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Polyphase deformation in a part of the South Delhi Fold Belt, Rajasthan, NW India

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Abstract: **The South Delhi Fold Belt (SDFB) constitutes a linear northeast-southwest trending fold belt of the Proterozoic age in NW India, with either north-easterly or south-westerly closing folds. The rocks from the Todgarh formation of SDFB show the occurrence of westerly closing folds. Systematic structural study and detailed mapping are carried out to interpret the westerly closing folds. Three generations of folds (F1, F2 and F3) are identified from the studied area. F1 is the early tight isoclinal folds with the development of bedding-cleavage intersection lineation (L1) parallel to the F1 fold axis. The F2 folds are non-cylindrical, with the formation of pucker axis (L2) parallel to the F2 fold axis. The interference pattern of F1 and F2 folds shows a hook-shaped outcrop. The F3 folds are open and conjugate in nature. Measurements of axial planes of the conjugate folds are employed to deduce the stress axis of the strain ellipsoid. The calculated maximum compression direction for the F3 folds shows an NW-SE compression direction similar to that of the F1 and F2 folds. The present study suggests that the westerly closing folds in SDFB are formed by reorienting the early F1/F2 folds due to the later F3 fold. Our work showed that the F1, F2 and F3 are developed in a broadly similar compressive regime.**

Index Terms: **Polyphase deformation, Proterozoic, Rajasthan, South Delhi Fold Belt, Todgarh formation.**

I. Introduction

The Aravalli mountain range is a 700 km long mountain chain consisting of multiply folded and poly-metamorphosed rocks of Proterozoic age in the northwestern Indian Shield. The general orientation of the Fold Belt is northeast-southwest trending. The previous workers have reported multiple deformations in all the Precambrian rocks from Rajasthan and formed a basic framework of Precambrian rocks of Rajasthan (Heron, 1917, 1953, Gupta, 1934, Gupta and Mukherjee, 1938, Choudhary et al., 1984, Roy and Jakhar, 2002, Chatterjee et al., 2017, 2020).

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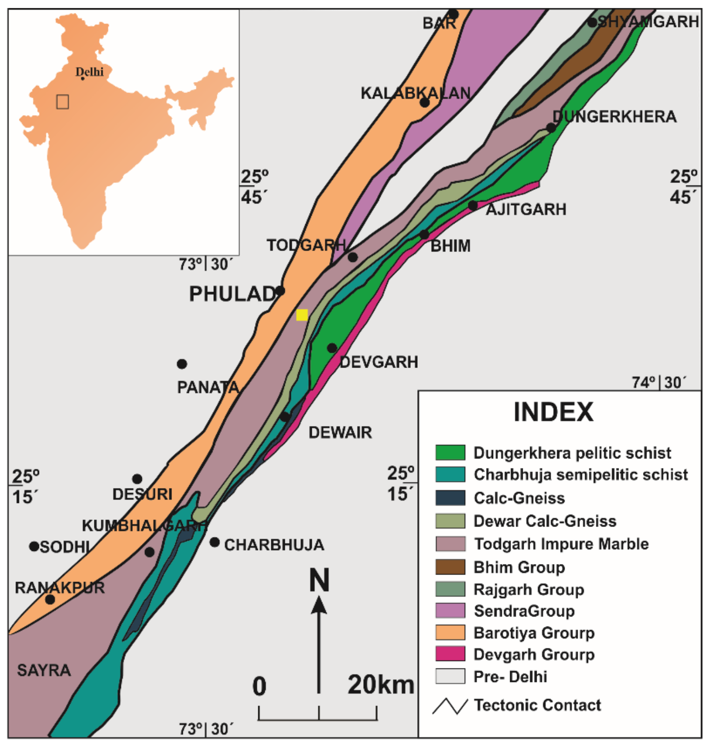

Fig 1: Lithological map of parts of Delhi Fold Belt, modified after Gupta et al., 1995. present study area is marked by square box (yellow coloured).

