Hourglass Structure: An Evidence of Buckle Folding

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Abstract: The Nimbahera shale beds show an hourglass map pattern due to juxtaposition of an anticline and a syncline along a common NNE striking, upright axial plane. Several possible hypotheses, such as superposed folding, sheath folding, variation in shortening, variation in orientation of pre-existing *S*- surfaces and coalescence of fold waves are tested for explaining the development of the hourglass structure. Evidence from geometrical characteristics of the folds, associated mesoscopic scale structures and the published experimental results suggest that the hourglass structure has developed due to the linkage of the two out-of-phase fold waves that propagated towards each other during the folding of the Nimbahera shale beds by buckling.

Keywords: Hourglass structure, Buckle folding, Nimbahera shale, Chittaurgarh, Rajasthan.

Introduction

The map pattern of folded beds, in areas of flat topography, may show wide variation depending on the three-dimensional geometry of the folds as well as the angles made by the fold hinges with the outcropping surface. Of the variety of outcrop patterns, the hourglass pattern can occur in several possible structural settings. In this article, we report the occurrence of an hourglass map pattern, discuss its origin in terms of various possibilities, and ascribe its development to the buckling process.

Hourglass Structure

In this study, we focus on the hourglass structure observed in the Nimbahera shale beds, which are exposed in the Berach river section near Chittaurgarh (N 24°54' 19"; E 74°37'33"), Rajasthan (Fig.1). Lying close to the Great Boundary Fault, these shale beds are deformed into a series of open to gentle upright folds that plunge at 10-20° towards NNE to NE.

Bedding surfaces in the Nimbahera shale trace an hourglass map pattern, which consists of a juxtaposed pair of anticline and syncline along a common axial trace (Fig. 2a). Structural mapping reveals that the main anticline branches into two narrow anticlines at low angles, and a syncline occupies the space between the branched anticlines (Fig. 2b). All the folds, namely, the main anticline, the syncline and the branched anticlines are upright and plunge at low angles towards NNE to NE (Fig. 1c). Although a cm scale transverse fault cuts through the shale beds at the contact between the main anticline and syncline, it neither offsets the beds appreciably nor affects the map pattern significantly.

Mechanism of Development

It is well known that the hourglass structures can develop in a variety of structural settings. In general, the three-dimensional geometry and the mutual arrangement of folds in the hourglass structure vary from one structural setting to another. We test the mechanism for development of the hourglass structure in the Nimbahera shale beds by comparing the geometry of the mapped folds with those that develop in the five relatively more common types of structural settings.

Type-1 Interference

The hourglass structure can develop due to interference between an antiformal fold and a synformal fold in accordance with type-1 pattern of Ramsay (1967). This type of superposition results into development of an antiformal depression and a synformal culmination, each containing a pair of adjacent folds, which share a common axial trace, but close and plunge in diametrically opposite directions (Fig.3a). A typical map pattern of the type-1 interference structure consists of two conjugate hourglass structures on the axial traces that are commonly inclined at moderate to high angle to each other (AT-1 and AT-2 in Fig. 3a). Whereas one of these hourglass structures represents a pair of coplanar antiforms plunging towards each other, the

