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Boudinage and composite boudinage in superposed deformations and syntectonic migmatization

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Abstract

The banded gneisses of the Jasidih–Deoghar area of East India behaved as a complex geological multilayer, which evolved through the combined effects of deformation and leucosome emplacement. The early foliation and banding were transposed and retransposed by two generations of isoclinal folds. The intensity of foliation development, the layer-thickness ratios and the rheological contrasts within the gneisses changed both in space and in time. Under layer-normal compression these complex multilayers gave rise to a variety of boudins and of their pegmatite-filled separation zones. The geometrical relations with successive generations of folds can distinguish the closely associated pre-F_1, syn-F_1 and syn-F_2 boudins. D_2 boudinage occurred at an advanced stage of F_2 folding so that boudinage-induced subhorizontal extension was considerably less than the total subhorizontal extension during D_2. Composite boudinage occurred during progressive syntectonic leucosome emplacement in the course of which a group of boudinaged layers with a profusion of coarse quartz–feldspar leucosome became more competent than the adjoining rocks and underwent boudinage as a whole.

1. Introduction

The structures produced in syntectonic migmatites have certain characteristics that set them apart from similar structures found in non-migmatized metasediments. The banding, which is deformed by folding and boudinage, is further modified by progressive emplacement of concordant and discordant veins and screens of leucosomes (Mehnert, 1968, p. 8) that alter the layer-thickness ratios within the multilayers. This process also causes compositional and grain-size changes within the banded gneisses. As a result, both geometrical characters and rheological contrasts within a multilayer alter and so change the way multilayers behave during synchronous deformation.

The modification of the course of structural evolution by synchronous neosome emplacement is especially well recorded in the syn-migmatitic boudinage structures of certain gneissic complexes. We describe later, boudinage structures from the Chotanagpur Gneissic Complex of the Jasidih–Deoghar area of Bihar, East India (Fig. 1). The structures are preserved in the banded gneisses in which parallel bands of foliated amphibolites, ranging in thickness from a few centimetres to a few metres, alternate with quartzofeldspathic gneisses.

The quartzofeldspathic gneiss has a granodioritic composition in most places. The amphibolites are mafic igneous rocks metamorphosed under upper amphibolite facies conditions. They commonly have a mineral assemblage of hornblende–plagioclase (andesine). Although in some places the amphibolites contain a few relict grains of clinopyroxene, the amphibolite bands are mostly pyroxene-free. Near the contacts with the gneiss and the neosome veins, the amphibolite may contain medium and coarse flakes of biotite. In some places, near the contacts with quartzofeldspathic gneiss, the amphibolites contain a few interstitial grains of microcline. The coarse-grained leucosome in the separation zones between boudins of amphibolite is composed of quartz, plagioclase and microcline.

A detailed study of the migmatization processes (Ashworth, 1985, p. 5) is outside the scope of this work. Evidently, since the palaeosomes show an amphibolite facies assemblage (hornblende + plagioclase), the leucosomes contain microcline, and the

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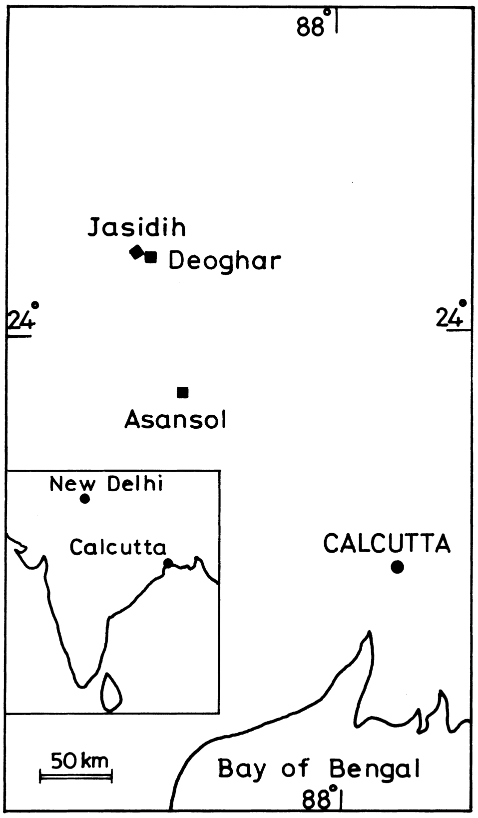

Fig. 1. Location of the Jasidih–Deoghar area in east India.

amphibolite borders show evidence of metasomatism, partial melting of amphibolite (e.g. Beard and Lofgren, 1991; Rushmer, 1991; Skjerlie et al., 1993; Wolf and Wyllie, 1994, 1995; Skjerlie and Patino Douce, 1995) cannot be a mechanism of migmatization. The most likely process of migmatization in this area is metamorphic differentiation. The biotitization of amphibolite bands towards their borders and the occurrence of interstitial microcline further indicate short-range metasomatic transfer of materials across and along the amphibolite–gneiss contact.

In the following sections we first enumerate the variety of boudinage structures and the geometry of leucosome-filled boudin separation zones in the Jasidih–Deoghar area. Boudinage has occurred in different phases of deformation. In the later sections we describe the successive stages of folding and the syntectonic character of migmatitic banding. There are three generations of boudinage structures in this area. The geometrical characteristics by which boudins of different generations can be distinguished from one another are then considered. We next describe the field features that indicate changes in the competence contrasts within the gneissic complex during progressive deformation. A special type of boudinage structure, the composite boudins, is described in detail.

2. Types of boudinage structures

There is a large variety of boudinage structures (Fig. 2) in the study area. The following are the principal types:

(i) *Single-layer boudins*: This is the classical type (e.g. Corin, 1932; Wegmann, 1932; Ramberg, 1955; Smith, 1977; Lloyd et al., 1982; Van Der Molen, 1985) in which extension fracture boudinage has occurred more or less independently in a single competent layer of amphibolite with quartzofeldspathic gneiss on either side (Fig. 2a).

(ii) *Multilayer boudins*: Boudinage has occurred in a multilayer as a whole. The multilayer is composed of alternate bands of amphibolite and quartzofeldspathic gneiss. The individual layers of amphibolite are not boudinaged independently of the amphibolite–gneiss multilayer (Figs. 2 and 3).

(iii) *Composite boudins*: These consist of two or more different orders of boudins. The composite boudins are relatively larger boudins within which smaller boudins of two or more layers or multilayers are nested (Fig. 2c). The composite boudins are discussed in detail in a later section.

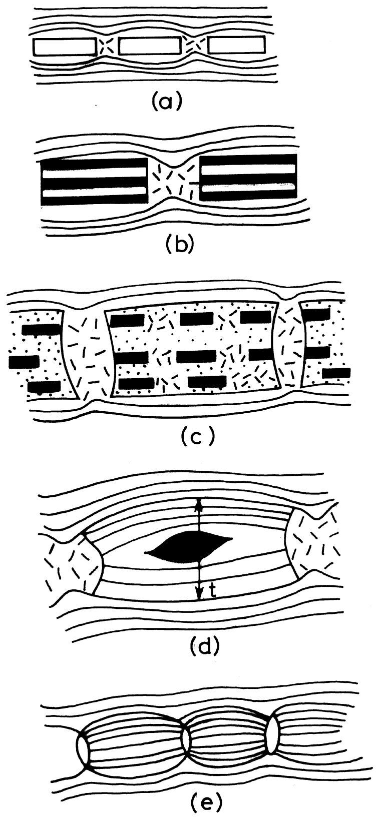

Fig. 2. Types of boudinage structures: (a) single layer, (b) multilayer, (c) composite, (d) mantled and (e) foliation boudins.

