Journal of Geology & Geophysics
ISSN: 2381-8719

Sahoo and Das, J Geol Geophys 2015, 4:5
DOI: 10.4172/2381-8719.1000222

Research Article Open Access

Lithofacies Superimposition in a Shallow Basin - Interplay of Tectonics and Sedimentation: Evidences from Kolhan Basin, Eastern India

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Abstract

The 2.2-2.1 Ga pear shaped Kolhan basin show the development of a time transgressive group in a half-graben setting developed during the fragmentation of the Rodinia supercontinent. The overall style of sedimentation reflect a switchover from low-sinuous avulsed channels developed within a braided-fluvial-ephemeral streams to a lacustrine fan-delta complex during the later part of the sedimentation history.

The fan-delta facies indicate sediment dispersal by hyperconcentrated flows in the form of sheetfloods and channelized flows. These different-scale cycles are interpreted as the sedimentary response to pulses of deformation of the basin margin at variable frequencies, related to the contemporary thrusts (ca. 20 km away from the basin). The episodes of tectonism downwarped the basin margin sediments and made the basin shift periodically toward the margin, and created progressive lithological changes in the sedimentary succession. The immediate effects of a tectonic pulse included lake transgression and accentuation of the structural hinge of the basin margin, causing a decline of sediment supply from the source rock. As the basin margin was subsequently reduced by denudation, the fans prograded and fan deltas were formed in normal conditions of graben subsidence. The sediment geometries and the climate exerted a major control on the processes of sediment transfer.

Our results show that the fluvio-lacustrine strata show on lap-pinch out relationship at the centre of the basin but only on lap relationship along the lateral edges. This transition can be best explained by the fault growth models.

Keywords: Lithofacies; Tectonics; Kolhan basin

Introduction

Lacustrine fan deltas are lake margin depositional systems that occur in a wide range of tectonic settings, but their facies assemblages and stratigraphic architecture vary, depending primarily on the basin margin tectonic regime and sediment dispersal processes, which account for the climatic and catchment conditions [1]. Whereas, interpretation of provenance from sediment compositional data requires consideration of controlling factors such as transport distance, time, energy, and climate of the basin [2]. Composition of detrital sediments is controlled by various factors, including source rocks, modes of transportation, depositional environments, climate, and diagenesis [3]. This paper attempts to briefly contrast the salient characteristics of Proterozoic clastic sedimentation with an attempt on some aspects of the lithofacies study and paleotectonics of Kolhans in the Chaibasa- Noamundi basin.

The Kolhans were deposited in the intracratonic basins that developed within the Singhbhum-Orissa Iron Ore carton and are preserved as isolated outliers that spread over four detached basins – Chaibasa- Noamundi basin (type area), Chamkapur-Keonjhar basin, Mankarchua basin and Sarapalli-Kamakhyanagar basin. After the close of the Iron Ore Orogeny, there was a phase of extension. During this phase, the eastern side of the Iron Ore synclinorium was faulted giving rise to a halfgraben structure. Within this half-graben, fluviolacustrine sedimentation took place. Because of the continued tectonic instability the Kolhan basin was transversely segmented into four smaller sub basins by en-echelon fault systems. After the separation of the basins, sedimentation in each individual basin took place in their own way. The overall style of sedimentation reflects a change from braided fluvial ephemeral pattern to a lacustrine fan delta type. The sediment geometries and the climate exerted a major control on the processes of sediment transfer. Repeated fault controlled uplift of the source followed by subsidence and regression, generated multiple sediment cyclicity that led to the fluvio lacustrine- fan delta sedimentation pattern. The Kolhans represent more than a single phase of deposition and the internal erosion surfaces are indicative of channel avulsions. The Kolhan sandstones and shales of the Orissa-Jharkhand state can be described by a time-transgressive lithofacies model consisting of an earlier braided stream-channel levee complex subsequently superimposed by a fan delta complex**.** The field and sedimentological evidences show the paleobathymetry, the depositional history and the time-transgressive nature of the lithofacies assemblage.

The concept of geochemical proxies of mineral alteration (i.e., weathering indices) relies on the selective removal of soluble and mobile elements from a weathering profile compared to the relative enrichment of rather immobile and non-soluble elements. The advantage of using Chemical Index of Alteration (CIA) to estimate paleoweathering in paleoenvironmental studies has proved valuable. The CIA has been extensively used for understanding the continental weathering and denudation studying the variability of the CIA determined for the mean suspended solids load of large world rivers [4]. Many authors made an interesting comparison between weathering intensity, concluding that CIA values reflect more aggressive chemical weathering during Proterozoic basins since less sediment residence

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Received August 13, 2015; **Accepted** September 25, 2015; **Published** September 30, 2015

Citation: Sahoo SR, Das S (2015) Lithofacies Superimposition in a Shallow Basin - Interplay of Tectonics and Sedimentation: Evidences from Kolhan Basin, Eastern India. J Geol Geophys 4: 222. doi:10.4172/2381-8719.1000222

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times due to the absence of vegetation cover and therefore faster transport time. The CIA actually reflects changes in the proportion of feldspar and various clay minerals in the weathering product [5]. As a consequence, CIA values of about 45-55 indicate virtually no weathering, whereas the value of 100 indicates intense weathering with complete removal of alkali and alkaline earth elements [4].

