Alluvial fan sedimentation in the Cretaceous Athgarh Gondwana basin, Orissa, India

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The Athgarh Formation forms an important stratigraphic unit of Upper Gondwana sediments of Peninsular India. The regional palaeocurrent indicates a consistent southeasterly dispersal of clastics from the Archaean source terrain located to the northwest of the basin. The Athgarh Formation represents deposition in an alluvial fan environment with the development of proximal, mid-, and distal fan subenvironments and the distal part of the fan merging into a lake. The buildup of the Athgarh alluvial fan system occurred in a humid climate. Stream-flow processes dominated and a fan was drained by braided channels. Debris flow processes also operated, but were prominent only in the proximal fan zone. Several fans coalesced along the basin margin, forming a southeasterly sloping, broad and extensive alluvial plain terminating to a lake in the center of the basin. Aggradation of fans along the subsiding margin of the basin resulted in the Athgarh succession showing a remarkable lateral facies change in the down-slope direction. The proximal fan conglomerates pass into the sandstone-dominated mid-fan deposits, which, in turn, grades into the cyclic sequences of sandstones and mudstones of a distal fan origin. Further down slope, thick sequence of lacustrine shales occurs.

Key words: alluvial fan, Athgarh Formation, Gondwana, Lower Cretaceous, sedimentary facies.

INTRODUCTION

The Athgarh Formation (Lower Cretaceous) forms an important stratigraphic unit of thick pile of fluviatile and lacustrine sediments well known in Indian stratigraphy as "Gondwana". The formation has been regarded as the northernmost extension of the east coast Upper Gondwana basins of India (Fig. 1). It extends 32 km in a north-south direction and 29 km in an east-west direction with a total areal coverage of about 800 km² (Fig. 2). The initial study of the Athgarh Formation dates back to Blanford et al. (1856). They reported the occurrence of these rocks around Athgarh and Cuttack and introduced the term Athgarh basin to demarcate the area over which the conglomerates, sandstones, and shales of this formation were found. From the time of discovery of the basin till present, many workers have contributed on various aspects of the formation. Much work has been done on the palaeontological aspect and many mega-plant fossils have been discovered and described (Feistmantel, 1877; Pandya and Patra, 1968; Patra, 1973; Sahoo and Patra, 1995; among others). The formation has also been encountered in course of petroleum drilling in the offshore of Orissa coasts (Kaila et al., 1987).

The depositional framework of the Athgarh Formation has been still controversial. Adyalkar (1965) attempted a sedimentological and petrographic study of the Athgarh sandstones and has indicated a lacustrine origin of these rocks under a warm and humid climate. Kumar and Bhandari (1973) inferred a southeasterly direction of
sediment transport and deposition in a fluvi- fluviodeltaic to marine shelf environments. Mishra and Pandya (1991) reported low variability of paleoflow directions towards the southeast and suggested a braided stream depositional environment. This study focuses on facies relationships within the Athgarh succession in the area along the northern boundary of the basin and reveals that the succession originated in a series of coalescent alluvial fans merging into a lake and that the distinctive proximal, mid, and distal fan segments developed in the alluvial fan system.

GEOLOGIC SETTING

The area under study is located around Athgarh (latitude 20°24'30"-20°35'N, longitude 85°35'-85°47'E) of Cuttack district, Orissa (Fig. 2). The Gondwana succession of the present area, the Athgarh Formation, is essentially a clastic succession constituted of conglomerates, sandstones, mudstones, and shales. The succession is underlain in the north and northwest by the Precambrian
basement rocks belonging to the Easternghats Group of Archaean age (Fig. 2), and is covered by the sub-recent and recent alluvial tract in the east. The best exposures of the basement rocks are found along the western and northwestern flank of the area, where they consist of basic granulites, charnockites and biotite gneisses. The contact between the basement rocks and the Athgarh Formation in its greater part is concealed by soil, alluvium, and laterite. Raja Rao and Mitra (1978) indicated a faulted nature of the contact. However, no evidence of fault displacement has been observed along the contact zone, and the fault might have been concealed under laterite and soil cover. The Athgarh Formation is intruded by a dolerite dyke only along the southern bank of the Mahanadi river near Naraj. Agrawal and Rama (1976) reported a K-Ar age of 109 ± 26Ma for this dolerite.

