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Deformation Episodes in Iron Formation of Eastern Province of North Odisha Iron Ore Craton, Eastern India

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Abstract

Banded Iron Formation (BIF), a bi-component rock of the Precambrian period is exposed along with iron ore in distinct geographical entities encircling the North Odisha Iron Ore Craton (NOIOC) in Odisha – Jharkhand states, eastern India. Iron formation of the eastern province is confined to Badampahar-Gorumahisani-Sulaipat belt. The litho assemblages belonging to this Iron Ore Group comprise of banded cherty quartzite, banded magnetite quartzite, banded magnetite grunerite quartzite, tremolite-actinolite schist and fuchsite quartzite. Deformations in phases affected the BIF members and associated rocks of the area resulting in successive fold structures. The first generation folds (F_1) are characteristically tight and isoclinal having NE plunging axes. The second phase fold (F_2) structures in the area with reference to first fold are co-axial, upright and tight to open in nature profusely overprinting the F_1 folds are parallel to the general trend (NE-SW) of the belt. Axial plane of the third phase folds (F_3) are gentle and broad warps having NW-SE trending axial planes and are found to be the last traceable ones in the area. trending in NW-SE direction are found to be the last traceable ones in the area having gentle and broad warps. The co-axial F_1 and F_2 folds along the general trend (NE-SW) of the belt are superposed by NW-SE trending F_3 fold, which exhibits a geometric configuration as F_1 // F_2 F_3. Such type of multiphase deformed terrain has produced many interference fold patterns in minor scale out of superposition *i.e.* dome and basin structures, hook shaped patterns, eyed fold and S, Z, and M shaped folds. The paper discusses the episodes of structural events and their signatures in the interference fold patterns in the eastern province of the NOIOC.

Keywords: Banded Iron Formation, Badampahar-Gorumahisani-Sulaipat Belt, Deformation Episodes, NOIOC

Introduction

The North Odisha Iron Ore Craton (NOIOC) of Odisha-Jharkhand states is a noted iron formation terrain in eastern India. Among the three major iron deposits encircling the North Orissa Iron Ore Craton (NOIOC) (Beura and Singh, 2005; Beura, 2007; Beura *et al.,* 2016; Nanda and Beura, 2021; Fig.1), the eastern province occurs at the Badampahar-Gorumahisani-Sulaipat (BGS) sector of Odisha and Jharkhand states. The BGS belt remains in a north-south direction where Sulaipat is sandwiched between Gorumahisani and Badampahar in north and south directions, respectively. The litho-units comprise of Banded Iron Formation (BIF) and associated rocks with varying degrees of metamorphism. The southern end of the belt diverges at Badampahar and gently truncated to the northwest in the north at Gorumahisani. The belt constitutes a representative horizon for the Archaean schist belt for having typical structural signatures.

The structural patterns in the iron formation of the eastern province of the NOIOC are abundant and quite interesting, which are hardly seen elsewhere in the Iron Ore Super Group (IOSG) of Odisha. Badampahar sector of the BGS belt is an anticlinal terrain (Chakraborty, 1958) comprising abundant incipient structural signatures on the lithobodies (Mukhopadhyay, 1968). Sarkar and Saha (1983) reported that there exist two synforms that accommodate an antiform within them. They have indicated BB' tectonites for the structural framework of the area where a set of N-NNE trending fold axes are folded with a high plunge. However, according to Ghosh (1986) the structure of the area comprises a series of antiforms and synforms. Low plunging early phase folds, which are refolded mesoscopically about steeply plunging axes represent mostly B-B' tectonites (Chakraborty and Majumder, 1986).

The entire belt is considered as a single basin deposit with local disparity in depositional environment signifying a varying accommodation of lithofacies, litho-association, metamorphism and structural intricacy. The basin of deposition has been originated due to spreading and extension along the margin of the cratonic massif subsequently led to thinning and on further extension resulted in rifting (Beura, 2014; Beura, 2015). In the event of post rifting grabenisation, depository basin was formed and received the iron materials from different sources. The basin also received volcanics of mafic to acid-intermediate composition, volcani-clastics and chemical precipitates.