The present study demonstrates the field observations for lithofacies analyses, sandstone petrography and shale geochemistry to explain the tectonics and sedimentation interplay in Kolhan basin.

Geological setting

The Proterozoic Kolhan Group is the youngest unit in the Pre-Cambrian Singhbhum–Iron Ore stratigraphy. The Kolhans were deposited in the intracratonic basins that developed within the Singbhum-Orissa Iron Ore craton. The Kolhans unconformably overlie the Singhbum granite at the eastern margin and shows a faulted contact with Iron Ore Group of rocks at the western margin [6] (Figure 1). The Kolhans are shale dominated succession, and consists of northeast trending and gently westerly dipping, unmetamorphosed and undeformed strata of conglomerate and sandstones at the base overlain by extensive occurrences of shale with lenticular patches of limestone. The strata encompass dome and basin structure in westward part and show low dip near Singhbhum granite. Tectonically the Kolhan basin represents an epicontinental type with a NNE-SSW alignment, controlled by the similar trend of the Iron Ore Group. It is remarkable however that major part of the Kolhans does not show any appreciable effect of the younger Singhbhum Orogeny (905-934 Ma) [7]. This is probably partly due to the distance of these rocks from the Singhbhum shear zone and partly due to the blanketing effect of the basement granite which acted as a shield to absorb the southwards directed tectonic movements.

Methods of Study

Field work has been carried out to study different lithounits exposed along the road cutting, railway cutting and river cutting sections. On the basis of dominant structures, texture and lithology various lithofacies have been identified. Lithologs were prepared on the basis of sedimentary structures, textures and grain size taken from 18 different locations viz. Gangabasa, ITI College (two sections), Rajanka, Gumuagara, Kamarhatu, Singpokharia, Arjunbasa, Tunglei, Gutuhatu, Bringtopang, Bistampur, Dyliamarcha, Matgamburu, Rajanka, ITI hill top, Surjabasa (Figure 2). There are five diagnostic characters of sedimentary facies namely, geometry, lithology (grain size), sedimentary structures, paleocurrent patterns and fossils [8,9]. Based on these parameters, six lithofacies have been established for the sandstone of Kolhan Group. Detailed petrographic studies of 105 sandstones samples were done for modal composition and a variety of other petrographical features. For each thin section 300 points were counted using the Gazzi-Dickinson method [8]. Shale samples were analyzed for major oxides by using XRF (X-ray Fluorescence Spectrometer).

Facies description

Lithofacies study has been done following standard litholog technique [9]. Eighteen different vertical sections prepared from different locations in and around Chaibasa-Noamundi basin show the coarsening to fining upward sequence from conglomerate, sandstone and shale resting unconformably on the Singhbhum Granite (Figure 2). The identified six lithofacies for the sandstone of Kolhan Group are (a) granular lag facies (GLA), (b) granular sandstone facies (GSD), (c) sheet sandstone facies (SSD), (d) plane laminated sandstone facies (PLSD), (e) rippled sandstone facies (RSD) and (f) thinly laminated siltstone-sandstone facies (TLSD). Primary sedimentary structures of varied scale and geometries recognized in the Kolhan sediments are trough cross bedding, symmetrical ripple, planar cross bedding, hummocky cross bedding, and graded bedding. Among the reported structures, the structures generated by flat beds are comparatively more noticeable than the structures related to the bedform migration. The layer thickness variation within the eighteen lithologs is non-uniform and shows asymmetricity (systematic thinning or thickening-upwards) with general thickening upward pattern which represents sand bar/ delta mouth bar deposits.

The GLA facies is characterized by the occurrence of laterally impersistent, massive, ungraded, fine matrix supported conglomerate which is oligomict in character towards south and polymictic towards north. These conglomerates are mostly immature to sub-mature, and quite similar to the overlying sandstone. (Figure 3a-b). GSD facies is characterized by moderately to well sorting, moderate clast : matrix ratio, textural bimodality and development of normal grading with fining upward sequence. Planar cross-stratification is more commonly found as compared to trough cross- stratification (Figure 3c-d). The SSD facies is defined by sheets of subarkose-quartz arenite, sometimes intercalated with thin laminated siltstone with profuse development of planar cross bedding, and locally developed herringbone cross-bedding (Figure 3e-f). The PLSD facies is defined by thick amalgamated well sorted subarkose-quartz arenite, with a moderate-high grain: matrix ratio. The sandstone is medium to fine grained. The prominent structures are planar cross bedding, asymmetrical ripple (ripple laminations) (Figure 3g-h). The RSD facies is defined by predominance of packages of rippled sandstone with prolific development of both