The Athgarh Formation attains a maximum thickness of 700 m, but rocks generally occur as isolated outcrops confined to the elevated topography of the area (Fig. 3). The succession dips uniformly towards southeast at low angles ranging from 3° to 10°, forming a homoclinal structure. The sandstones constitute the dominant lithology of the formation. In places, conglomerates and mudstones occur commonly as thin, lenticular or laterally persistent bodies.

The Athgarh succession shows a regular change in lithologic characteristics from the basin margin towards the basin center (from north to south). The marginal part of the basin is marked by a dominance of conglomerates, which occur either as independent rock bodies or interbedded with sandstones. The proportion of mudstones is minimal. In a southeasterly direction, the Athgarh succession shows a marked decrease in conglomerates and consequent increase in the proportion of sandstones, mudstones, and shales. In the extreme south, mudstones become
a dominant lithology and occur as thick, laterally persistent beds associated with sandstones.

**FACIES ASSOCIATIONS**

A regular change in the dominant facies types and association of lithofacies has been observed in the Athgarh Formation from the basin margin towards the basin center (north to south). Four major facies associations have been recognized in the continuum of the Athgarh rocks. They fit well into the proximal, mid, and distal subenvironments of an alluvial fan, and a lacustrine environment.

**Facies association I: proximal fan**

*Description*

This association occurs as five isolated outcrops close to the basin margin in contact with the Precambrian basement rocks surrounded by thick succession of sandstones. They extend 1 to 3 km inside the basin (Fig. 3). The predominant lithology of the proximal fan association is conglomerate with subordinate sandstone and rare intercalations of mudstone (Fig. 4).

Conglomerates are polymictic. Clasts are mainly composed of quartz and quartzite with minor amount of khondalite, gneiss, and granulite. Two principal facies are recognized in the proximal fan conglomerates: matrix-supported conglomerate and massive to crudely stratified, clast-supported conglomerate. The matrix-supported conglomerates are 0.5 to 6 m thick, and are laterally traceable over a distance of 100 to 400 m along the strike direction. They are poorly to very poorly sorted. Pebble- and cobble-sized clasts are most common, but boulders...
up to 30 cm in diameter are locally abundant. The beds are essentially unstratified and display no size grading. Clasts are randomly set in a medium to coarse sand and clay matrix. In places, clasts show preferred orientation with long axes aligning in a NW–SE direction. The basal surfaces of the beds are sharp and flat, and erosive features are rarely observed. The massive to crudely stratified, clast–supported conglomerates occur generally as 1 to 3 m thick, lenticular beds and locally as much as 5 m. They are poorly to moderately sorted and consist of pebble– to cobble-grade clasts with a medium to coarse sand matrix. The beds have undulose basal surfaces with shallow scours. Internally many of the beds are massive, but some show crude subhorizontal stratification that is defined by variations either in clast size or in degree of clast sorting.

Sandstones occur in units commonly 0.5 to 6 m thick, but locally as much as 10 m thick. They are interbedded with the conglomerates. The sandstones of the proximal fan association are either massive, flat stratified, or planar cross stratified. The massive sandstones are medium- to coarse-grained. Some beds contain granule-grade materials. The beds of massive sandstone are 1 to 8 m thick, and extend laterally as irregular and at places sheet-like bodies for a distance of 50 to 100 m. The basal surfaces of the beds are sharp and erosional, locally exhibiting a channel structure. The flat–stratified sandstones and planar cross–stratified sandstones are less abundant. The beds are up to 1 m thick and show limited lateral extent. These sandstones commonly occur as cappings of the conglomerate and massive sandstone beds. The flat–stratified sandstones are characterized by horizontal to subhorizontal, nearly plane–parallel stratification with stratification 2 to 5 cm thick. The planar cross–sets are 7 cm to 1 m thick. They occur either as large–scale solitary sets or cosets. The foreset inclination ranges between 10° and 25°, with an average of 16°. Rare intercalations of mudstone are commonly less than 20 cm thick and are laterally discontinuous.