According to the previous workers, the structures in the Aravalli Super-group of rocks and the banded gneissic complex are similar in nature whereas the Delhi super-group of rocks show a partly independent trend as suggested by (Naha et al., 1984, Naha & Roy, 1983, Naha and Halyburton, 1977a, b, Naha and Mohanty, 1990). The isoclinal 1st generation folds of the Aravalli Super-group of rocks show gentle westerly plunging nature striking NNE-SSW prior to later deformation. In contrast, there is no westerly plunging F1 and F2 folds in the Delhi super-group of rocks (Naha and Mohanty, 1990). According to our observation, rocks of Todgarh formation in the South Delhi fold belt (Fig: 1), Kamlighat, Rajasthan (Lat: 25°33′18.6″, Long: 73°51′15.1″) show westerly plunging folds (Fig 2). Although the early workers (Naha and Mohanty, 1990) suggested that the later folds (F3, F4) in the Delhi Group of rocks had been generated due to the sub-vertical N-S compressive (strain) regime, the present work can serve as a new illustration of the structural framework of the Delhi Group. The present study aims to understand the deformation pattern of the westerly closing folds in the SDFB rocks from the Todgarh formation.

II. Mesoscopic Structures

The rock type of the present study area is calc-silicate and belongs to the Todgarh formation of the SDFB. The rock is characterized by alternate dark and light coloured compositional banding. The thickness of the compositional bands varies from millimetres to a few centimetres. These compositional bands are denoted as S0 for the present study. The rocks show a series of multi-layer buckle folds (Ghosh et al., 1992, 1993, Ghosh and Chatterjee, 1985) with differently oriented axial planes (Fig 2). Westerly closing folds are developed on these calc-silicate rocks. Three generations of folds have been identified from the study area. Detailed mapping depicts the deformation patterns and interference patterns of the different generations of folds.

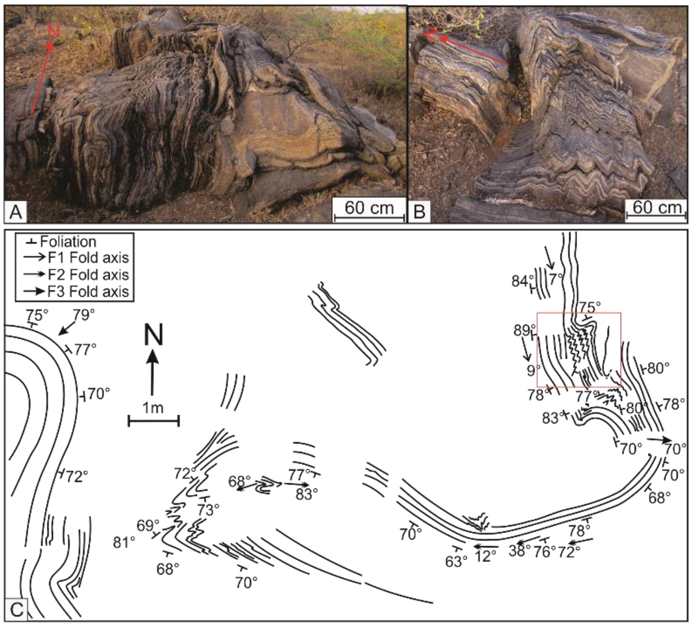

FIG 2: (A), (B) Different modes of buckle folding of thin and thick multi-layers of calc-silicate rock showing differently oriented fold axis with different plunge values. (C) Detail mapping of westerly closure fold associated with differently oriented folds. Location of figs 2A and 2B marked by red box.

A. *Structures of First Generation*

The earliest fold is on the compositional banding and marked as F1 fold (Fig 3). Long limbed, tight, isoclinal folds, upright and cylindrical, characterizes the F1 folds (Fig 3A). The F1 fold axis has horizontal to low plunging (12°) with an axial plane dominantly striking ~NNE-SSW and ~NNW-SSE at some places (Fig 3A, 3B, 3C). Depending on the rheological contrast of the layers, the F1 folds vary in geometry from class 1C to 1B (Ramsay, 1967). These calc-silicate rocks show prominent development of lineation due to bedding cleavage intersection (during this earliest deformation) termed as L1 (striping lineation) (Figs 3C, 3D). The development of this lineation is very persistent and occurs strictly parallel to the F1 fold axis. The crustal shortening has occurred along WNW-ESE, which is indicated by the orientation of the axial plane of the F1 fold.