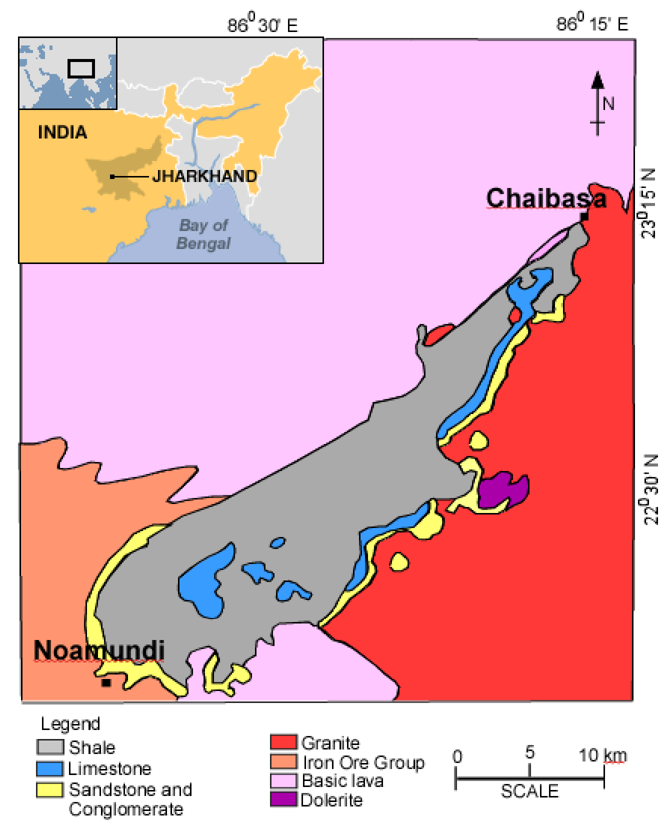

Figure 1: Geological Map of Chaibasa-Noamundi basin [4].

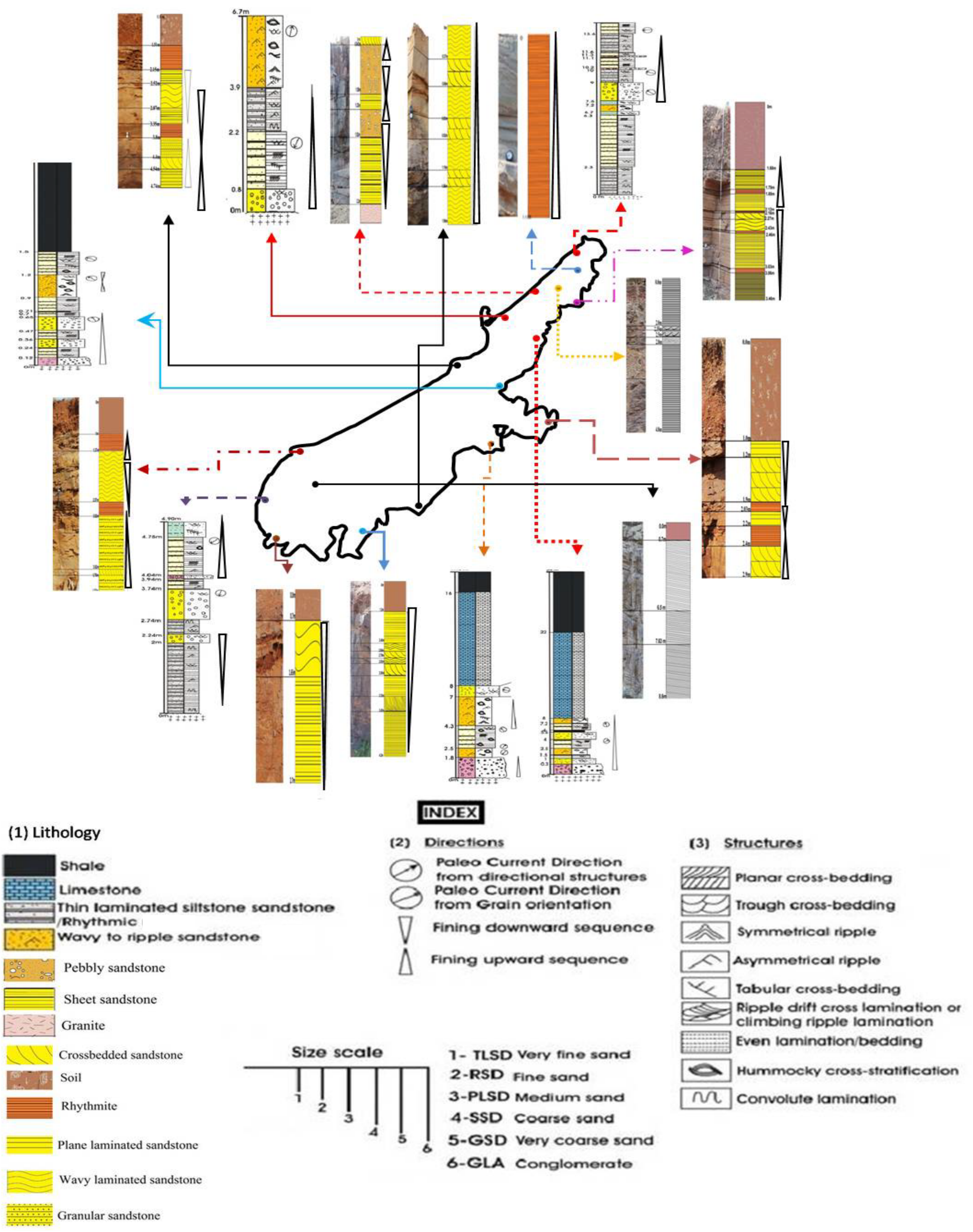

Figure 2: Sampling locales for seventeen vertical sections.