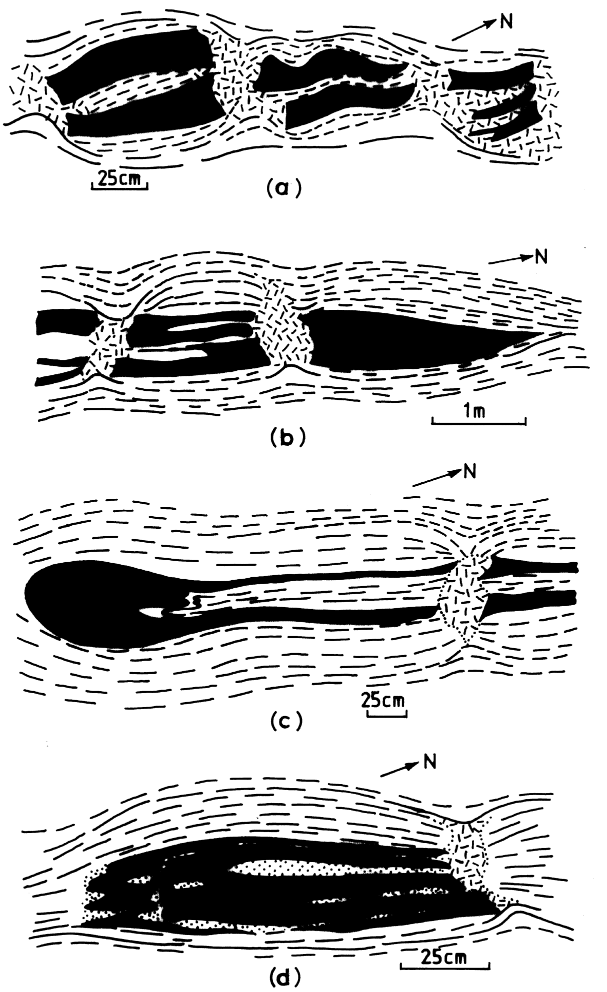

Fig. 3. Some multilayer boudins in banded gneiss. The black layers are amphibolites and the dashed areas gneisses. (a) Multilayer boudin, (b) multilayer resulting from subdivision of a thick amphibolite band into a number of thinner bands, (c) multilayer formed by repetition of a band by isoclinal folding, (d) multilayer resulting from combined effects of isoclinal folding and subdivision by screens of leucosome (dotted).

(iv) *Mantled boudins*: In the classical type of single-layer boudinage the limits of a single boudin are easily identified. Thus, the width of a boudin may be defined as the distance between successive scar folds (Whitten, 1966; Ghosh, 1993; p. 382) and the thickness of the boudin can be defined as the thickness of the competent unit itself. However, the thickness of a single boudin has to be redefined for some other types of boudinage structures, such as foliation boudins and mantled boudins. During boudinage, the external layering or foliation surface bends towards the separation zones between boudins so that oppositely directed bending folds (Ramberg, 1963; Ghosh, 1993; p. 281) develop on either side of a separation zone. The curvature and amplitude of the bending folds or scar folds are rapidly reduced as one moves away from the separation zone. The thickness (t) of a mantled boudin, ghost boudin or foliation boudin is the maximum distance between those two foliation surfaces which show the maximum curvature and amplitude near the oppositely directed scar folds (Fig. 2d). Mantled boudins (Fig. 2d) contain a kernel of a very competent unit (such as amphibolite or garnet-rich rock) and a mantle of less competent rocks (such as leucocratic gneiss). The maximum thickness of the kernel is typically much less (1:5 in one case) than the thickness of the mantled boudin as a whole.

(v) *Ghost boudins*: In the Jasidih–Deoghar area ghost boudins (Wegmann, 1932; Ghosh, 1993, p. 423) are those in which the amphibolitic palaeosome is no longer recognizable. The boudins are now largely represented by a leucosome with subordinate isolated clusters of mesosome and melanosome (Mehnert, 1968, p. 8; Johannes and Gupta, 1982). However, the typical boudinage structure, with its barrel-shaped form, scar folds and pegmatite-filled separation zones, has been preserved. Ghost boudins can be recognized only when the transitional stages of transformation (Fig. 4) are traced strike-wise along a train of boudins (Sengupta, 1985).

(vi) *Foliation boudins and foliation pinch-and-swells*: Foliation boudins (Platt and Vissers, 1980) develop in strongly foliated rocks in which there is no apparent lithological contrast between the boudinaged unit and the host rock (Fig. 2e). In the Jasidih–Deoghar area, both foliation boudins and foliation pinch-and-swells are fairly common. They are particularly well-developed in streaky gneisses and augen gneisses. The foliation boudins may be symmetrical or asymmetrical in shape. For both these types the separation zones are filled

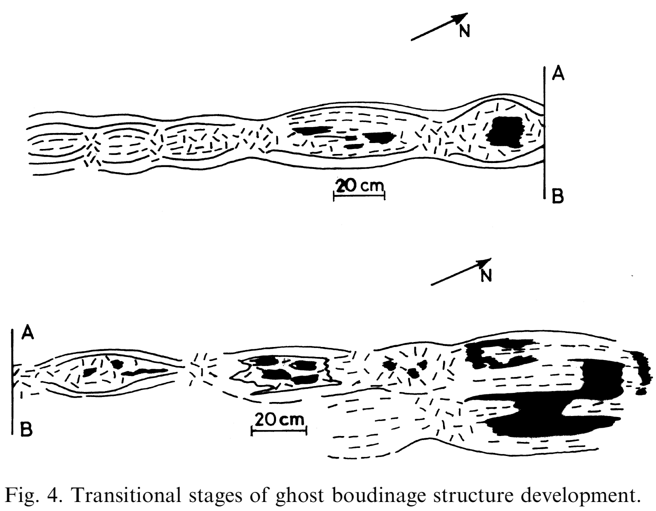

Fig. 4. Transitional stages of ghost boudinage structure development. The upper and lower figures are parts of a single continuous band. Black areas represent remnants of a boudinaged amphibolite band.

with a very coarse grained unfoliated leucosome. However, the gneisses also show foliation pinch-and-swells where there is a necking but no fracture-filled nodal leucosome.