Interpretation

The conglomerates and sandstones of this facies association represent deposition on a proximal part of an alluvial fan, on which both debris flow and stream flow are the principal processes for sediment transport and deposition (Rust and Koster, 1984). The debris flow processes are well documented by the matrix–supported conglomerates. The matrix–supported framework, poor sorting with polymodal grain–size distribution, poor internal organization, and the lack of erosional base are all in accordance with transport and deposition by a debris flow mechanism (Bull, 1972; Johnson, 1970; Lowe, 1982; Middleton and Hampton, 1976). Alignment of clast long axes subparallel to the down–slope direction is indicative of no bed–load rolling of clasts (Walker, 1984), and is consistent with a debris flow interpretation. Laterally extensive beds imply that debris flows spread out on a fan surface as lobate sheets (Rust and Koster, 1984). A sheet–like form is a common feature of debris flow deposits, in contrast to a channel form of stream flow deposits, on alluvial fans (Rust and Koster, 1984; Wells, 1984).

The massive to crudely stratified, clast–supported conglomerates are undoubtedly interpreted as stream flow deposits. Limited lateral extent of the beds suggests deposition in channel systems on the fan surface. These conglomerates are similar to framework–supported, gravely longitudinal bars in modern braided systems (Rust, 1972, 1978; Collinson, 1986), and probably represent superimposed longitudinal bar deposits. Longitudinal gravel bars are the primary bedform in equilibrium with high–stage flows (Rust, 1978). Subhorizontal stratification implies migration and accretion of low–relief bars during floods. The massive sandstones are interpreted as sheetflood deposits (Bull, 1972). The laterally extensive, irregular to sheet–like body, the markedly erosional basal surface exhibiting channel structures, and the lack of internal stratification are suggestive of rapid deposition from heavily sediment–laden flows which spread over a fan surface forming numerous shallow and broad channels. Planar cross–stratified sandstones represent accretion of sand wedges at the fronts or margins of gravel bars, or slip face accretion of a low bar form in a shallow channel either dissecting the gravel bar.
surface during waning floods or dissecting the unchannelized fan surface during waning sheetfloods. Flat-stratified sandstones were probably deposited in a shallow water depth in the waning stages of floods or sheetfloods.

These features, combined with isolated occurrences of these rocks close to the basin margin in contact with basement rocks, suggest deposition in the proximal part of a series of coalescing alluvial fans. Conglomeratic deposits of debris flows and stream flood flows accumulated both in fan-head channels and on unchannelized aggrading fan surfaces.

**Facies association II : mid fan**

*Description*

The mid fan facies association grades in the up-dip direction into and locally overlies the proximal fan conglomerates and sandstones (facies association I). The deposits of this association extend 5 to 6 km inside from the basin margin (Fig. 3). The mid fan association is basically represented by thick succession of sandstones with intercalations of conglomerate and mudstone. They are organized into up to 6.5 m thick, fining-upward sequences (Fig. 5).

Individual sequences comprise thin (commonly 10 to 50 cm) conglomerate resting on the undulose, erosional surface and the overlying thick sandstone. In some sequences, conglomerate is lacking, and the basal part of the sequence is represented by the cross-stratified pebbly sandstone. The sandstones occupying the major part of the sequences are locally pebbly, and are either trough cross-stratified or

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**Fig. 5** Measured sections of the mid-fan facies association. For legend, see Fig. 4.
planar cross-stratified. Trough cross sets are 10 to 30 cm thick. They are grouped into 0.5 to 3 m thick cosets. Planar cross sets are commonly 20 to 50 cm thick, but some sets attain as much as 1 m in thickness. Larger sets tend to occur as solitary set. The fining-upward sequences are commonly vertically stacked to form multistoried sandstone bodies. Locally intervening in the sandstone bodies are up to 1.5 m thick mudstones. They have a lateral extent of the order of 10 m. The mudstones show, in places, an erosional contact with the underlying sandstones, and pebbles and mudstone intraclasts are concentrated at the base of these mudstone beds. Mega-plant fossils belonging to Pteridophytes and Gymnosperms are commonly preserved within the mudstones.