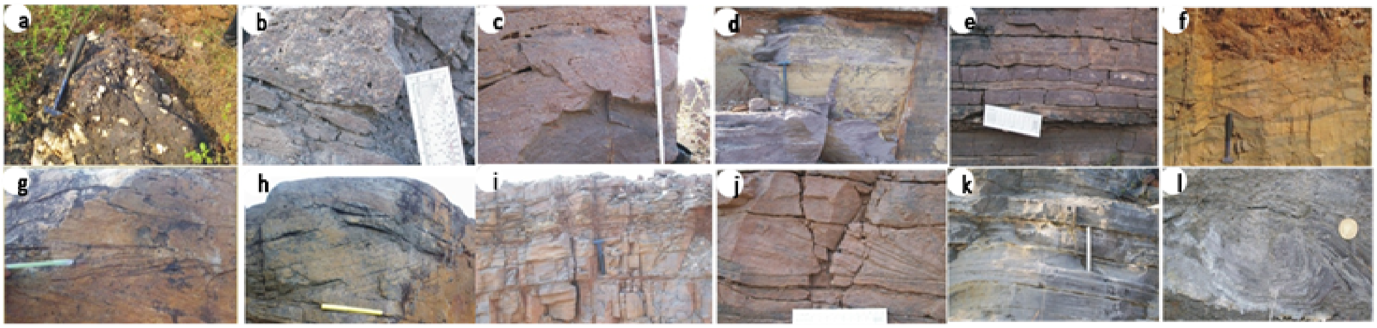

Figure 3: (a) GLA facies: Conglomerate with angular pebbles of quartzite and jasper around Matgamburu (Hammer 15 cm for scale). (b) Extraformational conglomerate, Bistampur (Scale-15 cm). (c) GSD facies: Pebbly sandstone at Matgamburu (Scale –measuring tape, 40 cm) visible. (d) Granular sandstone at Rajanbasa (Scale –Hammer, 15 cm for scale). (e) SSD facies: Sheet likes structures in sandstone at Matgamburu (15 cm scale). (f) Planar cross-bedding in sheet sandstone at Matgamburu (Scale –Hammer, 15 cm for scale). (g) PLSD facies at Deoposi river. Pen 12 cm for scale. (h) Planar cross-bedding in PLSD facies at Deoposi river. Pen 12 cm for scale. (i) RSD facies: Assymetric ripple marks Bistampur. Scale 15 cm. (j) Cross bedded unit with multiple toe scour like structure in RSD. Pen 12 cm for scale. (k) TLSD facies: Rhythmic sandstone. Bistampur. Ruler 30 cm for scale. (l) Convolute lamination in rhythmic sandstone, Bistampur. Coin diameter 2.50 cm.

symmetrical and asymmetrical ripples. It is very commonly associated with thinly laminated sandstone facies and plane laminated sandstone facies (Figure 3i-j). TLSD facies is defined by the rhythmic alternation of sandstone and shale units, in which sandy layers are thicker than shale layers. Prominent structures are convolute lamination, trough cross-bedding and asymmetrical ripples (Figure 3k-l).

Petrological characters

The Kolhan sandstones are composed mainly of an aggregate of sub-angular to sub-rounded quartz embedded in siliceous-ferruginous matrix, with subordinate amounts of feldspar, jasper, muscovite, rock fragments of BHJ, chert, phyllite, recycled pebbles of quartzite and conglomerate (Figure 4). Composition of granite pebbles in the conglomerates shows a close similarity with the basement suggest that such pebbles are recycled erosional products of the Singhbhum granite basement over which the conglomerates were deposited [10].

The sandstones are coarse-grained and show considerable compositional variability, ranging from quartz arenite to subarkose [11,12]. The quartz grains are mainly monocrystalline with weak or absent undulatory extinction. Polycrystalline quartz occurs in two varieties: (a) grains with a polygonal fabric of interlocking grains and (b) grains with elongate, lenticular, interlocking, sutured crystals (Figure 5a). The feldspars are K-feldspars, microcline, and albite-rich plagioclase (in descending order of abundance). K-feldspars are commonly clouded with alteration products and also show microperthitic intergrowth with Na-plagioclase. Matrix quartz shows feeble recrystallization and fused contacts with the framework grains (Figure 5b). Quartz grains show bimodal distribution in quartz arenite (Figure 5c). The feldspar grains show rounded inclusions of quartz (Figure 5d-f). Sedimentary rock fragments are intrabasinal, intraformational and extraformational. During point-counting all efforts were made to identify replaced feldspar grains and to record them as feldspars. Because of the considerable influence of feldspar alteration, orthoclase and plagioclase are not reported separately. Partial replacement of feldspars by calcite has been observed, but is less common. The feldspar content ranges from 1.46 to 13.54 %, and rock fragments (0.49 to 7.82 %) embedded in ferruginous-siliceous cement (0.00-7.97%) (Fig. 6F) and cherty-sericitic matrix (1.41-10.21%) are the main constituents of those rocks (Figure 6a-b). Figure 6c-d shows the sparking colour muscovite laths and Figure 6e shows the sericite matrix or reconstituted complex aggregates of chert and sericite matrix. As because the interest is more in the source area and the tectonic setting, only extrabasinal components have been considered.