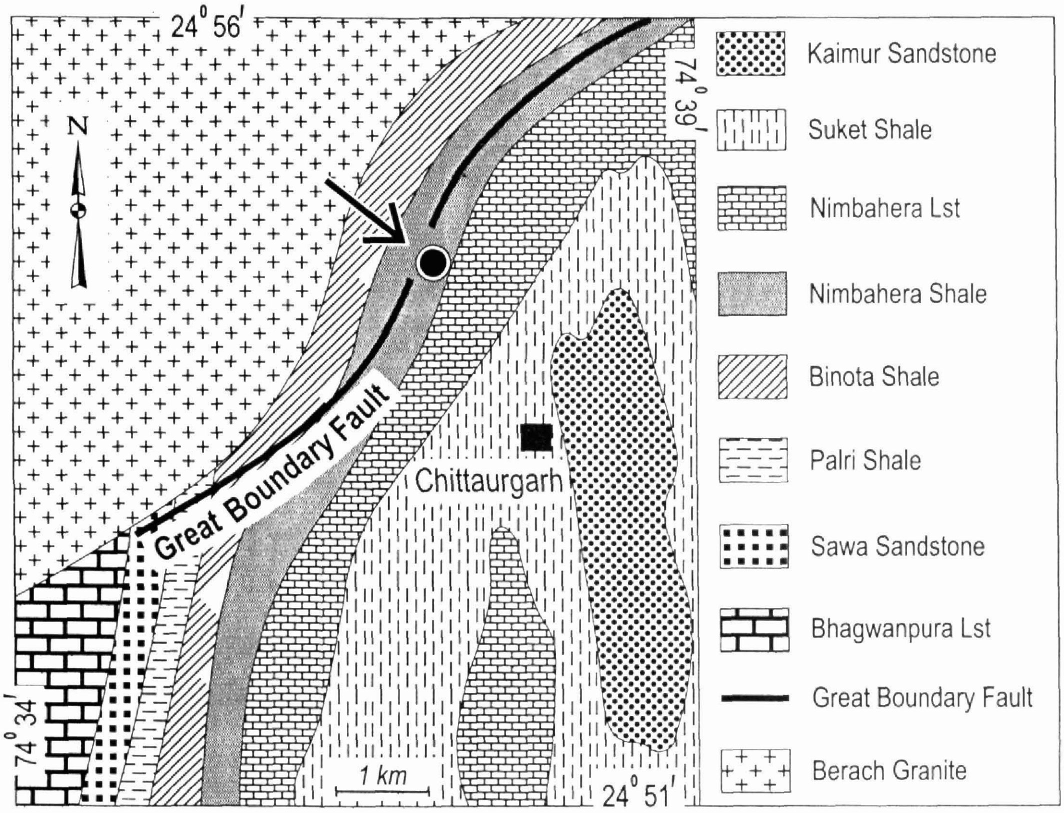

Fig.1. Geological setting and location of hourglass structure (*pointed by arrow*) in Nimbahera shale beds around Chittaurgarh. Lithological boundaries after Prasad (1984).

other represents a pair of coplanar synforms plunging away from each other.

There are three main reasons as to why the hypothesis of type-1 interference is not tenable for accounting the development of hourglass structure observed in the Nimbahera shale beds. First, unlike the type-1 interference where the two conjugate hourglass structures are developed at an angle to each other, the map pattern in the Nimbahera shale beds shows the presence of only one hourglass structure. Second, whereas the hourglass structure in type-1 interference represents either a pair of synforms, or a pair of antiforms, that plunge in opposite directions, the hour glass structure, reported in this study, consists of a coplanar antiform and a synform which plunge in the same direction (Fig. 2b). Finally, there is no independent structural evidence to suggest that the Nimbahera shale bed has been deformed by two fold systems, inclined at moderate to high angle with respect to each other.

Sheath Folding

Sheath folds in ductile shear zones may show hourglass map pattern due to their plane noncylindrical geometry and the hinge line inversion (Fig.3b; cf. fig.21.17 in Ghosh, 1993, p.525; fig.10c in Srivastava, 2001). The hourglass map pattern of sheath folds is made up of either two antiformal, or two synformal hinge zones, which lie along a common axial trace, and plunge either towards each other, or, away from each other, except in cases where sheath hinge lines are U-shaped.

Four main lines of evidence argue against the possibility that the hourglass pattern observed in the Nimbahera shale beds represents a sheath fold. First, the hourglass pattern consists of an antiform and a synform, rather than a pair of antiforms, or synforms. Second, the microscopic studies reveal that the surfaces that trace the hourglass structure are sedimentary in nature (Fig.4a). Third, there is a total lack of evidence in favour of ductile shearing or mylonitisation of the shale beds (Fig.4a). Fourth, hinge lines of folds in the hourglass structure plunge consistently at low angles towards NE to NNE, rather than showing any significant directional instability or inversion in the plunge direction.

Variation in Shortening and Tightness

Variation in amount of shortening perpendicular to axial plane may result in the development of antiformal depressions and synformal culminations (e.g. fig. 7-105 in