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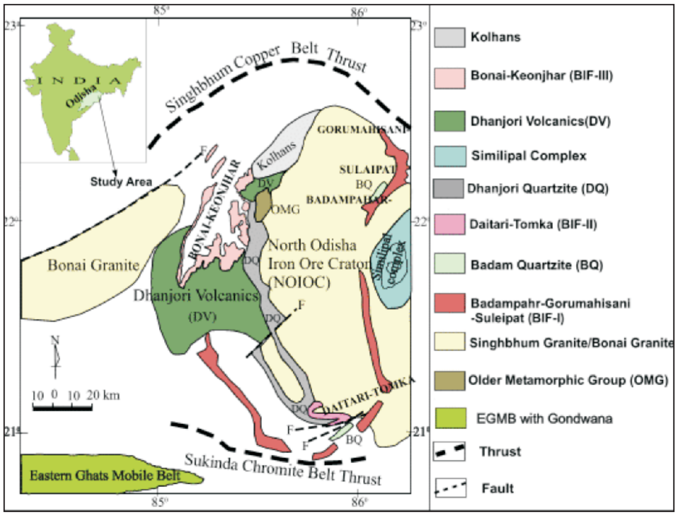

Fig.1. Regional geological setting of North Orissa Iron Ore Craton (NOIOC) (*Modified after*, Beura *et al.,* 2016).

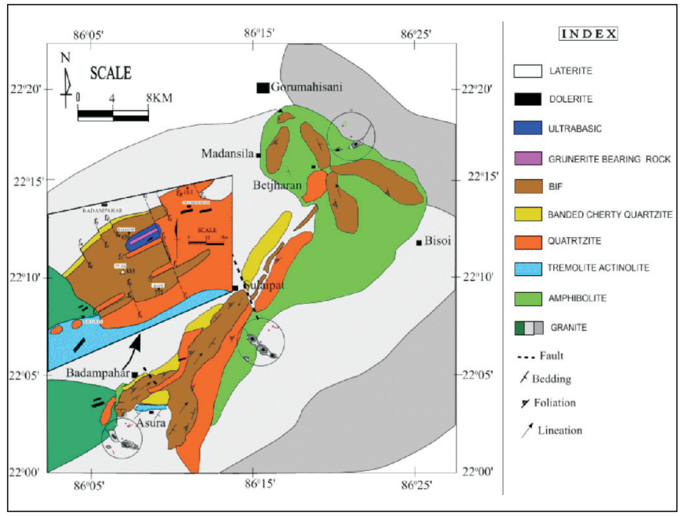

Fig.2. Geological map of Badampahar-Gorumahisani-Sulaipat belt (*Modified after*, Beura, 2015)

In the post tectonic period, the litho-assemblages are subjected to several episodes of folding and faulting. The general trends of litho-unit are mainly aligned along NE-SW direction. The basin structure is affected mainly by continuous transverse faults and thrusts followed by numerous concordant to sub-concordant boundary faults.

Geology

The eastern periphery of the North Orissa Iron Ore Craton (NOIOC) represented by Badampahar-Gorumahisani-Sulaipat (BGS) province remains as a key horizon comprising Banded Iron Formation (BIF) and iron ores as major economic litho-parts (Fig.2). The BGS province is an arcuate belt that extends from Badampahar to Gorumahisani through Sulaipat. Singhbhum granite complex along with enclaves of Older Metamorphic Group (OMG) and Older Metamorphic Tonalite Gneiss (OMTG) forms the cratonic mass (Hofmann *et al.,* 2022). The granite bodies around the basin margin have got their nomenclature differently according to their characters and field relations.

The supracrustal assemblages of the basin consist of Banded Magnetite Quartzite (BMQ), Banded Magnetite Grunerite Quartzite (BMGQ) and Banded Cherty Quartzite (BCQ) intruded by younger dolerite dykes and ultrabasics. The lithosome of the BGS belt is considered as the oldest Iron Ore Group in the region and is termed as BIF-I (Acharya, 1984; Acharya, 2000). There are some exposures of basement rock belonging to OMG, which include amphibolites, tremolite-actinolite schist and granite (Singhbhum granite). The basin deposits are disposed into a series of anticlines and synclines by iron ore orogeny that runs parallel in NE-SW in Badampahar and Sulaipat sector but losses symmetry in the Gorumahisani sector (Fig.2). The lithosomes attaining to medium-grade metamorphism have been folded and faulted several times in accordance with multiple phases of deformation (Beura *et al.,* 2016). Sedimentary signatures in the litho-assemblages are mostly modified by diagenetic and metamorphic processes. Some iron formations of later appearance owe to the igneous origin and maintain the intrusive character with the rocks particularly in the Sulaipat sector.