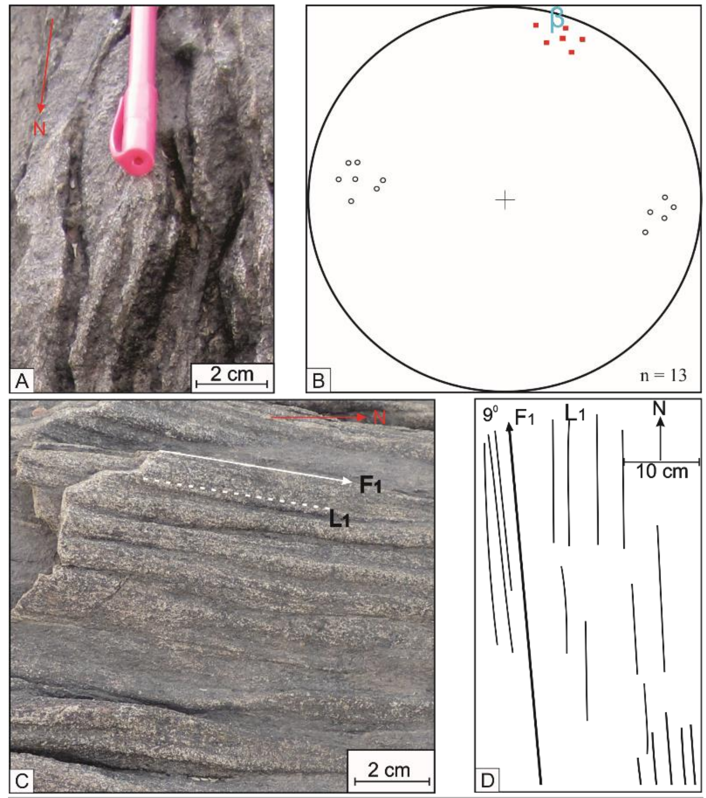

FIG 3: (A) Tight isoclinal, upright fold (F_1) demarcated by folding of bedding planes with low plunging fold axis. (B) Stereographic projection of F_1 fold, where red dots indicate the striping lineations. (C) Due to bedding, cleavage intersection striping lineation formed which is parallel to the F_1 fold axis, denoted by white dotted line. (D) Tresses of striping lineations (L_1) and F_1 fold axis of an unrolled F_1 fold, on a paper showing parallel relation between them.

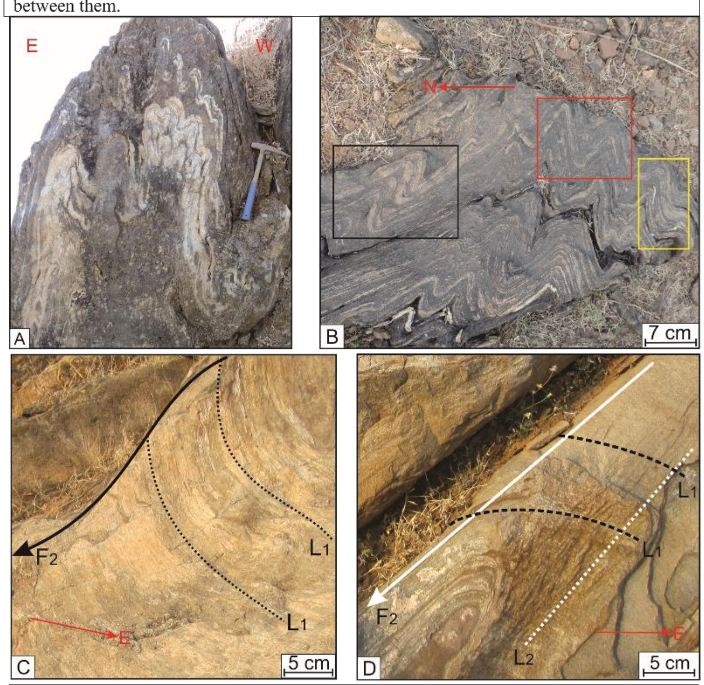

FIG 4: Field photographs (A) vertical section showing the F_2 fold. (B) in horizontal section, F_2 fold shows Z (black rectangle), M (red rectangle), S (yellow rectangle) type folds. (C) Striping lineations (L_1) present at high angle with F_2 fold axis. (D) Pucker axis (L_2) is parallel to F_2 fold axis, Striping lineations (L_1) present at higher angle with F_2 fold axis and pucker lineation (L_2).

