation of principal strains did change to some extent during the later part of deformational movement. The early and late fold axes have nearly the same trend except for departures at certain places. This suggests that the orientation of principal extension remained much the same during early and later phases of progressive deformation. But the axial plane trend of later folds is much different from that of early folds. Thus it is possible that only short and intermediate principal strain axes were swapped during the later part of the movement. This statement is however based on the assumption that the cleavage may have formed parallel to the XY plane of the finite strain ellipsoid and therefore has limitations.

Under the newer orientation, the layers which originally contracted did not undergo stretching but the layers which were boudinaged did undergo contraction, though not exactly in the same direction in which they underwent stretching. Thus the boudins formed during the early phase were folded during the later phase of progressive deformation. Thus the history of these layers is similar to the history of layers in zone 1 of Ramsay (1967 *a*) as stated earlier. The reason why type 1 and type 3 rotation are commonly observed in the field and type 2 only rarely may be that the direction of principal extension was nearly maintained during all stages of the progressive deformation. The boudins can be said to have undergone folding in the same direction as that of the stretching only if the fold axes are considered to have undergone extension parallel to the intermediate axis of the finite strain ellipsoid and do not represent directions of principal extension.

ACKNOWLEDGEMENTS

The author is thankful to Professor W. D. West for providing all the necessary facilities and to Prof. U. Aswathanarayana for constant encouragement. Room and board facilities extended by Dr. P. C. Sen, Medical Officer, Primary Health Centre, Badnore during early visits to the field are gratefully acknowledged.

REFERENCES

Cloos, E. (1947). Boudinage. *Trans. Am. geophys. Un.*, **28,** 626-632.

de Sitter, L. U. (1956). *Structural Geology.* McGraw Hill, New York, 551 p.

————(1958). Boudins and parasitic folds in relation to cleavage and folding. *Geol. en Mijnbouw,* **20,** 277-286.

Durney, D. W., and Ramsay, J. G. (1971). Incremental strains measured by syntectonic crystal growths, in *'Gravity and Tectonics'* (*Eds.* de Jong & Scholten. Wiley Interscience, New York, 67-96.

Fleuty, M. J. (1964). The Description of Folds. *Proc. geol. Assoc. (Engl).,* **75,** 461-492.

Flinn, D. (1962). On folding during three dimensional progressive deformation. *Q. J. Geol. Soc.,* **118,** 385-433.

Gupta, B. C. (1934). The geology of Central Mewar. *Mem. Geol. Surv. India,* **65** (2), 75 p.

Heron, A. M. (1953). The geology of Central Rajputana. *Mem. Geol. Surv. India,* **79,** 389 p.

Knill, J. L. (1960). A Classification of cleavages with special reference to the Craignish district of the Scottish Highlands. *Bull. Int. Geol. Congr. XXI,* Copenhagen, **18,** 317-385.

Lohest, M. (1909). l'origine des veines et des ge'odes des terrains primaires de Belgique. *Soc. ge'ol. Belgique Annals.,* **36,** 275-281.

Nadai, A. (1963). *Theory of Flow and Fracture of Solids.* McGraw Hill, N.Y., 705 p.

Quirke, T. T., (1928) Boudinage, an unusual structural phenomenon. *Bull. geol. Soc. Am.,* **34,** 649.

Ramberg, H. (1955). *Natural and experimental boudinage and pinch and swell structures. J. Geol.,* **63,** 512-526.

————(1959). Evolution of Ptygmatic Folding. *Norsk. geol. Tiddsskr.,* **39,** 99-151.

————(1975). Superposition of homogeneous strain and progressive deformation in rocks. *Bull Geol. Inst. Univ. Uppsala,* N.S., **6,** 35-67.

Ramsay, J. G. (1960). The Deformation of early linear structures in areas of repeated folding. *J. Geol.,* **68,** 75-93.

————(1967 *a*). *Folding and Fracturing of Rocks.* McGraw Hill, New York, 568 p.

————(1967 *b*). *A Geologist's Approach to Rock Deformation.* Imperial College, London, 21 p.

————(1969). The measurement of strain and displacement in orogenic belts, in *'Time and Place in Orogeny'. Geol. Soc. London,* spl. pub. 3, 43-79.

Ramsay, J. G., and Graham, R. H. (1970). Strain variation in shear belts. *Can. J. Earth. Sci.,* **7,** 786-813.

Rast, N. (1956). The Origin and Significance of Boudinage. *Geol. Mag.,* **93,** 401-408.

Rickard, M. J., (1961). A Note on Cleavage in Crenulated Rocks. *Geol. Mag.,* **98,** 304-332.

Roday, P. P. (1976). Pegmatites of Badnore Area, Central Rajasthan : A Field Study. *Bull. Ind. Geol. Assoc.,* **9(1),** 42-51.

Roy, A. B., Paliwal, B. S., and Goel, O. P. (1971). Superposed folding in the Aravalli rocks of the type area around Udaipur, Rajasthan. *J. geol. Soc. India,* **12**(4), 342-348.

Sanderson, D. J. (1974). Patterns of Boudinage and apparent stretching lineation developed in folded rocks. *J. Geol.,* **82,** 651-661.

Sutton, J. (1960). Some cross folds and related structures in Northern Scotland. *Geol. en Mijnbouw,* **39,** 149-162.

Turner, F. J., and Weiss, L. E. (1963). *Structural Analysis of Metamorphic Tectonites.* McGraw Hill Book Co., New York, 545 p.

Wegmann, C. E. (1932). Note sur le boudinage. *Soc. G'eol. France C. r. Ser.,* **5,** 2, 477-489.