The rocks are characterized by well developed bands, small-scale folds, faults and certain non-diastrophic structures such as pinch-and-swell, scour and fill *etc.* that indicate primary sedimentary origin. Complexity in folding and faulting of rocks are well observed in superposed structures at many localities.

Structures

The structure of the area encompasses quite enduring platform for assigning it as a separate depositional block in the IOSG of Odisha. The structural configuration of the belt along with the structural features carries strong validation in studying various aspects of the belt like basin development, mineral evolution, metamorphism and ore formation etc.

The BGS belt has undergone several episodes of deformation subsequent to tectonic event and basin development (Beura, 2014; Fig.3). The earliest folds are characteristically tight to isoclinal with a high amplitude/wavelength ratio, which are categorized as first generation folds (F_1) (Fig.4A). Axial planes of F_1 folds are steeply dipped (70°-80°) towards NW with strike varying from NE-SW to NNE-SSW direction. So far as the geometry is concerned the F_1 folds are tight to isoclinal, reclined, and disharmonic in styles.

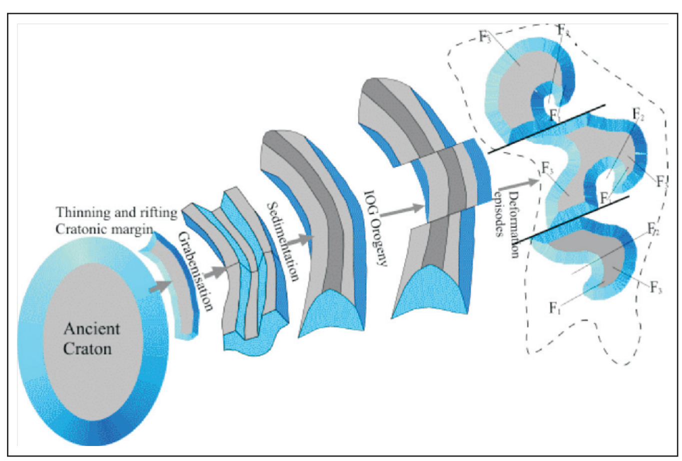

Fig.3. Schematic diagram showing tectonic event and basin development of the BGS belt

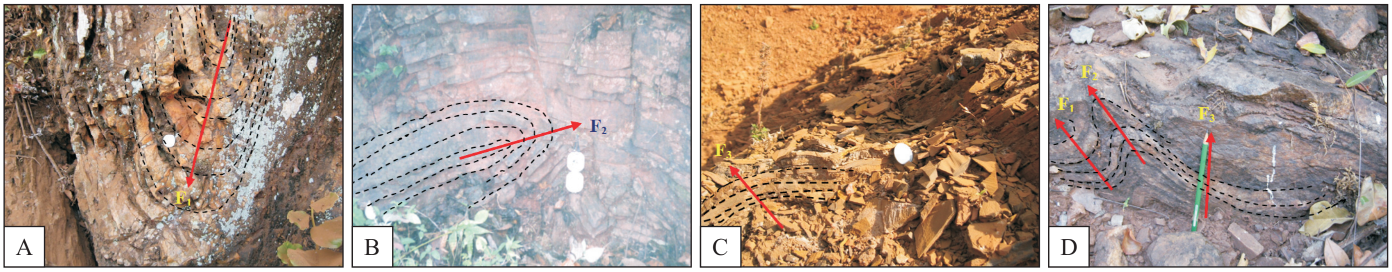

Fig.4. (A) Tight to isoclinal F_1 fold structures with thick hinge and thin limbs, (B) Tight, recumbent F_2 fold structures, (C) Broad and open F_3 fold structures, (D) F_1, F_2 and F_3 fold structures occur together

Kinematically buckling initiated the F_1 folds and was modified later by superposition of homogenous strain, which produced successive deformations. Parasitic folds are commonly found in the hinge zones of the major folds. Extremely thickened hinge and thin limbs of F_1 folds show resemblance with the flattened similar folds of Ramsay (Class 1C) (Ramsay, 1967).