Veins of pegmatite have also been emplaced within the quartzofeldspathic gneisses at different stages of deformation. The earlier veins are mostly parallel to the foliation and often show a pinch-and-swell structure. Some of these are cut across by veins that are isoclinically folded, with the enveloping surfaces at a high angle and the limbs parallel to the foliation. These are again cut across by later veins showing weaker folding. The veins generally have a distinctly larger grain size than the gneissic host. However, along zones of localized shearing, the earlier foliation-parallel veins have locally acquired a finer grain size by post-emplacement recrystallization (cf. Ashworth, 1979; Ashworth and McLellan, 1985, p. 188). The intensity of foliation development within the quartzofeldspathic gneisses shows a wide range of variation in the different foliation-parallel domains. As a result, the quartzofeldspathic gneiss has acquired significant differences in composition, grain size and intensity of foliation development, leading to differences in the rheological property in different domains. During layer-parallel shortening, these sharp differences in the mechanical property of the foliation-parallel domains has led to profuse development of small-scale buckle folds on the gneissic foliation. It is likely that these differences would also lead to the development of foliation boudins and foliation pinch-and-swells under foliation-normal compression of the gneisses.

3. Leucosome filling of boudin separation zones

The amphibolite layers never show a type of boudinage in which the enveloping gneiss swerves inward to completely fill the gaps between boudins. As commonly found in other terrains of migmatites (e.g. Van Der Molen, 1985, pp. 301–302), boudinage in this area is always associated with emplacement of a quartzofeldspathic leucosome in the separation zones. The leucosome in the boudin separation zones is a very coarse grained (grain size 5–25 mm) and unfoliated quartz–plagioclase–microcline rock. Its grain size is larger by more than one order of magnitude than the grain size of either the amphibolite or the gneiss. In this sense it may be regarded as a pegmatite (Ashworth and McLellan, 1985). The emplacement of the nodal pegmatite is strictly synkinematic. Pegmatite in the separation zone may simply fill a crack between boudins (Fig. 5a), may occur as a narrow transverse vein extending into the enveloping gneiss (Fig. 5b) as an oval body between inward curving lateral edges of two adjoining boudins (Fig. 5c), as a thin thread between boudins (Fig. 5d), or it may be drawn out in a dumb-bell-shaped body between the boudins (Fig. 5c).

The nodal leucosome often extends along the gneiss–amphibolite contacts. Associated with these there are a large number of amphibolite boudins in which the leucosome from the separation zones extends deep inside the boudins as layer-parallel veins (Fig. 5f). The resulting structure is similar to what was described by Wegmann (1965, fig. 13) as a 'spider' structure. In certain places the tongues of pegmatite from the separation zone have completely surrounded (cf. Van Der Molen, 1985, p. 304) the boudins (Fig. 5).

In addition to filling by the nodal leucosome, the boudin separation zone draws in a part of the adjoining gneissic material. This causes an additional extension of the layer where it locally bends towards the separation zone. Consequently, separation of larger boudins may itself cause localized boudinage of thinner competent units near the separation zone. Fig. 6 shows an excellent example of such *separation-induced boudinage*, where relatively thick (about 30 cm) bou-

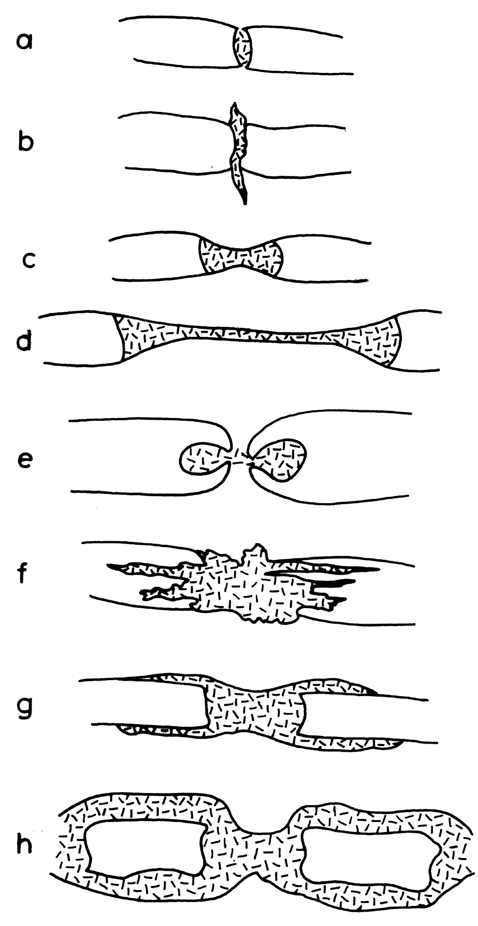

Fig. 5. Geometrical types of nodal leucosomes.

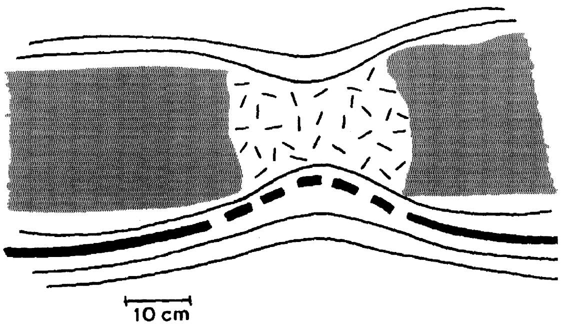

Fig. 6. Separation-induced boudinage. Boudinage in the thin band of amphibolite occurred in response to its bending towards the separation zone between two larger boudins of amphibolite.

dins of amphibolite occur within a quartzofeldspathic gneiss. An adjoining thin (about 1 cm) layer of amphibolite bends in the form of a scar fold towards the separation zone. Since the curved form of a layer showing bending folds near separation zones has a larger arclength than the straight line distance of the widths of the boudins and their separation zones, there must have been an additional layer-parallel extension over the bending folds. A row of small boudins has formed only over the curved segment of this bending fold. It is noteworthy that, unlike buckling folds, bending folds may cause a layer-parallel extension even when the fold is very gentle.

Boudins of the same generation are not all strictly synchronous. Depending on the thickness and the mechanical properties, boudinage and infilling of the separation zones with pegmatite occur at different stages in adjoining bands. The separation of relatively later boudins in one band typically causes modification of the shapes of earlier boudins in neighbouring bands. Figure 7 shows, for example, an early-formed D_2 boudin in a band of amphibolite sandwiched between two trains of relatively later D_2 composite boudins. The two long sides of the amphibolite boudin are locally deformed into oppositely directed bending folds (A and B in Fig. 7) curving towards the separation zones of the composite boudins on either side. At location C however, a foliation-parallel domain of the quartzofeldspathic gneissic host has swelled out as a result of being drawn towards the separation zones on either side.