The deposits of the mid fan association are locally rich in conglomerate (Fig. 5, section E and G). The lower part of these conglomeratic sequences are composed of up to 2 m thick, lenticular conglomerate beds. Most of the conglomerates are clast-supported and are massive to crudely stratified. Some trough cross-stratified conglomerates occur as infillings of shallow and broad scours, 1 to 2.5 m deep and 5 to 10 m wide. Planar cross-stratified beds also occur, commonly as solitary set. Planar foresets are better defined in the down-current direction, whereas in the up-current direction cross sets generally show a lateral transition to the massive to crudely stratified conglomerates. Matrix-supported conglomerates are less common. They are no more than 1 m thick, and occur as lenticular intercalations within the clast-supported conglomerates.

Interpretation

This association contrasts with the conglomeratic proximal-fan association in the well-developed internal organization exhibited by fining-upward sequences, implying an important role of perennial stream-flow processes in the deposition of this association. The lateral transition from the proximal-fan association, paleocurrent orientations, and smaller grain size are all consistent with this association being the down-slope equivalent of the proximal-fan association, and a mid-fan origin is suggested. The multistoried sandstone bodies composed of fining-upward sequences are interpreted as the deposits of a braided-stream system on the mid-fan surface. The conglomerates at the base of individual fining-upward sequences rest on the erosional surface, suggesting that the conglomerates were transported and deposited as a channel lag or a diffuse sheet on the channel floor. The conglomerates generally pass upwards through trough cross-stratified sandstone into planar cross-stratified sandstone. This is indicative of in-channel deposition from migrating dunes followed by transverse bar development and its down-stream migration (Walker and Cant, 1984). Vertical stacking of fining-upward sequences without intervening fine-grained deposits is attributable to rapid lateral migration of braided channels and bars. Locally occurring mudstones could be interpreted as infillings of abandoned channels or vertical accretion deposits on the flood plain. The limited lateral extent, erosional basal surfaces, and pebbles and mudstone intraclasts concentrated on the basal surface are highly suggestive of deposition of these mudstones in abandoned channels.

The locally occurring, conglomeratic sequences are related to depositional processes similar to those of the proximal-fan association, but are different in that stream-flow processes were more important as evidenced by predominance of stratified or cross-stratified conglomerates. These conglomeratic sequences undoubtedly represent transitional proximal/mid-fan deposition. The lenticular, trough cross-stratified conglomerates represent scour and infilling of a shallow channel. Planar cross-stratified conglomerates that are laterally transitional to the massive to crudely stratified conglomerate are interpreted to have been formed either by lateral modification of longitudinal gravel bars during falling flood stage (Rust, 1978) or by vertical growth of bars with continued bar-top sediment transport, resulting in development of bar-front foresets (Hein and Walker, 1977). Matrix-supported conglomerates are interpreted as debris-flow deposits, alike those in the proximal fan association. A lenticular form within the stream-flow conglomerates suggests that debris flows may have extended down into the mid-fan sector through laterally confined channels.
Planar cross-stratified or plane stratified sandstones resting on the conglomerate portion of the sequences represent vertical aggradation on the gravel bars followed by channel shifting.

Facies association III: distal fan

Description
The distal fan association is laterally transitional from and locally overlies the mid fan association, and extends over 4 km basinward merging the mid-fan association (Fig. 3). This association consists of fining-upward sandstone sequences. These sequences are up to 7 m, commonly 3 to 4 m, thick, and are vertically stacked with or without intervening mudstones (Fig. 6). Individual fining-upward sequences have a sharp, erosional basal surface, on which thin bed of pebble conglomerate may rest, and have a gradational to abrupt contact with the overlying mudstones. The sandstones are fine- to coarse-grained, locally containing fine pebble- to granule-grade materials. In many of the sequences, the sandstones are planar cross-stratified in sets several decimeters thick. Planar cross-sets commonly superimpose to form up to 5 m thick units. Set thickness tend to decrease upward within a sequence. Trough cross-stratified sandstones also occur, but are uncommon. They occupy either the entire thickness of the sequence or the lower part of the sequence.