Tectonic setting

Bivariate plot between Al_2O_3 and TiO_2 indicates the source rock to be granitic composition (Figure 7a). It has been shown for ancient as well as for modern mudstones that their SiO2 content and K_2O/Na_2O ratio can be used to discriminate between shales deposited in passive margin/cratonic, active margin, and island arc tectonic settings [13]. A prior knowledge on the tectonic setting of the Kolhans, a SiO_2 v. K_2O/Na_2O Figure 7b clearly show the plots of the Kolhan shales into the passive margin/cratonic field. In the K_2O vs.Na_2O plot, the Kolhan shale fall in quartz rich field suggestive of lithounits were deposited in plate interior either at stable continental margin or in the intracratonic basin [14] (Figure 7c). High SiO_2/Al_2O_3 and K_2O/Na_2O ratio of these shales imply their derivation from a granite dominated upper continental crust [4]. In the CaO-K_2O-Na_2O ternary plot the studied shale samples plot in passive margin field (Figure 7d) [15]. The rate of chemical weathering of source rock and the erosion rate of weathering profile are controlled by the prevailing climate, source rock composition and tectonics as well.

Paleoweathering-paleoclimate

A functional technique to assess the paleoweathering and tectonic history of the rock is the Chemical Index of Alteration (CIA)=$\{Al_2O_3/(Al_2O_3+CaO+Na_2O)\} \times 100$, to monitor the progressive alteration of plagioclase and K-feldspar to clay minerals [5]. CIA value increases with increasing weathering intensity, reaching 100 when all Ca, Na and K have been leached out from weathering residue. The CIA value for the Kolhan shale vary from 70.7 to 80.3, (average 75.2) indicating that the source rock underwent moderate to high degree of chemical weathering in humid tropical condition. The weathering intensity of sedimentary rock can be inferred from the concentration of Al_2O_3 and Na_2O [15]. In the discriminative diagram of Al_2O_3 and Na_2O, the plots are in the field of Amazon mud which indicates the high intensity of chemical weathering (feldspars have been altered to clay minerals) (Figure 7e). The weathering history of igneous rocks and the source for various clastic sedimentary sequences have been evaluated by using the A-CN-K ($A=Al_2O_3$; $CN=CaO+Na_2O$; $K=K_2O$) triangular diagram [5]. In A-CN-K plot Figure 7f; the compositional trends of various rocks during initial stage of weathering would be almost parallel to A-CN line from their respective fresh unweather points. These pathways

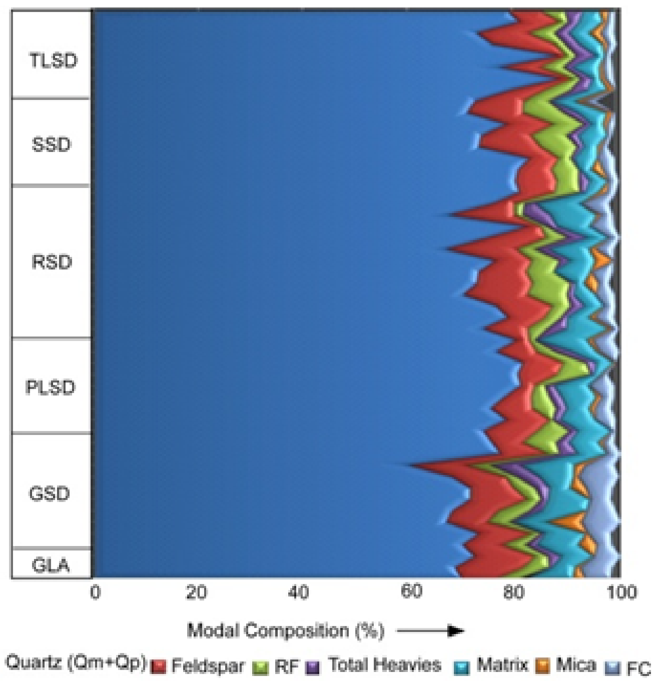

Figure 4: Variation of modal mineralogical composition of sandstone samples of six different lithofacies constitute quartz (60.37 % - 89.21 %), feldspars (1.46 - 13.54%), and rock fragments (0.49 to 7.82 %), embedded in ferruginous-siliceous cement (0.00-7.97%) and sericitic matrix (1.41-10.21%) of the Chibasa-Noamundi basin along a vertical profile.

of weathering for mafic and felsic igneous rocks are confirmed by weathering profile and thermodynamics/kinetic calculation [16]. The pathways are parallel to A-CN line because in the initial stage of weathering Na and Ca are removed from plagioclase and as the degree of weathering increases, K-feldspar are destroyed releasing K in preference to Al. During this process the residual bulk composition is enriched with Al_2O_3. All samples of Kolhan shale plot parallel and close to the Al_2O_3-K_2O boundary implying that their source area had undergone extensive weathering and produced shaly sedimentation. The A-CN-K triangular plots indicate potassium enrichments in the samples.