4. Boudinage in relation to folding episodes

There are three major phases of folding in the Jasidih–Deoghar area. The earliest folds are isoclinal. Where least affected by later folds, the axial surfaces of F_1 have an easterly strike (080–110) and northerly dip. The γ F_2 folds range in tightness from isoclinal to close folds. Their N- to NNE-striking axial surfaces are steep, almost vertical, with the plunge of fold axis ranging from gentle to moderate (average 25°) towards north to north-northeast. These are the most commonly seen folds in this area. In some places γ F_1 and F_2 axes are nearly coaxial; elsewhere, they are at a significantly large angle. Both hook-shaped and crescentic (Fig. 8) outcrops of F_1/F_2 interference are present. F_3, the last generation of folds, is gentle to close, with subvertical easterly striking axial surfaces and steep easterly or westerly plunging axes. F_3 folds are found in almost all places excepting those areas where the layers trend more or less easterly and are in the extension field of D_3 deformation. In these domains no new

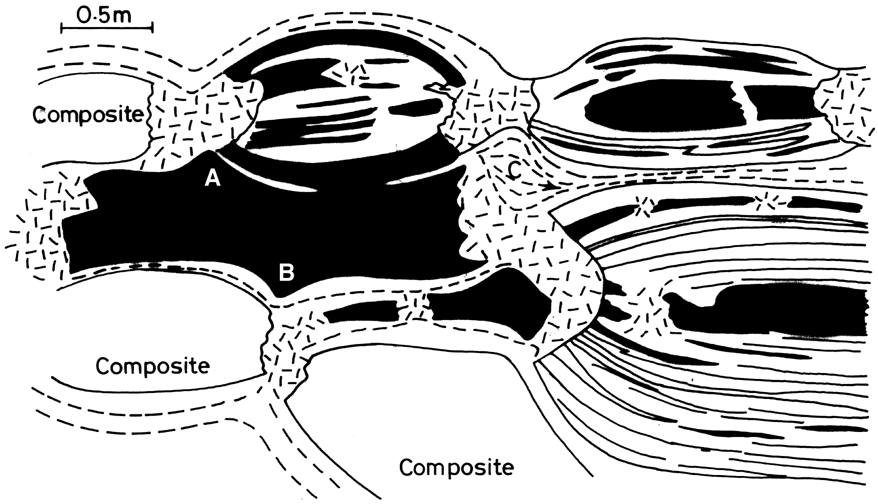

Fig. 7. Map of composite boudins from the southeastern slope of the hillock of Ratanpahar in Jasidih. The large boudin of amphibolite (black) shows cuspate-and-lobate folds on one lateral edge. The long edges of the boudin were drawn in opposite directions (A and B) towards separation zones of composite boudins. At C, the enveloping gneiss shows a swelling because it has been drawn towards the boudin separation zones in opposite directions.

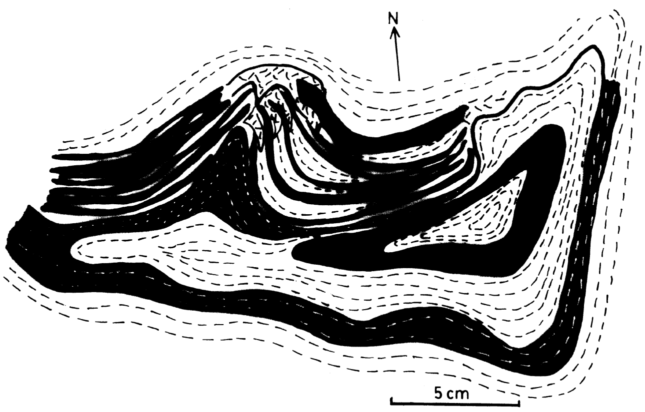

Fig. 8. Crescentic outcrop resulting from F_1/F_2 fold interference. The pegmatite-filled separation zone between D_1 multilayer boudins is deformed over an F_2 hinge.

folds have formed but the orientation of the F_1 axial surfaces have been modified and the folds further tightened by a N–S shortening.

The F_1 folds have deformed the layering of the banded gneisses. The layering and the layer-parallel foliation of the amphibolites wrap around the noses of these earliest recognizable folds. This indicates that a foliation (S^*) was produced during a pre-F_1 or D^* deformation.

A convenient method of identifying different generations of boudins is to relate them to folds of successive generations. Thus, for example, the occurrence of a boudin separation zone at the hinge of a fold indicates pre-folding boudinage. Shortening of a boudinaged layer may give rise to a variety of characteristic structures, e.g. single boudins deformed to half waves, trapezoidal boudins with flame-shaped projections, stiff boudins piled up on one another in an imbricate manner and bending of fold axial surfaces near boudin separation zones (Sengupta, 1983).

The consistent occurrence of boudins at the limbs of isoclinal folds, along with their absence at the hinge zones, indicates broad synchronicity of folding and boudinage. There is excellent evidence in the Jasidih–Deoghar area for development of boudins and pinch-and-swell structures of three generations, pre-F_1, syn-F_1 and syn-F_2. Pre-F_1 boudins can only be recognized where undoubted F_1 folds are plentiful. Fig. 9 shows the pegmatite-filled separation zones of pre-F_1 boudins deformed at the hinge zone of an F_1 fold. Such pre-F_1 boudins could be identified in only a few places. Syn-F_1 boudins and pinch-and-swell structures, occurring only at the limbs of isoclinal F_1 folds, can be recognized in several localities. The pegmatite-filled separation zones of such D_1 boudins are often deformed over the hinge zones of the F_2 folds (Fig. 10a). Fig. 8 shows an example of deformation of F_1 boudins. Here, a crescentic outcrop pattern has been produced by F_1/F_2 interference. The pegmatite-filled separation zone between two D_1 multilayer boudins is deformed over the hinge zone of an F_2 fold. Boudinage has also occurred in certain bands of a foliated garnet-rich rock occurring within the quartzofeldspathic gneiss. Fig. 10(b) shows rotated D_1 boudins of a garnet-rich rock at the hinge zone of an F_2 fold. In some places the D_1 boudins of amphibolite have undergone a tile-like imbrication by layer-parallel compression during D_2 deformation.

D_1 pinch-and-swells deformed by F_2 folds are exceptionally well exposed in the large outcrop of banded gneiss southwest of Jasidih. Fig. 11 shows a pinch-and-swell structure deformed over the hinge of an F_2 fold. The limbs of these folds have undergone boudinage (probably syn-F_2).

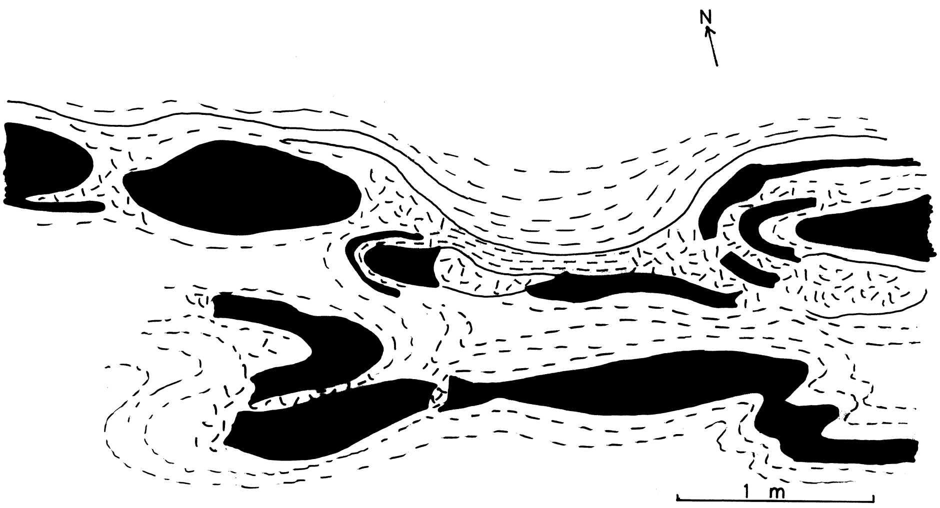

Fig. 9. Pre-F_1 boudins deformed by F_1. From banded gneiss near Rohini, southwest of Jasidih.