The intervening mudstones are up to 2.5 m, commonly in the order of 1 m, thick. They extend laterally over a distance of 30 m. Plant fossils belonging to Pteriodophytes and Gymnosperms are commonly preserved within the mudstones.

Interpretation
This association is similar to the mid-fan association in exhibiting fining-upward sandstone sequences, and is interpreted to have originated due to stream-flow processes alike the latter. On the other hand, smaller grain size and occurrence of laterally more persistent mudstones intervening the sandstone sequences are indicative of this association being the distal representative of the mid-fan association. Lateral transition from the mid-fan association and paleocurrent azimuths are consistent with a distal-fan interpretation for this association.

The braided-stream system on the mid-fan surface undoubtedly extended down-slope onto the distal segment of a fan, and produced the fining-upward sandstone sequences of this association. Predominance of planar cross sets within the sequences is indicative of development and coalescence of transverse bars (Walker and Cant, 1984). Upward decrease in planar cross-set thickness within a sequence is attributable to shallowing water.
depth due to accretion and aggradation of bars. Trough cross-stratified sandstone sequences represent in-channel deposition from migrating dunes and continued channel aggradation. However, the less common occurrence of the trough cross-stratified sandstone is suggestive that channels were relatively shallow to enhance the development of transverse bars (cf. Miall, 1977; Walker and Cant, 1984). The mudstones on the top of the sequences represent deposition of fine materials on the stabilized bar surface or on the inactive tracts in the braided system.

**Facies association IV: lacustrine**

**Description**

This association occurs in the extreme southeastern part of the study area (Fig. 3), and extends over 10 km inside the basin. The succession of this association is subdivisible into two units; the lower, carbonaceous shale unit and the upper, interbedded mudstone and shale unit (Fig. 7). In the section M near Naraj, these units are laterally traceable over a distance of 250 m.

The lower, carbonaceous shale unit is more than 20 m thick. Shales are ash gray to dark black in color and are thinly laminated. At places, however, shales are blocky and massive. Shales are rich in carbonaceous materials and contain some floral impressions. The upper, interbedded mudstone and shale unit, 10 to 15 m thick, gradationally rests on the carbonaceous shale unit, and is, in turn, covered by the sandstones of the distal fan association. Individual mudstones within the upper unit are 10 to 15 cm thick. The beds are laterally persistent across the outcrops. They are internally massive. The shales are around 1.5 m in thickness. They are argillaceous and thinly laminated.

The deposits of the lacustrine association have also been encountered near Barang, 10 km southeast of Naraj, in a well and in a borehole. Underlying up to 10 m thick laterites or clayey soils, carbonaceous shales form monotonous succession that attains a thickness of 79 m (Fig. 7). These carbonaceous shales are quite similar in lithology and in color to those observed in the outcrops near Naraj.

**Interpretation**

The widespread extent of the succession dominantly consisting of shales is most compatible with the deposition of fine materials in a large, standing body of quiet water. Occurrence of continental plant fossils including well-preserved impressions and complete absence of marine fauna are suggestive of a lacustrine environment. The carbonaceous shales are undoubtedly attributable to slow settling of silt, clay, and vegetal debris from suspension under very low intensity of water motion, which is akin to a lake-basinal condition. On the other hand, the interbedded mudstones and shales represent deposition in a more marginal part of a lake, in which fluctuations in supply of suspended materials through alluvial channels, along with an influence of possibly
DISCUSSION AND CONCLUSIONS

The Athgarh Formation in the study area represents deposition in an alluvial fan environment with the development of distinctive proximal, mid, and distal fan subenvironments and the distal part of the fan merging into a lake. Several fans coalesced in the study area along the basin margin, as indicated by the occurrence of proximal fan deposits in the isolated outcrops close to the Archaean basement rocks and surrounded by the laterally extensive succession of the mid-fan deposits (Fig. 3). Regional paleocurrents indicate a consistent southeasterly dispersal of detritus from a source terrain located towards the northwest (Fig. 3). The Athgarh alluvial fans, thus, formed a southeasterly sloping, broad alluvial plain which terminated to a standing body of lake water in the center of the basin. The fans aggraded along the subsiding margin of the basin. The resultant Athgarh succession shows a remarkable lateral facies change; the proximal fan conglomerates pass in a down slope direction through the sandstone-dominated mid-fan deposits into the cyclic sequences of sandstones and mudstones of a distal fan origin (Fig. 3). Further down slope, thick sequence of lacustrine shales occurs.