The CIA has been used to evaluate the intensity of weathering in the source area [16-18]. However, uncertainties exist because of possible post-depositional mobility of alkali and alkali earth elements. In near carbonate-free Kolhan shales, the CaO and Na_2O content should be always quite low. As because potassium probably experienced local redistribution (from detrital K-spar and K-mica to illite) during diagnosis, the CIA value of the Kolhan shale should only show minor post-depositional modification [19]. The average CIA value for the Kolhan shales is 75.2, suggesting moderate-to-intermediate chemical weathering [16].

Basin Model

The origin, characteristics, distribution and spatial arrangement of the various lithofacies, the predominance of stream flow over debris-flow deposits, the semi-radial, fan-like dispersion pattern of the paleocurrents, the associated subaerial and subaqueous depositional settings are indicative of a fan-delta system [20]. Aninterplay between several intrabasinal and extrabasinal controls probably determined the fan evolution. This is suggested by the occurrence of traction deposits, tectono-depositional intervals and their textural characteristics, and by the evidence of synsedimentary extensional tectonism. The shallow water settings are highly sensitive to subsidence, and the presence of fine-grained sedimentation above coarse-grained deposits in a tectonically controlled sedimentary succession is the best indicator of renewed tectonic activity. As the rifting processes compartmentalized the basin into fault blocks, and grabens were consequently separated, subsidence lowered the floor of these grabens below base level, and lakes were formed as an immediate response to tectonics (Figure 8). A large volume of sediment was then available for erosion due to the differential relief between the uplifted source area and the subsided basin, and the fan-delta systems began to prograde into the lakes. In some compartments of the basin, where the lakes were probably relatively deeper due to a greater subsidence rate, the initial clastic progradation took place through sandy flows, formed when heavily sediment-laden, sandy gravity flows or stream flows were introduced into the lakes.

Conclusion

Singhbhum granitoid terrain and Iron Ore Group may be the source for Kolhan sedimentation. Evidences of such nearby provenance are indicated by clast to matrix ratio, textural and mineralogical maturity of SSD, PLSD and RSD facies, association of fresh feldspar grains, angularity and poor sorting in case of GLA and GSD facies and sediment structure. A three dimensional conceptual model has been created to discuss the depositional environment in high energy coastal complex near the margin of the Late Precambrian Epeiric Sea. The fluvial action persists throughout the deposition of the siliciclastics as GLA and GSD facies. Tidal conditions are abruptly superimposed on fluvial deposits with greater probability of storm event in near shore environment due to marine transgression [21,22]. This is proved by the scouring or erosional surfaces with granule layers in SSD, PLSD and diffused nature of contact between RSD and TLSD, megaripples, reactivation surfaces and weak linkage between SSD, PLSD and RSD facies suggesting partial obliteration and redistribution of coarse to fine sands during high energy, upper regime plane bed flow condition [23]. Dominance of mud in silts of TLSD facies and presence of asymmetric ripple marks on the top reflects waning phase during the stormy period in a shallow-coastal marine zone. Moreover, marine energy regimes are variable all along the coast, changing from wave and storm dominated in northern and north-central portion to tide dominated in the south and south-west. The superimposition of retrograding shore-line features on earlier prograding humid alluvial fans sand flat complex may be developed.

The sandstone petrography and the shale geochemistry clearly indicate that the Kolhans had both IOG and Singhbhum granite as the source rocks. In sandstones derived from low-to moderate relief source areas under humid climatic conditions there may be a depletion of feldspars and rock fragments and enrichment in quartz. Whereas sandstone petrography suggests a peneplained craton, dry climate, and very limited chemical weathering, the shale geochemistry (CIA) indicates a moderate-to-intermediate degree of chemical weathering. The abundance of shale itself poses another problem as because it is commonly assumed that the mud formation is very limited under conditions that favour arkoses. Apart from the fact that the CIA as used to determine weathering intensity in the source areas of shales is in need of reassessment and refinement, the conflict climate signals between sandstones and shales of the Kolhans may also be inherent in the way sandstones and shales are produced. As pointed out above, unaltered feldspars and well-rounded quartz and feldspar grains in conjunction with low latitude suggest that the Kolhan Formation was deposited in a