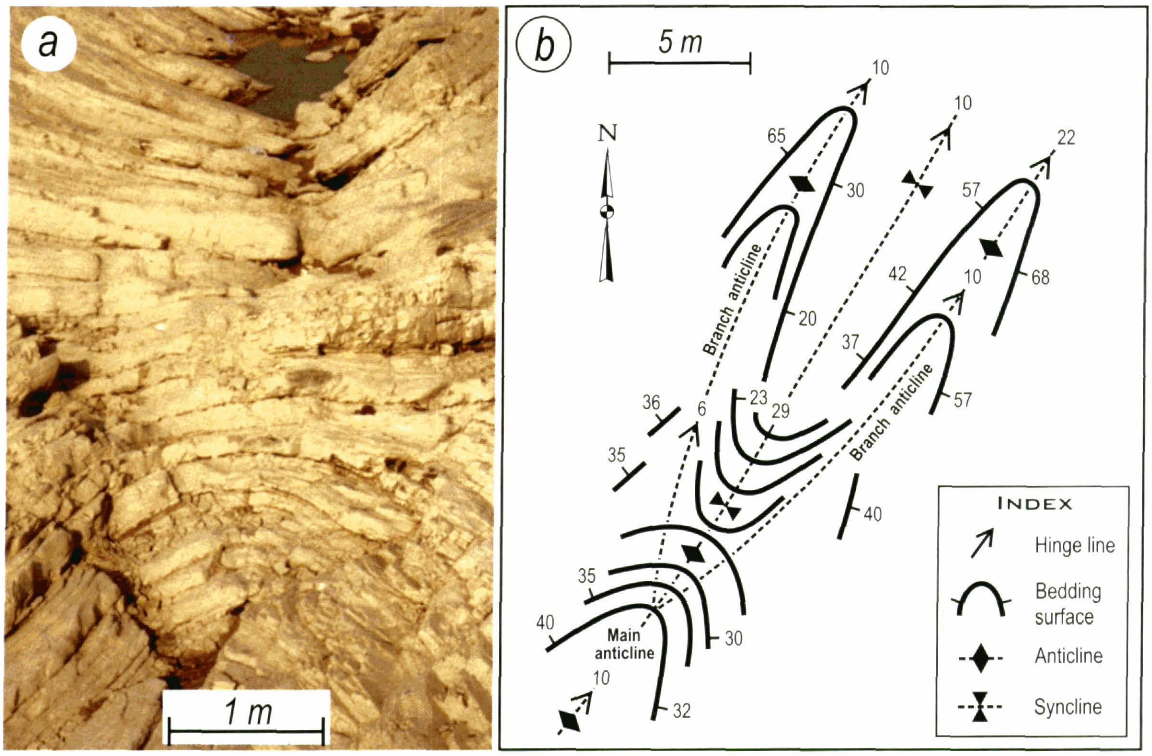

Fig.2.(a) Juxtaposition of anticline and syncline in the hourglass structure. **(b)** Map pattern of hourglass structure in the Berach river section.

Ramsay, 1967,p.436). Alternatively, the superimposition of tight to isoclinal late folds on open to gentle early folds may also result in the development of antiformal depressions and synformal culminations of the late folds (fig. 15.23 in Ghosh, 1993, p. 352). Both these mechanisms are capable of producing the hourglass map pattern consisting of the folds, which share a common axial trace, but plunge in the opposite directions. The antiform and the synform in the hourglass structure, reported in this study, are open to gentle, plunge in the same direction, and there is no evidence in favour of superposed folding. For these reasons, neither the variation in axial compression across the axial plane, nor, the overprinting by tight late folds is a tenable hypothesis.

Variation in Orientation of *S*-Surfaces

In some areas of superposed folding, an antiformal fold may change to neutral and synformal fold along a common