B. Structures of Second Generation

The F2 folds are close to tight, asymmetrical, non-cylindrical folds with upright to inclined axial plane (Fig 4). The fold axis varies from horizontal to steeply plunging (78°) in nature, with the axial plane striking NNE-SSW to NE-SW (Figs 4C, 4D). Due to varying tightness, the geometry varies from class 1C (tight) to 1B (close). Parasitic folds are symmetrical at the hinge part and asymmetric in the limb part of the large F2 fold, showing Z, M and S folds (Fig 4B). The F2 fold reoriented the early L1 striping lineation (Figs 4C, 4D). The angle between L1 and F2 fold axis varies from high to low with the F2 fold axis with the varying plunge of the F2 fold. The pucker lineation is associated with the F2 folds and is always parallel to the F2 fold axis. The pucker lineation (L2) (Fig 4D) is not penetrative throughout the F2 fold (localized in a few zones of the F2 fold). The general compression direction of F1, F2 fold is NW-SE which matches with the general compression direction of SDFB.

C. Structures of Third Generation

F3 folds are open, moderate to steep plunging fold axis and are conjugate in nature (Fig 5, 6). F3A and F3B are the two fold axes of the conjugate fold, with the axial planes (S3A and S3B) striking around 050° and 094°, respectively identified. The intersection line of the two axial planes gives the P_{int} (65°→ 083°), and consequently, the pole bisecting of the acute angle between the shears P_{min} is found 24°→ 250° and bisecting the obtuse angle between the planes P_{max} is obtained as 7°→ 344°. The calculated maximum compression direction is ~NW-SE. The compression direction of the F3 fold is similar to that of F1 and F2, which matches the general compression direction of DFB. F3 fold reoriented the previous lineations (L1, L2) and folds (F1, F2). Due to the superimposition of different generation folds, differently oriented folds (F1, F2) are observed in different locations. Westerly closure folds are observed, originally, which are the hinge parts of F2 folds and are now placed into a westerly closure of F3 fold due to rotation during F3 fold formation.

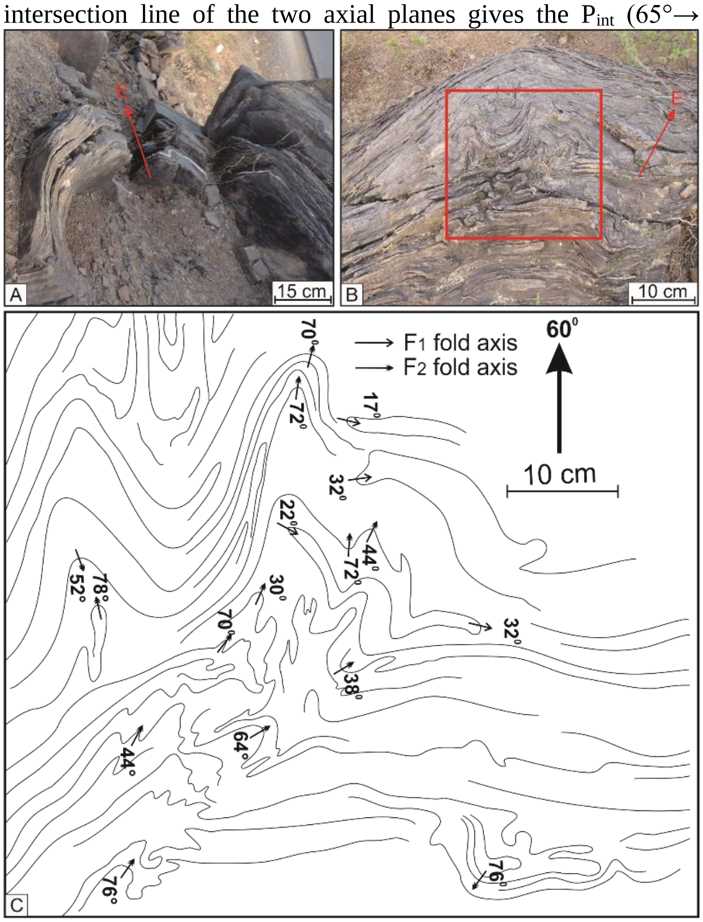

FIG 5: (A, B) Open fold with steeply plunging fold axis (F3). (C) Simplified map with Tresses of F1, F2 fold axis in a large F3 fold hinge.