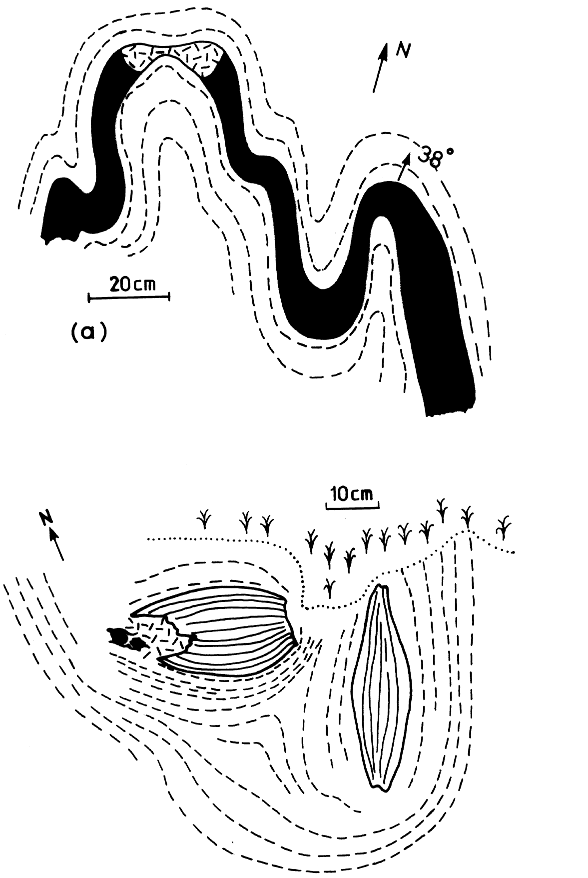

Fig. 10. (a) A dumb-bell-shaped pegmatite-filled separation zone folded at the hinge of an F_2 fold. (b) D_1 boudins of garnet-rich rock rotated at the hinge zone of F_2. Mahesthar, southwest of Jasidih.

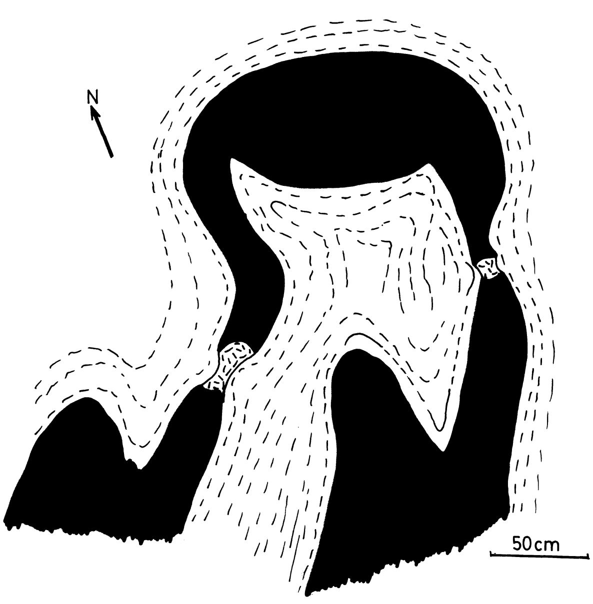

Fig. 11. D_1 pinch-and-swell structures deformed by an F_2 fold.

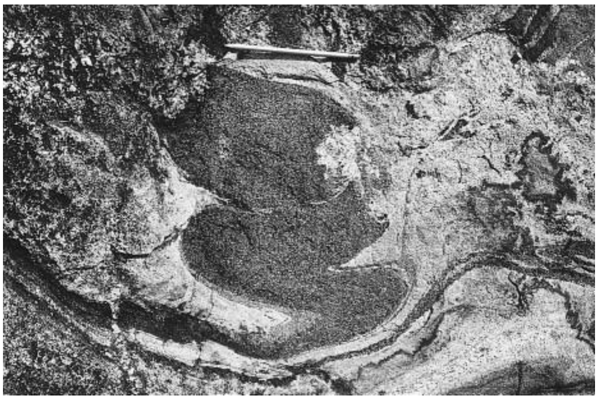

Fig. 12. Boudinaged hinges of F_2 folds. Ratanpahar, Jasidih.

The boudins that are most commonly found in this area developed during F_2 folding. Boudinage in this phase of deformation occurred towards a late stage when the folds had become tight or isoclinal. D_2 boudins are easily identified when they occur on the limbs of F_2 folds while the hinge zone remains free of boudinage. D_2 boudins are also identified when the boudin separation zones extend across both limbs of an isoclinal F_2 fold or the thickened hinges are boudinaged as a whole (Fig. 12). Excellent evidence of boudinage during the late stage of F_2 folding is found when the axial surfaces of isoclinal F_2 folds in the host gneiss bend towards the separation zone between boudins of amphibolite (Fig. 13).

F_3 folds with their E- to ESE-striking steep axial surfaces are best developed where the F_2 folds are tight or isoclinal with N- to NNE-striking axial surfaces. There has been no boudinage during F_3 folding. Instead, the D_2 boudins are strongly deformed by the F_3 folds. The scar folds associated with the D_2 boudins have axial surfaces at a low angle with the F_3 axial surfaces. Consequently, these scar folds have been tightened during F_3 folding. Where the D_3 deformation is relatively strong in northerly striking layers, we occasionally find isoclinally folded gneissic bands penetrating deep inside the separation zones between thick

Fig. 13. Bending of the axial surface of isoclinal F_2 towards the separation zone of multilayer boudins. Ghorlas, southwest of Jasidih.

boudins. The structure is likely to have developed by the combined effects of drawing of the gneissic bands in the form of bending folds towards the separation zone during D_2 and by later tightening of these folds by a shortening of the separation zones during D_3 deformation.

5. Change of competence contrast with progressive deformation

Apart from the boudinage-induced bending folds, the folds of all three generations initiated by buckling. This is shown by the development of larger folds on thicker layers or multilayers, by the presence of disharmonic folds, by the occurrence of congruent *S* and *Z* folds on the limbs and *M* folds at the hinge zones and by the contrasting geometry of the folds, with class 1B and 1C folds in competent layers and class 3 folds in incompetent layers. The fold geometry indicates that the bands of amphibolite generally behaved as competent units with reference to the gneissic rocks during fold initiation. The greater competence of the amphibolite bands is also indicated by the profuse development of boudinage and pinch-and-swell structures in these bands. However, the following structural features show that, during certain stages of the deformation history, the large competence contrasts between the amphibolites and the associated granite gneiss were reduced or even reversed in many places.