The second-generation folds (F_2) are mostly upright with tight to open geometry. At some places, isoclinal and recumbent folds owe to their origin in the second phase deformation episode (Fig.4B). F_2 is a predominant structure that controls the regional outcrop pattern. The axial planes of F_2 folds have strikes ranging from NNE-SSW to ENE-WSW and dip (80º to 85º) towards NW. Often they possess plunging value of moderate to high angle (20^o-40^o) towards NE. The transformation of the early isoclinal folded (F_1) into F_2 folds during second phase deformation gives rise to a larger wavelength in second folds compared to F_1 folds. The third generation of folds (F_3) appears on the limbs of earlier first and second generation folds in form of a broad and open fold (Fig.4C) with distinctive broad warp. The NW-SE striking axial planes (S_4) of F_3 folds have a steep dip towards NE. F_3 folds plunge (30^o-55^o) towards NW. At some places around the Badampahar area all the three fold episodes are found to appear together in the same rock unit (Fig.4D).

The axial plane cleavages (S_2) of first folds are pervasive in nature on stratification (S_1) holding the linear structures (L_1). F_1 folds being characteristically isoclinal, the axial plane schistosity (S_2) so developed stands parallel to the S_1 (S_2//S_1) but remains at a right angle to S_1 (S_2S_1) at the hinges (Fig.5A). F_1 folds in BIF comprising multiple layers of different competency shows fanning and refraction of S_2. The axial planes of the F_1 folds (S_2) along with S_1 stratification have been involved in coaxial upright folding (F_2). F_2 folds on S_2 develop convergent axial plane (S_3) and linear structures (L_2) (Fig.5B). NE-SW compressive stress on F_2 folds has produced the axial plane schistosity (S_4) corresponding to F_3 folds, which are manifested by parallel fractures along NW direction (Fig.5C). Linear structures (L_3) corresponding to F_3 are developed due to the intersection of S_4 with S_1, S_2 and S_3 (Fig.5D).

The π and β diagrams of stratification (S_1), axial plane schistosity (S_2, S_3 and S_4) in the synoptic diagrams of the whole area show the orientations and variations of lineations (Fig.5E). The