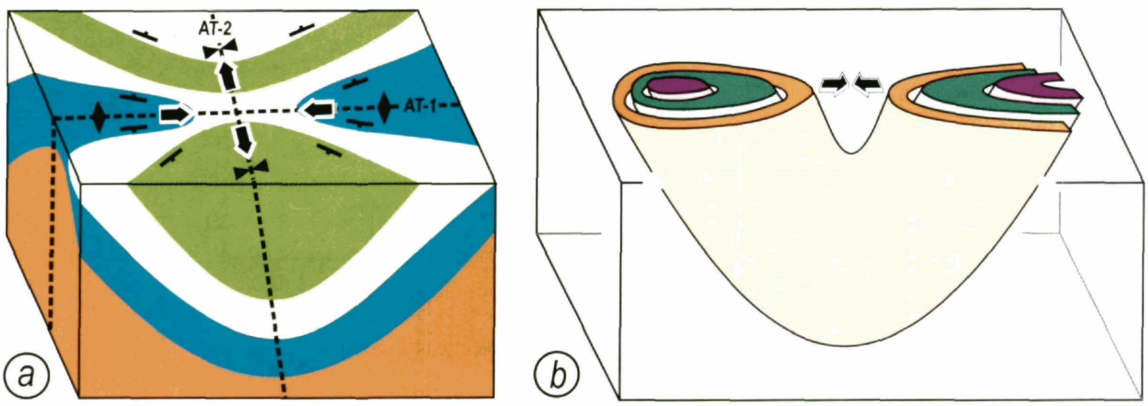

Fig.3. Three-dimensional geometry and outcrop pattern. **(a)** Type-1 interference structure (based on fig. 15.6 in Ghosh, 1993, p. 337). AT-1 and AT-2 are the axial traces of anticlinal and synclinal hourglass structures. Arrow-plunge direction. **(b)** Sheath fold. Arrows indicate reversal in plunge direction due to hinge line inversion.