The shapes of the boudin profiles and their pegmatite-filled separation zones were essentially controlled by the relative competence of the boudinaged amphibolite bands. These geometrical characters indicate a wide range of competence contrasts of the amphibolite boudins with respect to the associated quartzofeldspathic materials. After initiation of boudinage, and depending on the competence of the boudins themselves, the total extension of a boudinaged layer was achieved partly by elongation of the boudins and partly by an increase in the width of the separation zones. For very competent boudins with sharp rectangular profiles, post-boudinage plastic deformation of the boudins was very small, and further extension of the boudinaged unit was achieved by separation of the boudins. The nodal pegmatite could then undergo necking and give rise to a spindle- or dumb-bell-shaped separation zone. In the other extreme, for easily deformable boudins, separation of the boudins was accompanied by layer-parallel elongation of the boudins. The flow of the incompetent host material caused a stretching of the outer part of a boudin to a larger extent than its interior. This is the reason for the development of fish-head boudins (Wegmann, 1932, fig. 1; Ramberg, 1955, fig. 1B) in which the corners of a boudin are drawn out as pincers which almost completely encircle an oval pod of nodal pegmatite (Fig. 5e). For development of fish-head amphibolite boudins it is necessary that, during post-boudinage plastic deformation, the amphibolite boudins have a small competence difference with the host gneiss and that they behave as incompetent units with respect to the nodal pegmatite. In certain places post-boudinage reduction in competence contrast is also indicated by the development of a necked region in the middle of a boudin.

Trapezoidal boudins with flame-shaped marginal aprons (Sengupta, 1983, 1985) are an interesting product of deformation of D_1 boudins during the D_2 deformation. The development of these structures requires not only a shortening of the boudinaged layer in a later deformation, but also a reduction in the competence contrast between the amphibolites and the quartzofeldspathic rocks, so that a layer-parallel shortening of a boudinaged layer can squeeze out the quartzofeldspathic material of the separation zone (Fig. 14b). As in the case of a fish-head boudin (Fig. 14a) the flow of the quartzofeldspathic material draws out the lateral edges of a boudin, but unlike the fish-head boudin, the flame-shaped lateral projections are in a direction transverse to the layering (cf. the experimental simulation of such structures by Sengupta, 1983). The occurrence of such structures implies that, at that stage of deformation, the amphibolite behaved as a weakly competent material with reference to the gneissic rock. It was also necessary that, with respect to the amphibolite, the quartzofeldspathic material of the separation zone was incompetent so that it could be squeezed out from between the boudins. The trapezoidal form of the boudins resulted from the tangential

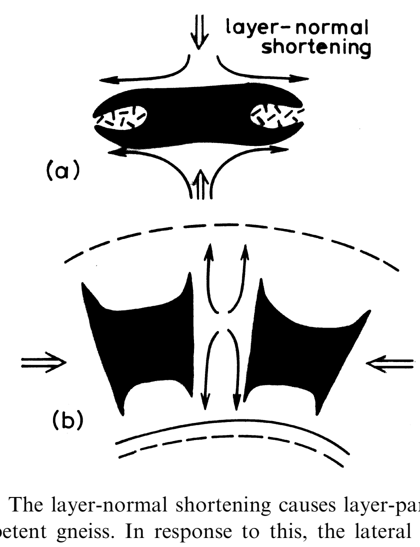

Fig. 14. (a) The layer-normal shortening causes layer-parallel flow of the incompetent gneiss. In response to this, the lateral edges of the boudin are drawn out as prongs and produce the fish-head form of the boudin. (b) Development of trapezoidal boudins with flame-shaped projections.

longitudinal extension of the outer arc of a folded boudin and tangential contraction of the inner arc.

The fold geometry of the amphibolite bands indicates that these bands generally had a significantly large competence difference with the associated granite gneisses during fold initiation. However, the frequent occurrence of parasitic, *S*- and *Z*-shaped, flame folds or arrow head folds (Kranck, 1953; Ghosh, 1993, p. 231) in the amphibolite bands, with sharp pointed outer arcs and rounded inner arcs, indicates that at an advanced stage of folding, the amphibolite behaved as an incompetent material. In the Jasidih–Deoghar area, two types of these structures were observed. In one, the layers of amphibolite occurring within the granite gneiss are deformed to become disharmonic folds, with congruous *S* and *Z* folds on the limbs. This geometry confirms that the folds had initiated as buckling folds on competent amphibolite layers. Yet, some of these folds show an arrow-head geometry. Such structures could only have been produced by a reversal of the competence contrast during the progressive tightening of the folds. The other type of structure, with cuspate-and-lobate folds (Ramsay, 1967), has not affected an entire band but only the interface between amphibolites and quartzofeldspathic gneisses. The rounded fold-forms point toward the amphibolite and the sharply pinched folds point toward the gneiss. These structures occur at the inner arcs of hinge zones of larger buckle-folded amphibolite bands and indicate a reversal of the competence difference between the amphibolite and the granite gneiss (cf. Ramsay, 1982; Ramsay and Huber, 1987, p. 401; Talbot and Sokoutis, 1992). Similar cuspate–lobate interfacial folds, indicating a competence reversal, are also seen at the lateral edges of amphibolite boudins. Since in Fig. 7 the folds occur on interfaces that are at a high angle to the layering, the competence reversal and the development of these cuspate–lobate folds must have occurred in continuation of the same layer-normal compression which initiated boudinage. In the boudin shown in Fig. 15, the geometry of the cuspate–lobate folds indicates relative incompetence of the amphibolite. The folds appear on an interface that is at a very low angle to the layering. The leucosome occurring at the cores of the lobate folds shows a weakly developed axial planar cleavage at a distinct angle to the general gneissic cleavage. It is likely that these interfacial folds were produced in response to a layer-parallel shortening during the D_3 deformation.

The reduction and reversal of competence difference is clearly related to development of biotite within these rocks (cf. Sengupta, 1997). The thin amphibolite bands that show arrow-head folds or the domains of amphibolite that show cuspate–lobate folds invariably have a significant amount of biotite along with hornblende and plagioclase. In contrast, the central part of thick bands of amphibolite or bands that are deformed to class 1B or 1C type of folds do not contain biotite.

The veins of unfoliated pegmatites, with grain size greater than that of the gneisses by at least one order of magnitude, behave as competent bodies with respect to the gneisses (cf. Ramberg, 1952, p. 125; Naha and Sen, 1965; Mehnert, 1968, pp. 317–320; Ramsay and Huber, 1987, p. 384). Typically, the concordant veins of pegmatite show pinch-and-swell structures and the veins at a high angle to the gneissic foliation are buckle-folded. Wherever coarse pods of pegmatite occur within the gneiss, the foliation invariably swerves around these competent bodies. Buckle-folded veins of pegmatite occur within the amphibolites also. Similar relationships have been recorded from many other gneissic terrains. Ramsay and Huber (1987, p. 385) record an example in which pegmatite is distinctly more competent than amphibolite. Consequently, in the banded gneisses, where a profusion of pegmatitic neosome is emplaced within a zone of multilayer, the relative competence of the multilayer may increase with respect to the adjoining rocks.