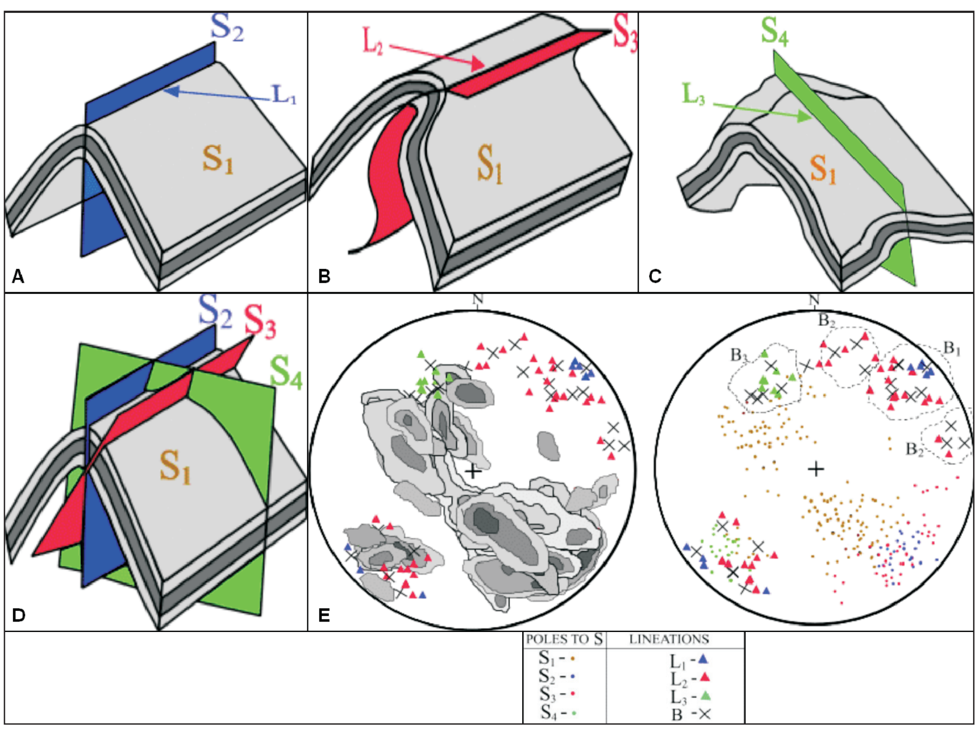

Fig.5. (A) S_1- stratification, S_2-first phase axial plane schistosity, (B) S_3-second phase axial plane schistosity, (C) S_4-third phase axial plane schistosity, (D) S_2, S_3 and S_4 axial plane schistosity on S_1, (E) orientations of axial planes and linear structures from the whole area are presented in synoptic stereograms

major fold axis βS_1 is paralleled by the folds in outcrop and intersection of S_1 and S_2/S_3. Axial plane schistosity (S_3) of second fold (F_2) generally show a small spread, but βS_2 almost always coincides with βS_1 showing that the fanning of axial planes of folds (F_2) are coaxial with the first fold (F_1) on stratification (S_1) (Beura, 2015). There is homogeneity of minor folds on stratification in the mesoscopic scale as well as with the outcrop scale in the study area. The presence of cross girdles in the stereogram with axes of folds (F_1, F_2 and F_3) indicates the occurrence of superposed folds in the study area.

The fold structures of three generations have been imprinted and superposed among themselves to generate various interference patterns. The interference between F_1, F_2 are prevalent in the area where second phase folds are overriding ones that modify the first phase fold (F_1). As a result, the first folds are often undetected in the original outcrop pattern, which has been distorted to a complex one in a superposed environment. The third phases of folds (F_3) have been developed over the earlier F_1 and F_2 without changing their fundamental structural characteristics.

Interference patterns are developed in the belt at best by three possible combinations of three phases of folds like F_1XF_2, F_1XF_3 and F_2XF_3 (Beura and Singh, 2005; Beura, 2015). Typical hook-shaped fold structures having curved axial planes with double closures (Type 3 of Ramsay) are produced by the interference of F_2 folds on F_1 folds (Ramsay, 1967) (Fig.6A). In some hook folds at places, F_1 folds are turned into recumbent or reclined types at the hinges of the F_2 folds. Overprinting of open and steeply inclined F_3 folds with NW striking axial planes upon NE tending isoclinal F_1 folds could give rise to mirror image pattern (Type 2 of Ramsay) (Ramsay, 1967) (Fig.6B). The geometry of F_1 fold shows mirror symmetry about the axial trace of the F_3 fold. Among two sets of first fold on both side of the third fold axial trace, one set fold of first structure is oblique in nature while another set of folds appears with plunges opposite to the first set, which produce mirror image structure. Doubly plunging antiforms and synforms produced by superposition of F_3 on $F_1$and F_2 characteristically gives rise to eyed folds and dome-and-basin structures (Type 1 Ramsay, 1967; Fig.6C). These folds are formed as a result of strong later compression of earlier folds having initial non-rectilinear axes (Mukhopadhyay and Sengupta, 1979). Superposition of two phases of folds i.e. F_3 on F_1 folds develops eyed structures on S_2 cleavage giving a scope to the sub horizontal axial planes of the F_1 folds to be modified by F_3 folds (Beura and Singh, 2009). The eyes having long and short diagonals are parallel to the F_1 and F_3 axial traces respectively. The superposition of F_3 on $F_1$and F_2 folds {F_3XF_1, F_3XF_2, F_3X (F_1XF_2)} (Beura and Singh, 2009) is instrumental in producing an interference pattern of three dimensional structures dome and basin structures (Type 1 of Ramsay) (Ramsay, 1967) with variable styles. Domes and basins are developed as a result of shortening of fold axes along two perpendicular directions in a constrictional type of strain (Mukhopadhyay *et al.,* 1997).