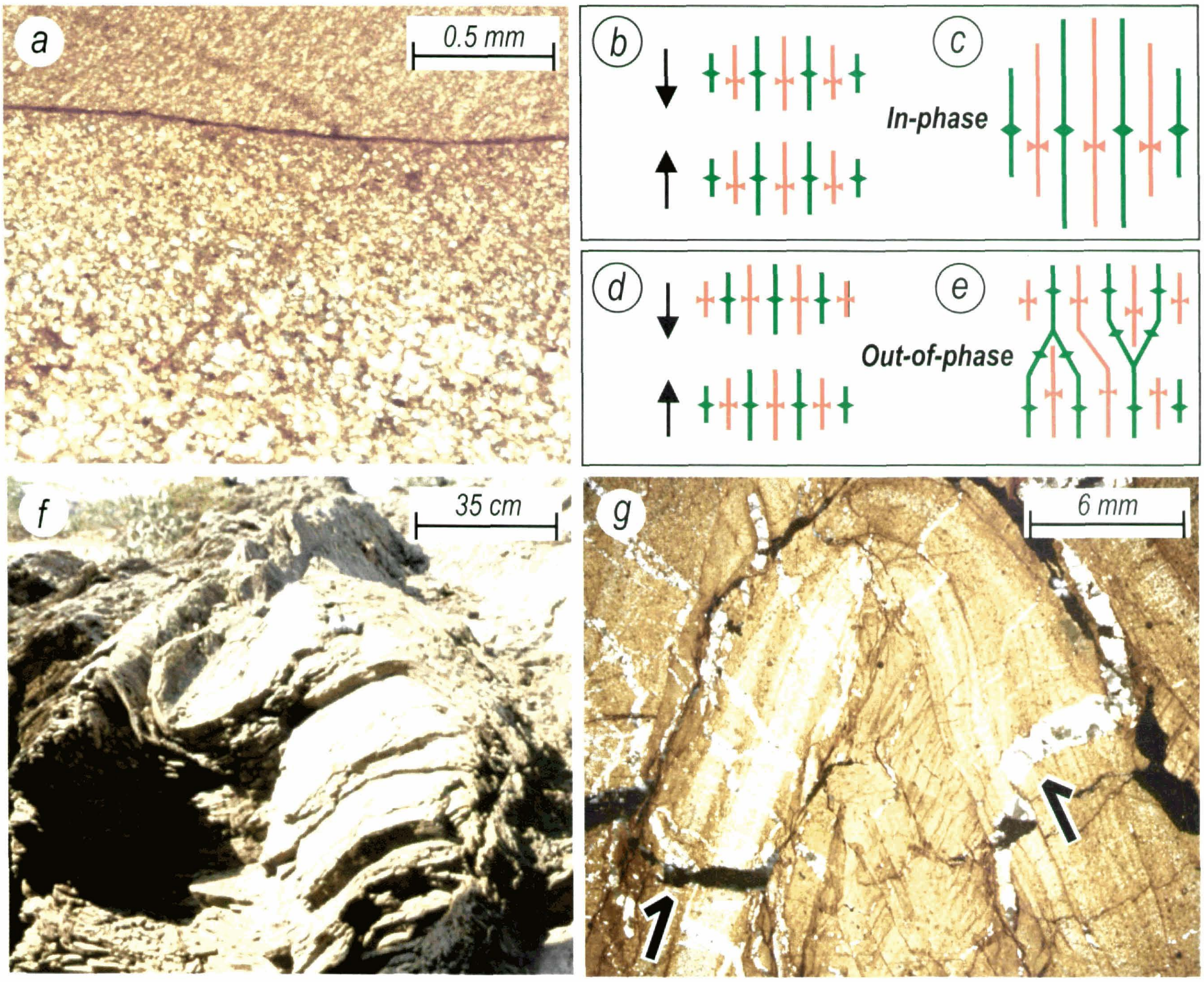

Fig.4.(a) Photomicrograph shows graded bedding structure in the Nimbahera shale/siltstone (crossed nicols). The grains size becomes progressively finer upwards. **(b-e)** Coalescence between fold waves propagating towards each other (after Dubey and Cobbold, 1977). Black arrow- propagation direction. Each fold wave consists of alternate anticline (green) and syncline (red). ***b***- Two fold waves propagating towards each other are in the same pahse. ***c***- Coalescence of two in-phase waves leads to linking of anticline and syncline in one wave with the anticline and syncline of the second wave, respectively. ***d***- Propagation of two out-of-phase fold waves towards each other. ***e***- Anticlines in one wave bifurcate and link with the two nearest anticlines in the second wave. Note the juxtaposed pair of anticline and syncline share a common axial trace. **(f)** Bifurcation of an anticlinal hinge line. **(g)** Offset of quartz veins due to flexural slip folding of the Nimbahera shale beds. The arrows show sinistral and dextral offset of the quartz veins on the right and left limbs, respectively.

axial trace. For example, Ramsay (1958 and 1967) and Ramsay and Huber (1987) show that the geometry of some of the late folds, in the Loch Monar area, changes from antiform to synform along a common axial trace (fig. 22.23 in Ramsay and Huber, 1987, p.501). They further demonstrate that such changes in fold geometry, and the accompanying low axial direction stability in the hinge lines are due to the superimposition of the late folds on the variably oriented S-surfaces at the southeastern limb of the Loch Monar synform. That the hourglass structure in the Nimbahera shale beds has not development due to folding on variably oriented S-surfaces is evident from the lack of superposed folding and the high stability in the hinge line orientation.

Coalescene of Fold Waves

Soft model experiments on the buckling of multilayer packets show that the fold hinge lines commonly branch out or bifurcate (Ghosh and Ramberg, 1968) due to the interaction between the propagating fold waves (Dubey and

Cobbold, 1977). These experiments further demonstrate that the nature of interaction between the two fold waves propagating towards each other is a function of the phase difference. For example, if the two fold waves are in the same phase, then the folds grow by coalescence of anticlines and synclines in one wave with the corresponding anticlines and synclines in the other wave. This type of in-phase fold wave interaction, which leads to growth of folds without any branching or bifurcation of hinge lines, does not give rise to hourglass map pattern (Figs.4b-c).

If, however, the two propagating fold waves are out-of-phase, then their interaction results in bifurcation of a main anticline of the first wave into two branched anticlines, such that the branched anticlines merge with the two nearest main anticlines in the second wave (Figs.4d-e). In this type of interaction, a syncline, developed between the two branched anticlines, truncates against the main anticline along a common axial trace. The resulting hourglass structure, formed in this manner, consists of a juxtaposed pair of anticline and syncline, which close in diametrically opposite directions, but plunge in the same direction. The hourglass structure in the Nimbahera shale beds satisfies all these geometrical conditions.

Conclusions

The hourglass map pattern in the Nimbahera shale beds consists of juxtaposed anticline and syncline that occur along a common axial trace and plunge in the same direction. Although different mechanisms, such as the superposed folding, the variation in compression across the axial plane, the folding on variably oriented S-surfaces, and the sheath folding can produce hourglass map patterns, there is no evidence to support any of these deformation schemes in the study area. Furthermore, neither the three dimensional geometry, nor the high axial directional stability, nor the arrangement of the folds, in the mapped hourglass structure, is consistent with the corresponding elements in the hourglass structures that may be produced by any of the above listed mechanisms.

On the basis of the structural data, the map pattern and the occurrence of small scale folds showing branched hinge lines (Fig. 4f), we infer that the hourglass map pattern is a consequence of the interaction between the two out-of-phase fold waves during the buckling of the Nimbahera shale beds. Several lines of evidence, such as the direct relationship between the bed thickness and fold wavelength, the class 1B fold geometry of folds, the occurrence of hinge line normal striae on the fold limbs, and the bedding parallel shear offset of quartz veins imply that the folds constituting the hourglass structure was formed by flexural slip mechanism during the buckling of the Nimbahera shale beds (Fig. 4g). We conclude that the hourglass map patterns, if produced due to branching of hinge lines, are important evidence in favour of the buckling mechanism of folding in layered rocks.

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