6. Composite boudins

Composite boudins develop in multilayers in which there have been different orders of boudinage. Thus, a

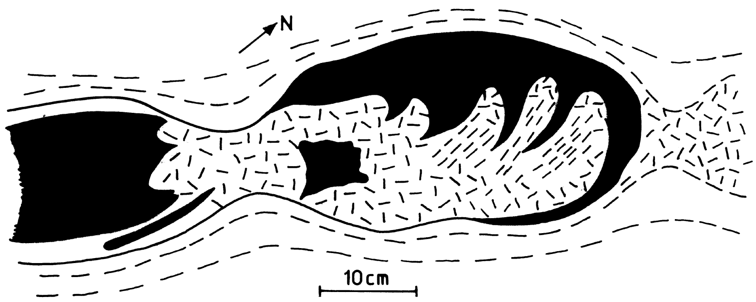

Fig. 15. Remnant boudin of amphibolite showing cuspate-and-lobate folds on an interface that is at a low angle to the layering. Note incipient foliation development in gneissified pegmatite at the cores of lobate folds. Note also the development of cuspate–lobate folds on the lateral edge at a high angle to the layering of another boudin.

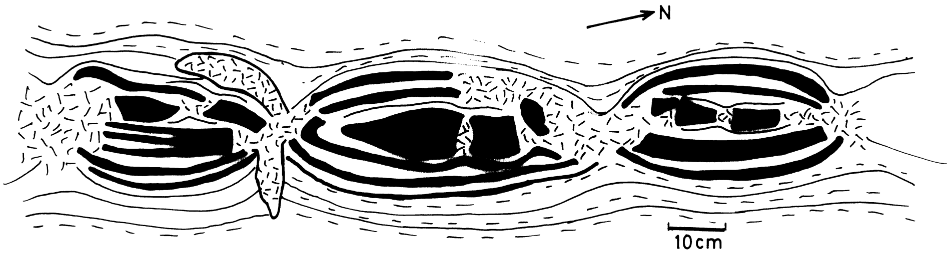

Fig. 16. A row of composite boudins from Ratanpahar, Jasidih.

composite boudin shows smaller boudins in individual layers while boudinage has also occurred on a larger scale within a packet of such layers. This, in turn, may be part of a still larger boudin within a thicker packet of multilayers. The composite boudins of the Jasidih–Deoghar area developed during the D_2 phase of deformation.

The simplest type of composite boudins shows relatively small boudins in two or more individual layers, the smaller boudins being nested within a larger boudin. In such a simple type, the boudinaged individual layers can be traced all along a row of composite boudins. The majority of composite boudins in the Jasidih–Deoghar area are more complex. The boudinaged individual layers within them cannot all be traced strike-wise in a row of composite boudins. This is partly because of the heterogeneous character of neosome emplacement and partly because of boudinage in isoclinally folded layers. There is a considerable variation in the geometry of the individual amphibolite layers in a row of composite boudins (Figs. 16–18). A boudinaged layer may be thick in one composite boudin and thin in another. A thick layer of one unit may be subdivided in another unit into a number of thinner layers separated by screens of leucosome. A straight boudinaged layer of one composite boudin may be repeated several times in another by isoclinal folding. Figs. 17 and 18 in which both the thickness and the number of layers vary along the row of composite boudins show one of the finest examples of composite boudinage in this area. A composite boudin may itself be nested within a larger composite boudin. The central unit of Fig. 17 shows two orders of composite boudins. A complex structure with several fragments of folded amphibolite in a composite boudin is shown in Fig. 19.

Composite boudins are sites of extensive neosome emplacement. Quartzofeldspathic neosome is not only emplaced along the separation zones of boudins of different order, but diffuse patches of leucocratic neosome are often emplaced within the boudins themselves. Because of such extensive neosome emplacement the remnants of the nested bodies within a larger composite boudin may occur in a partly gneissified quartzofeldspathic matrix and may give rise to an agmatitic (Sederholm, 1926; Hopgood and Bowes, 1978) structure, a term now used in a purely morphological sense.

Composite boudinage has taken place from the scale of a few decimetres to the scale of a few tens of metres. The larger composite boudins, identified only by detailed mapping, generally consist of several orders of nested composite boudins. The problem of determination of boudinage-induced elongation, from the widths of boudins and their separation zones, becomes difficult where such large or map-scale composite boudins are present. In the general situation, boudins in a single layer or a single thin multilayer have relatively large separations, whereas the composite boudins have relatively small separations. The total boudinage-induced elongation can only be determined by combining the elongations of the different orders of boudins. Unless the composite boudins are recognized in the field, both in the outcrop and the map scales, the elongation measured from the individual boudins will give a low estimate of the actual elongation.

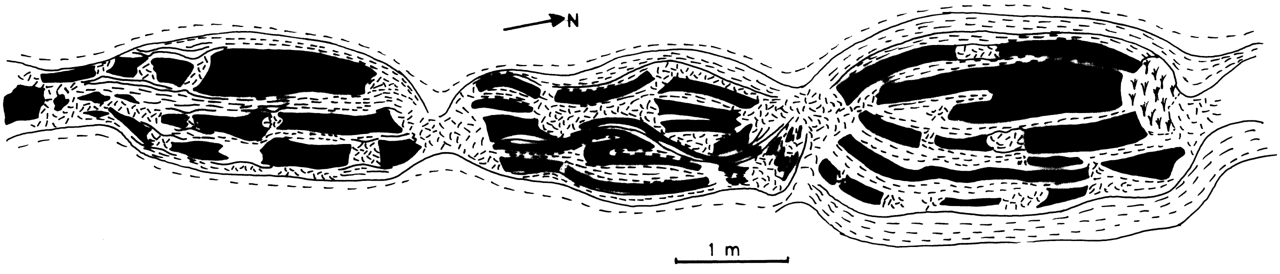

Fig. 17. Map of a row of composite boudins from southeastern slope of Ratanpahar.

Fig. 18. Composite boudins. These are the same as the two northern composite boudins shown in Fig. 17. Because of the low angle of photography, the boudin on the far side appears greatly foreshortened.

7. Boudin aspect ratio and boudin axis orientation

In transverse sections the boudinage structures show a variety of shapes, e.g. rectangular, lenticular, barrel-shaped and fish-head. The rectangular boudins have undergone an essentially brittle failure without significant post-boudinage plastic deformation. In contrast, the fish-head boudins, wrapping over a part of the nodal pegmatite, have suffered considerable post-boudinage deformation. The lenticular boudins with their tapering edge and thin pegmatite-filled separation zones have undergone boudinage only after a large amount of necking. In most cases of boudinage the development of extension fractures was both preceded and followed by a significant amount of layer-parallel longitudinal extension. The behaviour of the amphibolite layers not only changed in the course of time, but there were also significant differences in the behaviour of the bands of amphibolites from domain to domain. Thus, for example, certain large outcrops of banded gneiss show a predominance of pinch-and-swell structure and few real boudins of amphibolite. On the other extreme, there are regions where boudinage is plentiful but pinch-and-swell structures are rare.

The boudins, which developed during F_2 folding, show a wide range of variation in the width to thickness ratio (w/t). This suggests that the boudins of the same generation did not all initiate at the same time. Some of the extension fractures developed at different times in different layers or in different segments of the same layer. This is also evident from the wide range of variation of the widths of the boudin separation zones. However, for the area as a whole, the most frequently observed boudin aspect ratio is about 1.8.