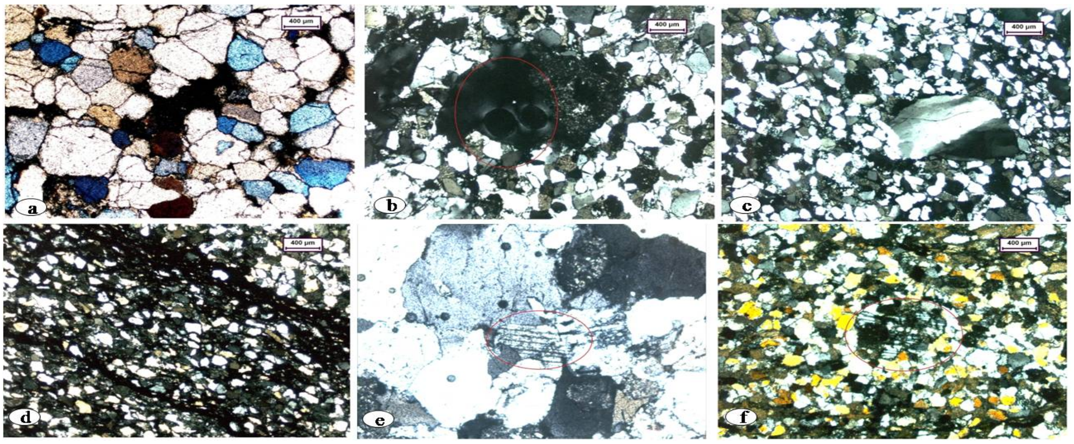

Figure 5: (a) Moderately well sorted, medium-coarse grained sandstone, well rounded quartz grains with long and concavo-convex contact. (b) Rounded to sub-rounded monocrystalline framework quartz grains in quartz arenite, Matrix quartz shows feeble recrystallization and fused contacts with framework grains. (c) Quartz grains showing bimodal distribution in quartz arenite. (d) Rhythmic sandstone thin section. (e & f) feldspar showing rounded grains.

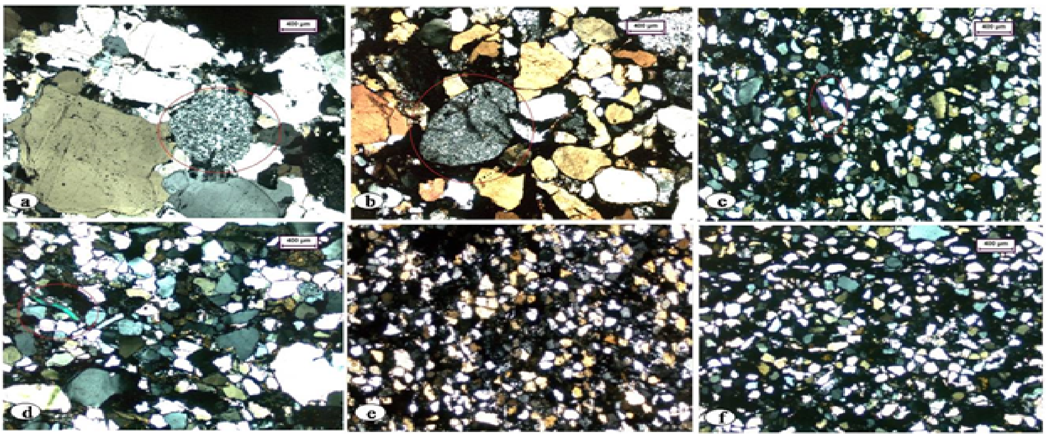

Figure 6: (a & b) Lithic fragment in sandstone shown inside red circle. (c & d) Sparking colour muscovite laths shown inside red circle. (e) Sericite matrix or reconstituted complex aggregates of chert and sericite matrix. (f) Silica and ferruginous cement.