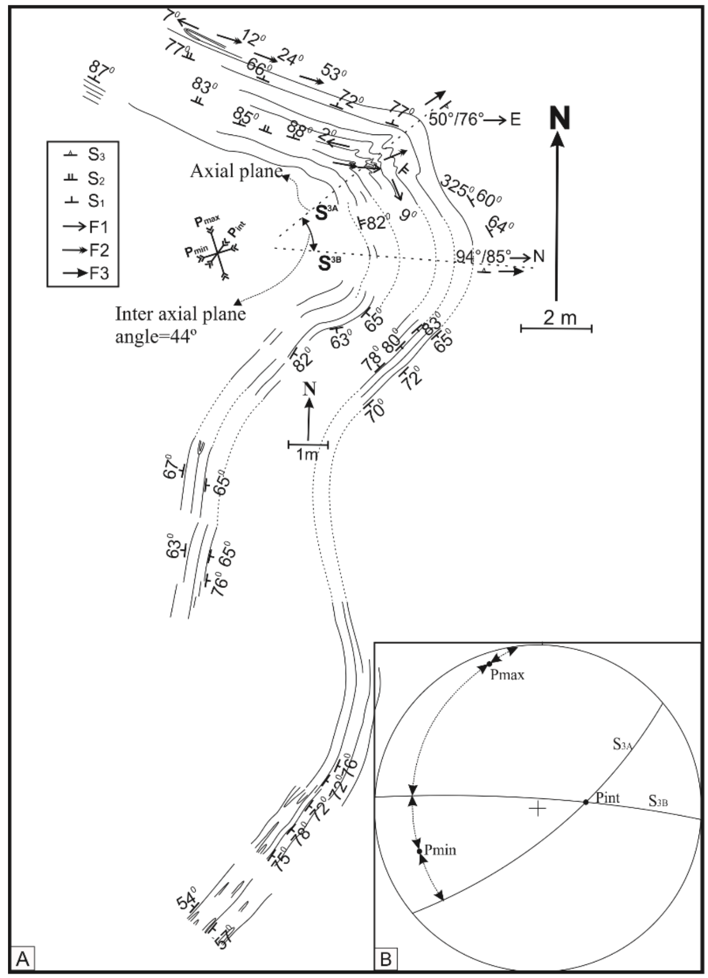

FIG 6: (A) Detail map of the study area showing differently oriented fold axis (F1, F2) and the orientation of F3 fold axis, F3 fold is conjugate in nature. (B) stereographic projection of the axial planes of F3 fold form which maximum compression direction (NW-SE) is calculated.

III. Interference Pattern

The Kamlighat area offers to study the effect of superimposition of three generations of folding. Superposed folding gave rise to different types of interference patterns. F1 - F2 Interference pattern: The refolding of 1st generation tight, isoclinal fold gives rise to hook-shaped outcrop patterns (Fig 7).

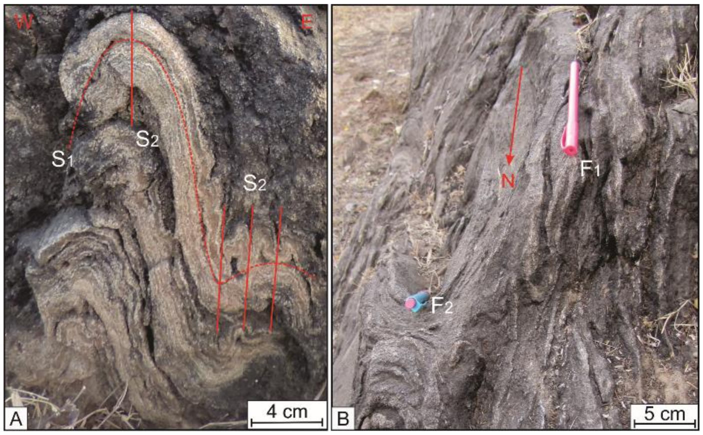

FIG 7: (A) Hook-shaped outcrops and S_1, S_2 foliations in calc-silicate rock in vertical section. (B) Type 3 interference pattern giving rise to hook-shaped out crop in Precambrian rocks. Pink pen indicates F_1 fold axis and blue pen indicates F_2 fold axis.

This is a Type-3 interference pattern (non-plane cylindrical). This suggests that the F1 and F2 folds are nearly co-axial.