The orientation of the boudin axes (Fig. 20) could be measured in several places in the large outcrops of banded gneiss east of Jasidih. The boudins here mostly developed during γ F_2 folding. The orientations of the boudin axes could be measured from the exposed hinge lines of the bending folds or scar folds at the separation zones of boudins. The boudin axes show a steep plunge of about 80° in a west-northwest direction. Hence the subhorizontal outcrops show an essentially transverse section of the boudins. The steep set of boudin axes is neither parallel nor perpendicular to the F_2 fold axis. Since the F_2 folds were superimposed on earlier folds it is unlikely that the F_2 axis would coincide with a principal axis of strain during D_2. This may explain the obliquity of the fold axis and the boudin axis.

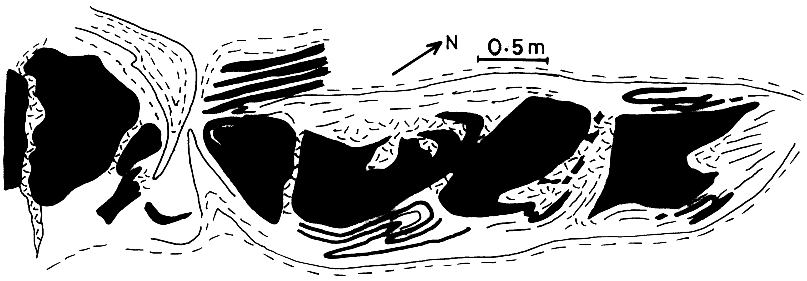

Fig. 19. Composite boudins with folded fragment of amphibolite. Nandanpahar, north of Deoghar.

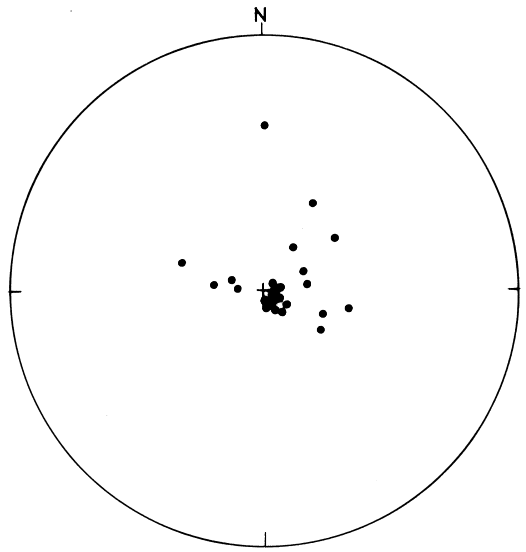

Fig. 20. Lower hemisphere equal area projection of boudin axes from Ratanpahar.

8. Discussion

Boudinage in single layers has been studied by a number of authors. In contrast, there are very few studies of boudinage in multilayers. Cobbold et al. (1971) discussed the theoretical principles of boudinage, kink band formation and development of interlocking pinch-and-swells in anisotropic materials. Price and Cosgrove (1990) have also discussed the problem of development of these structures, and Kidan and Cosgrove (1996) have made a detailed experimental investigation. However, there are very few detailed field studies on the development of boudinage and pinch-and-swell structures in natural multilayered rocks.

Kidan and Cosgrove (1996) considered two situations. In one of these the structures developed more or less independently in the individual layers within a multilayer, whereas in the other situation the extensional structures developed in the multilayer as a whole. The experimental boudins in the individual layers developed either by extension fracture or by shear fracture. In the experiments of Kidan and Cosgrove (1996), multilayer boudins did not develop by extension fracture. Instead, under a layer-normal compression, a stack of layers was deformed to pinch-and-swell structures or normal kink bands. In one of their experiments, with a complex multilayer containing layers of different thickness and different rheological properties, rectangular boudins developed first in the individual layers. The thinner boudinaged units were then deflected towards the separation zones between boudins of thicker layers. A series of such deflections throughout the multilayer gave rise to pinch-and-swell structures and finally to normal kink bands by linking up of the neck regions. Although in these experiments, small boudins in individual layers were nested within larger pinch-and-swells in multilayers, composite boudinage, i.e. different orders of extension fracture boudinage, with smaller boudins nested within larger boudins, did not develop.

Evidently, the development of composite boudins requires a special situation. The field structures suggest that the most important reason for the frequent development of composite boudins in a migmatitic terrain is the progressive emplacement of a coarse grained quartzofeldspathic neosome within a group of layers that was undergoing boudinage. The smaller stretch of the composite boudins as compared to the relatively larger stretch associated with the nested individual boudins implies that composite boudinage took place after the development of the nested boudins. The coarse pegmatitic materials has not only sealed the extension fractures of the smaller boudins in the individual layers, it has in many places projected within an entire zone of boudinaged layers. It is suggested that because of the emplacement of coarse unfoliated leucosomes, a group of boudinaged layers may acquire a sharp rheological contrast with the adjoining rocks and may undergo boudinage as a whole and thereby produce a train of composite boudins. Successively higher orders of composite boudins develop with progressive spreading of the zone of leucosome emplacement through thicker stacks of boudinaged layers.

9. Summary and conclusions

The multilayered character of the banded gneiss evolved through the combined effects of deformation and leucosome emplacement. A foliation parallel to the banding was present before formation of the earliest recognizable folds. The early foliation and banding were transposed and retransposed by two generations of isoclinal folds, F_1 and F_2. The open F_3 folds developed wherever the layering was in the compression field of the D_3 deformation; elsewhere, no new folds developed but the earlier folds were rotated and tightened.

Apart from the repetition by isoclinal folding, the banded character changed by emplacement of foliation-parallel quartzofeldspathic screens of leucosome. Consequently, the thickness ratio, the layer spacing, the intensity of foliation development and the rheological contrasts within the packets of multilayers changed in both space and in time. Under layer-normal compression these complex multilayers gave rise to a variety of pegmatite-filled boudin separation zones and a variety of boudins e.g. single-layer boudins, multilayer boudins, mantled boudins, ghost boudins, foliation boudins and composite boudins. Although three generations of boudins, pre-F_1, syn-F_1 and syn-F_2 are closely associated in this area, their geometrical relations with the successive generations of folds can distinguish them. For the syn-F_2 boudins, the dominant set of boudin axis is subvertical and the principal layer-parallel extension is essentially parallel to the strike of the F_2 axial surface.

The banded gneisses show different orders of boudinage, with early-formed smaller boudins nested within relatively late larger boudins of the same generation. Such composite boudinage occurred during progressive emplacement of a quartzofeldspathic neosome, which filled the boudin separation zones and extended within and around the boudins themselves. Consequently, a group of boudinaged layers containing a large quantity of interconnected pegmatitic leucosome acquired the mechanical property of a single relatively thick unit that could undergo boudinage as a whole under continued layer-normal compression. Successive higher orders of composite boudins formed by progressive leucosome emplacement through thicker zones. Pegmatite-filled oblique shear fractures occur in some places within the gneisses. However, the majority of composite boudins initiated by extension fracture. They are quite distinct from the rhombic structures produced by development of conjugate kink bands in anisotropic materials (Price and Cosgrove, 1990).

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