The buildup of the Athgarh alluvial fan system occurred in a humid climatic setting, and the fans were dominated by stream-flow processes. Streams emerging from a mountain canyon bifurcated and joined to form a braided channel system draining on the fan surface. Debris flow processes also operated, but were prominent only on the proximal fan surface with occasional invasion onto the mid-fan zone via confined channels. Limited importance of debris-flow processes was due to high precipitation and perennial discharge in a humid climate. These factors tend to prevent fine materials to accumulate in a catchment area and to stabilize the mountainous land surface by a vegetation cover (cf. Bull, 1972; Rust and Koster, 1984; Galloway and Hobday, 1996). Even in such a condition, heavy rainfall occasionally triggered a debris flow. The debris flows flowed down the steep and confined, mountainous canyon and deposited at the fan head zone as the gradient rapidly reduced. The deposits of debris flows had relatively low preservation potential because of subsequent reworking by dominant stream-flow processes.

Competence of stream flows rapidly reduced at the fan head as a result of percolation and reduction in gradient, depositing conglomerates in the proximal part of a fan. Finer fractions were capable to be transported further down-fan and progressively deposited on a mid- and distal fan surface with decreasing grain size. The channel pattern and depositional bar form also changed progressively down-fan. In the proximal fan zone, deposition occurred mostly in fan-head channels, in which conglomerates deposited as longitudinal gravel bars during floods with modification in the waning stage of floods. Down-slope onto the medial part of the fan, sandy braided channels dominated. Gravel occurred commonly on the channel floor as a lag. Channels were more braided probably due to development of transverse bars. This reflects decrease in the grain size to water depth ratio (Rust and Koster, 1984). In-channel deposition from migrating dunes was followed by transverse bar development and its down-stream migration, producing a distinct fining-upward sequence. Rapid lateral migration of braided channels and bars was responsible for the buildup of the multilateral and multistoried, mid-fan sandstone bodies. The braided channels extended down-slope onto the distal fan zone, in which sand was deposited producing fining-upward sequences. Channels were, however, relatively shallow compared with those on the mid-fan surface, enhancing development of transverse bars rather than channel fill sedimentation (cf. Miall, 1977; Walker and Cant, 1984). Channel stability was higher than on the mid-fan area, as suggested by superimposed transverse bar deposits within a sequence and by common occurrence of laterally traceable, overbank fine deposits.
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白亜紀アトガー・ゴンドワナ堆積盆地における扇状地堆積作用


アトガー累層（下部白亜系）は上部ゴンドワナ累層群の代表的な地層の１つで、マハナディ地域溝帯の東端部に分布する。アトガー堆積盆地は、半島インド東岸の他の上部ゴンドワナ堆積盆地と同様に、インドのゴンドワナ超大陸からの漂移に関連して形成されたとみなされている。堆積盆地の北および西縁では、アトガー累層は複合扇状地を形成して堆積した。古流方向は一定していては南東方向への砂層物の供給・分散を示す。扇状地の末端は盆地部の湖に面していた。扇状地堆積物は堆積物の著しい側方変化を示す。すなわち、下流方向へ向かって、土石流堆積物を含む礫質の上部扇状地から、側方移動の激しい砂礫質層状チャネルの発達した中部扇状地を経て、安定度の高い砂礫質層状チャネル群からなる下部扇状地へと変化する。アトガー累層の扇状地は湿潤気候下で形成された。そのため、水流作用の卓越する中部および下部扇状地が広い分布を示し、土石流作用は基盤に近接して点在する上部扇状地には限られている。