Generation wise rock deformations in the belt have produced many minor fold structures comprising various shapes like M, Z or S patterns (Fig.6 D, E and F). These minor folds are formed both on the limbs and hinge of the main folds based on their orientation on limbs and hinge zones. This multiple folded terrain undergoing interference activities develop varieties of such shape combinations (Ramsay, 1967). The geometrical principles of superposed folding are such that the axes of latter folds are guided by the intersection of early axial planes with the form surface at any point (Naha, 1983).

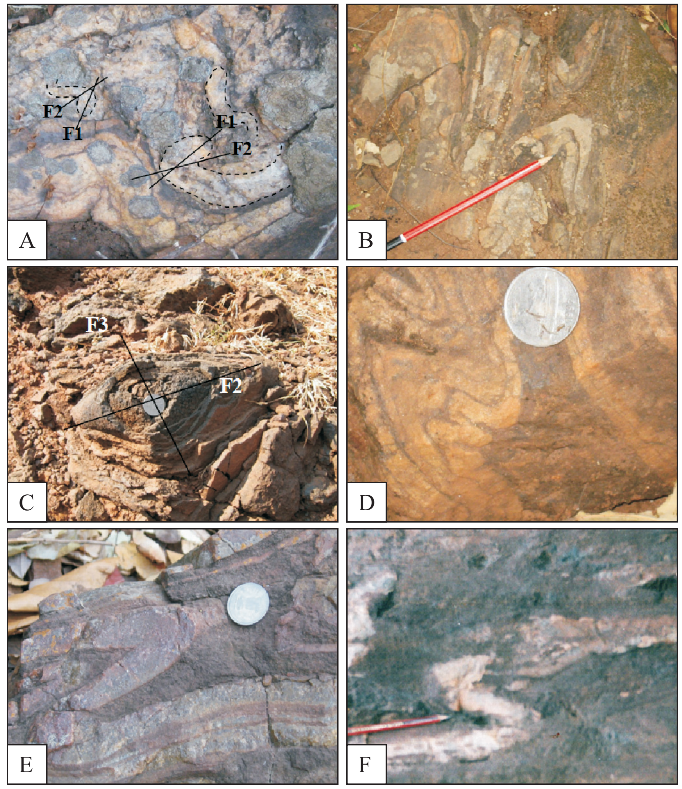

Fig.6. (A) Hook-shaped pattern due to F_1 and F_2 interference in quartzite, (B) Mirror image interference pattern in quartzite due to over printing of open F_3 folding on isoclinal F_1 folds (Ramsay,1962), (C) Eyed fold structure, (D) 'M' shape minor fold, (E) 'Z' shape minor fold, (F) 'S' shape minor fold

Conclusions

The BIF and other litho-types of the eastern province of NOIOC constituting mainly the Badampahar-Gorumahisani-Sulaipat belt belong to the Archaean Schist belt, which has experienced complex structural events. The belt has been aligned along the axial direction of the anticlines and synclines that indicate the regional trend. The NE-SW trend of the belt, though maintained throughout the region, has been changed in the southeast of Gorumahisani where the surface expression of the third fold attests to the structural signature. It represents the axial plane in NW direction. Though the same thing happens in many localities of the belt the general trend is maintained in concurrence with the dominating second fold axial plane. The rocks are intricately folded and faulted and metamorphosed mainly to lower amphibolite facies. At least three phases of folding episodes have been delineated in the province. The planar and linear structural elements and fold geometry indicate that the first fold (F_1) is tight, isoclinal and reclined; second fold (F_2) is tight to open and isoclinal and third fold (F_3) is broad and open in nature. F_2 deformation is abundant and dominant in the whole region signifying its control over the regional structural configuration. Interference patterns are produced due to the superimposition of F_2 over F_1 and F_3 over F_1 and F_2 as F_1, F_2 and F_3 folds are in a sequence from early to late.

Authors' Contributions

D. Beura: Conceptualization, Visualization, Software, Investigation, Supervision, Reviewing and Editing. **S.K. Nanda**:

Investigation, Writing- Original Draft Preparation, Reviewing and Editing. **A. Parida:** Investigation, Formal Analysis, Validation and Writing- Original Draft and Editing. **L. Pattanayak**: Investigation, Methodology and Formal analysis.

Conflict of Interest

Authors declare no conflict of Interest.

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