Interference patterns between F2 and F3: Although F2 is the dominant and regional fold of the area, the outcrop patterns of the rocks are controlled by the relative intensity of superimposition of F3 on F2. The interference pattern of F2 and F3 develops a non-plane-non-cylindical (type-2) interference pattern.

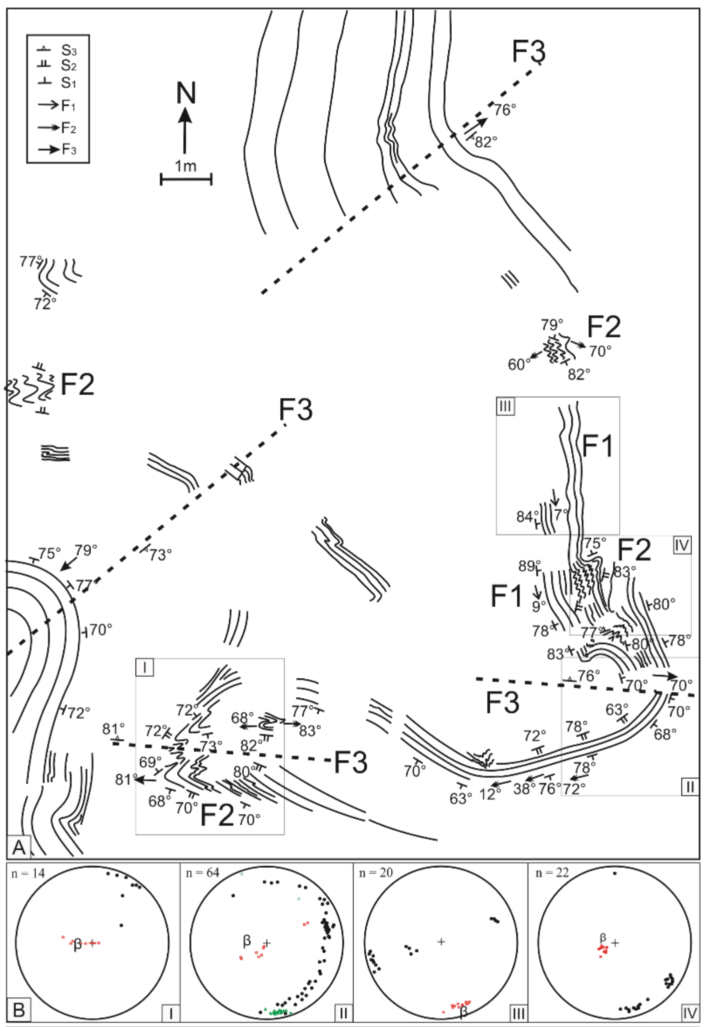

FIG 8: (A) Detail map of the study area showing the disposition of three generation folds, where last fold (F_3) rotate the early fold (F_2) and placed it westerly in some locations. (B) Stereographic projections of the marked places. Black dots are the poles of foliation, red dots are the fold axis and green dots are the pucker axis (L_2 lineation).

Conclusion

In the present study, detailed structural studies and detailed mappings of two locations are carried out to interpret the westerly closing folds (later fold) that were observed from the rocks of the Todgarh formation of SDFB. This study identifies three generations of folds (F1, F2 and F3) from the studied area.

F1 is the early tight isoclinal folds on the compositional banding with a sub-horizontal fold axis. F2 folds are close to tight with variable plunges. The F2 folds are plane, non-cylindrical folds. The interference pattern of F1 and F2 folds at places shows a hook-shaped outcrop. The F3 folds are open folds and caused random rotation of the early F1 and F2 folds (Fig 8). In the domains where F1 and F2 folds are unaffected by later F3 folds, they show the general orientation of SDFB, i.e. northeast-southwest. This indicates that F1 & F2 folds are formed in an NW-SE compression regime. The F3 folds are conjugate in nature, with two orientations of the axial planes inclined towards each other. Measurements of axial planes of the conjugate folds are employed to deduce the stress axis of the strain ellipsoid. The calculated maximum compression direction for the F3 folds is also in the NW-SE direction. Our work shows that the stress direction for F1, F2 and F3 are broadly similar and thus suggested to form under the similar compressive regime. The present study suggests that the reorientation of the F2 fold forms the westerly closing folds due to later F3 folds.

Acknowledgment

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