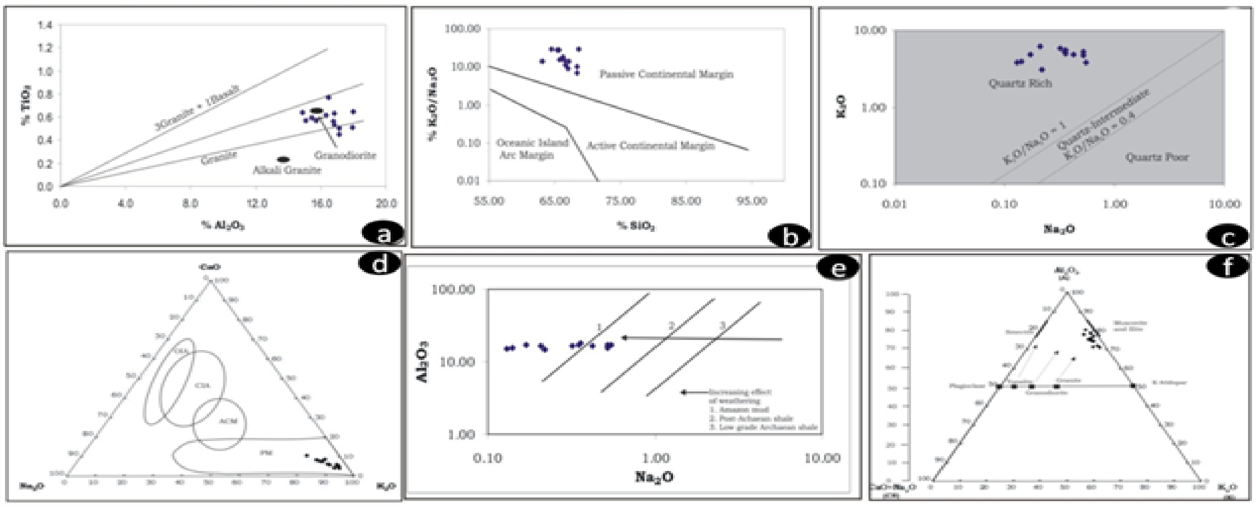

Figure 7: (a) Bivariate plot between Al_2O_3 and TiO_2 indicating the source rock to be granitic composition. (b) Tectonic discrimination diagram for the Kolhan shale indicating the passive margin setting. (c) K_2O-Na_2O diagram classifying Kolhan shale as quartz rich type [11]. (d) CaO-K_2O-Na_2O triangular diagram showing Kolhan shale in the passive margin (PM) field [13]; and also shown fields of different tectonic settings. CAN Active Continental Margin, OIA-Oceanic Island Arc, CIA-Continental Island Arc. (e) Discriminative diagram showing intensity of weathering [14]. (f) A-CN-K compositional space showing weathering trends for the Kolhan shale. The best fit line parallel to the A-CN join indicates the source to be granite to granitiod. CIA values have been represented in the vertical line the left of the A-CN-K compositional space

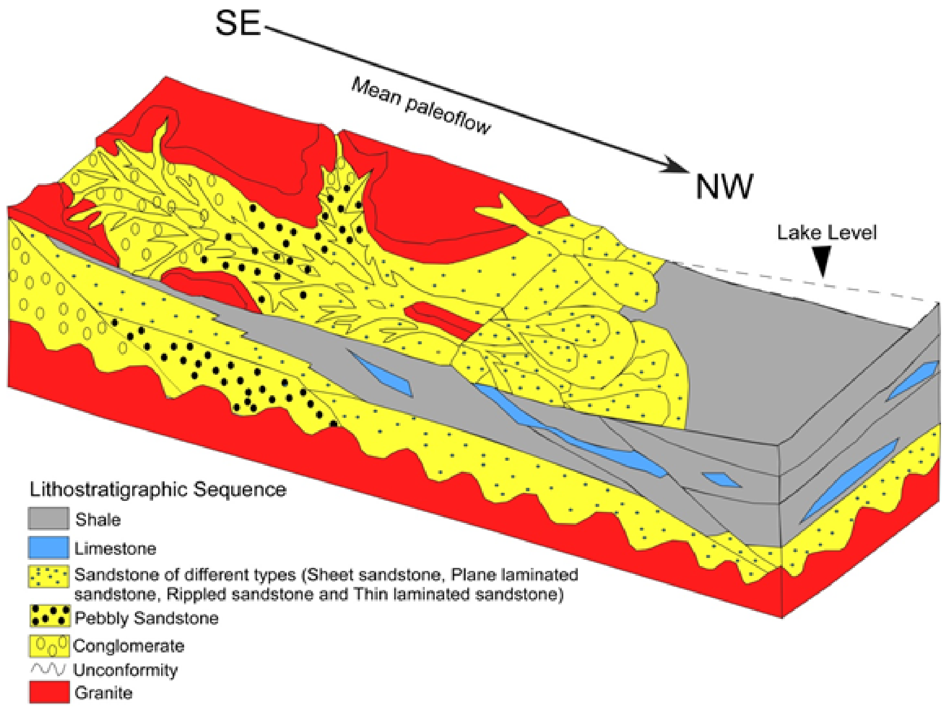

Figure 8: Block diagram to illustrate how erosion levels in the catchment area of the Kolhan basin have reached the proximal deposits supplying detritus for the Kolhan fan-delta system.

arid to semi-arid climate. In such a climatic setting, unaltered feldspars would become concentrated in sandy deposits of braided streams and may also undergo inland reworking, whereas fine detritus and clay (from feldspar weathering) would be carried to the basin as suspended load, thus leading to a separation between intensely (clay fraction) and incompletely weathered (sand fraction) material. Therefore intensities of chemical weathering indicated by shales will tend to be higher than those indicated by sandstones. It appears therefore that for realistic estimates of source area weathering conditions the data from shales and sandstones should be considered in conjunction.

The Kolhan basin activated as an asymmetric extensional basin, probably related to the reactivation of older thrusts in the chain. The sedimentation along the basin's northern margin was characterized by periodic transgressions of the lake, alternating with periods of fluvial fan progradation and fan-delta development. It is here suggested that syndepositional tectonism greatly overwhelmed a possible and concurrent climate forcing on the sedimentary dynamics recorded by the lithological successions. The episodes of thrusting forced the basin margin shifts onto the downwarped alluvial substrate and hindering temporarily the supply of sediment from fan catchments and causing sediment receive from the Iron Ore Group. The alluvial fans were coarse-grained, flood-dominated depositional systems, active during the post extension periods of intense denudation and slow normal subsidence. The alluvial sediment dispersal was predominantly by hyperconcentrated flows, generated by the sediment bulking in flash water flows, combined with their gravity transformation. The repetitive, high-frequency flood events are thought to have been generated by aerographic situations. The present case study demonstrates that an understanding of depositional processes is crucial to the reconstructions of sediment dispersal dynamics and basin-fill history.

Acknowledgement

The authors are grateful to Prof. D. Sen Gupta, Head of the Department, Department of Geology and Geophysics, IIT Kharagpur for providing necessary facilities to carry out the present investigation.

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