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Cyclic sedimentation and facies organisation of the coal-bearing Barakar Formation, Talchir Gondwana basin, Orissa, India: a statistical analysis of subsurface logs

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Abstract

The Barakar Formation of the Talchir Gondwana basin consists of nine lithofacies. These are thin conglomerate, flat-bedded pebbly to coarse-grained sandstone, trough cross-bedded coarse-, medium- and fine-grained sandstones, ripple-drift cross-laminated fine-grained sandstone, interbedded sandstone and shale, gray shale and interbanded carbonaceous shale, shaly coal and coal. In conformity with bore-hole records and for the convenience of Markov chain and entropy analyses, these lithofacies were condensed into five facies states viz. coarse-, medium-, fine-grained sandstones, shale and coal. The Markov chain analysis suggests the cyclical nature of lithofacies states and their organisation in a distinctive pattern forming fining-upward asymmetric coal cycles. A complete cycle starts with sandstone accompanied by local basal conglomerate and terminates with coal seam, being attributed to lateral migration of braid channels and bars within a meandering fluvial system. The entropy sets for facies states, on the other hand, do not fit into any idealised plots of asymmetric cycles. The deposition of sandstones seems to represent a most random event, which was possibly brought about by random change in the depositional mechanism triggered by the differential subsidence of the depositional area. Intrabasinal differential subsidence might have been responsible for the rejuvenation of the river system and the consequent initiation of a new cycle with freshly transported sediments.

Key-words : Barakar Formation, Talchir Gondwana basin, lithofacies, cyclicity, basin subsidence, statistical analysis.

Introduction

The Talchir basin (Fig. 1), named after the old feudatory state and town of Talcher, presently in the Angul district of Orissa, lies in the valley of the Brahmani river. It is the south-easternmost end member of the Son-Mahanadi valley basins. The basin is 112 km long, 26 km wide and forms one of the most important coalfields of Orissa. Early work in the basin dates back to 1837, when Lt. Kittoe discovered occurrences of coal near Talcher, but the knowledge about the basin was in an embryonic stage till 1856, when Blanford et al first mapped it. The strata recognized by them consisted of the Talchir, Damuda (Barakar) and Mahadeva beds. Brief accounts of the geology, structure and coal seams of the basin have been given by Fox (1934), Pascoe (1959), Subramanian (1971), Das and Rath (1974) and Raja Rao (1982). The Barakar Formation, due to its huge coal resources, has attracted the attention of different exploring agencies. As a result, the National Coal Development Corporation, the Indian Bureau of Mines, the Geological Survey of India, the Central Mine Planning and Design Institute, and the Directorate of Geology, Govt. of Orissa, undertook both preliminary and detailed exploration work. The reports, though unpublished, mainly deal with the coal resources of the basin. Little work has been done on the analy-

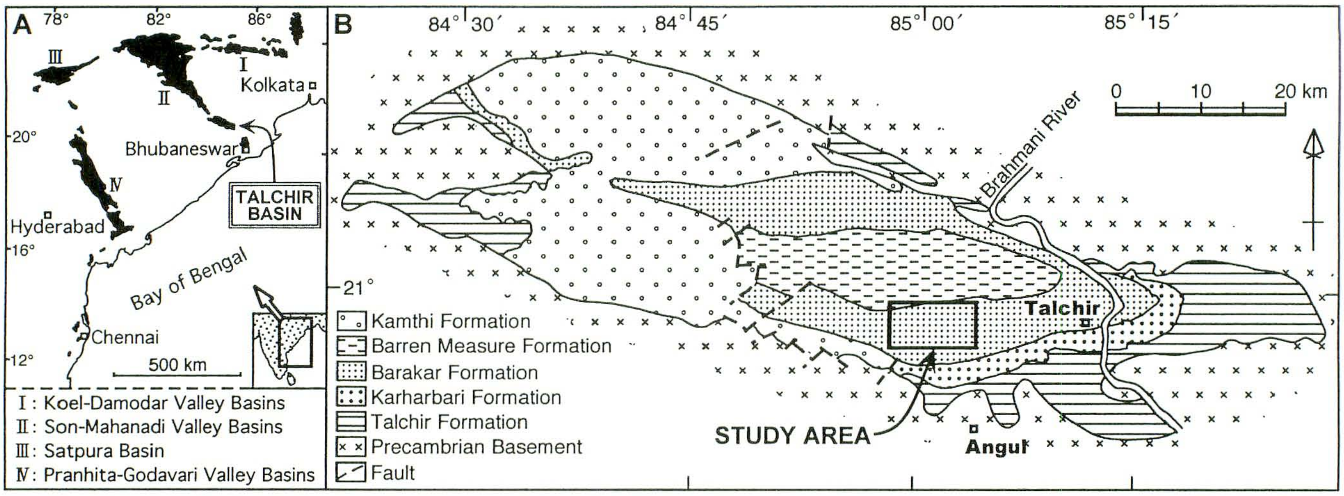

Fig. 1 A: Distribution of Gondwana basins in the eastern part of Peninsular India and location of the Talchir basin. B: Geologic sketch map of the Talchir basin, modified after Raja Rao (1982), showing the location of the study area.

sis of lithofacies, their association and organisation, which are vital for the reconstruction of the depositional environment of the coal-bearing strata. In view of this, a segment of the Barakar Formation exposed in the southeastern part of the Talchir basin was selected for detail investigation with a view to studying the lithofacies, their association and organisation and to deduce the depositional environment of the coal bearing Gondwana strata.

Study Area

The area investigated is located in the southeastern part of the Talchir basin (Figs.1 and 2). It is bounded by latitudes 20°55′ N and 20°59′28″ N, longitudes 84°58′09″ E and 85°06′19″ E and forms a part of the Survey of India toposheet Nos. 73 D/13 and 73 H/1. The area is located 12 km west of Talcher township and 15 km northwest of Angul township. The Singarhajhor is the main drainage in the area, which flows in an easterly direction for some distance and then takes a sharp northerly turn. It is fed by a system of northerly, northeasterly and southeasterly flowing ephemeral streams, which rise from the Boulder Gravel Unit in the south and Barren Measures Formation in the northwest. Due to the thick alluvial cover over the greater part of the area, study of lithofacies was largely confined to the rocks exposed in the stream sections and their organisation was established from subsurface information available in borehole records.

Geologic Setting

The Gondwana sediments in the study area represent a continuous succession of strata comprising a part of Damuda Group, which is divisible into the Karharbari, Barakar and Barren Measures Formations from bottom to top. The lower two formations are coal bearing and host a total number of eleven coal seams, one in the Karharbari and ten in the Barakar Formation. The Barakar Formation, to which the present study pertains, attains a thickness of 275 m. It is underlain by a Boulder Gravel Unit in the south and overlain by Barren Measures Formation in the northwest (Fig. 2). The Barakar Formation strikes east-west and dips towards north at low angles, ranging from 2 to 10 degrees, forming a homoclinal structure. It is composed of thin conglomerate, pebbly to fine-grained sandstones, interbedded sandstone-shale, gray shale and coal seams. The coal seams consist of interbanded carbonaceous shale-shaly coal-coal. The Barakar strata are intersected by a series of faults which do not display any relationship with pattern of sedimentation or sedimentary cycle and have, therefore, been regarded as post depositional (Hota and Pandya, 1997).

Methodology

Fieldwork was carried out to describe and characterise the gently dipping beds of the Barakar Formation along the northerly flowing stream sections (Fig. 2). At each exposure, different lithofacies were studied and

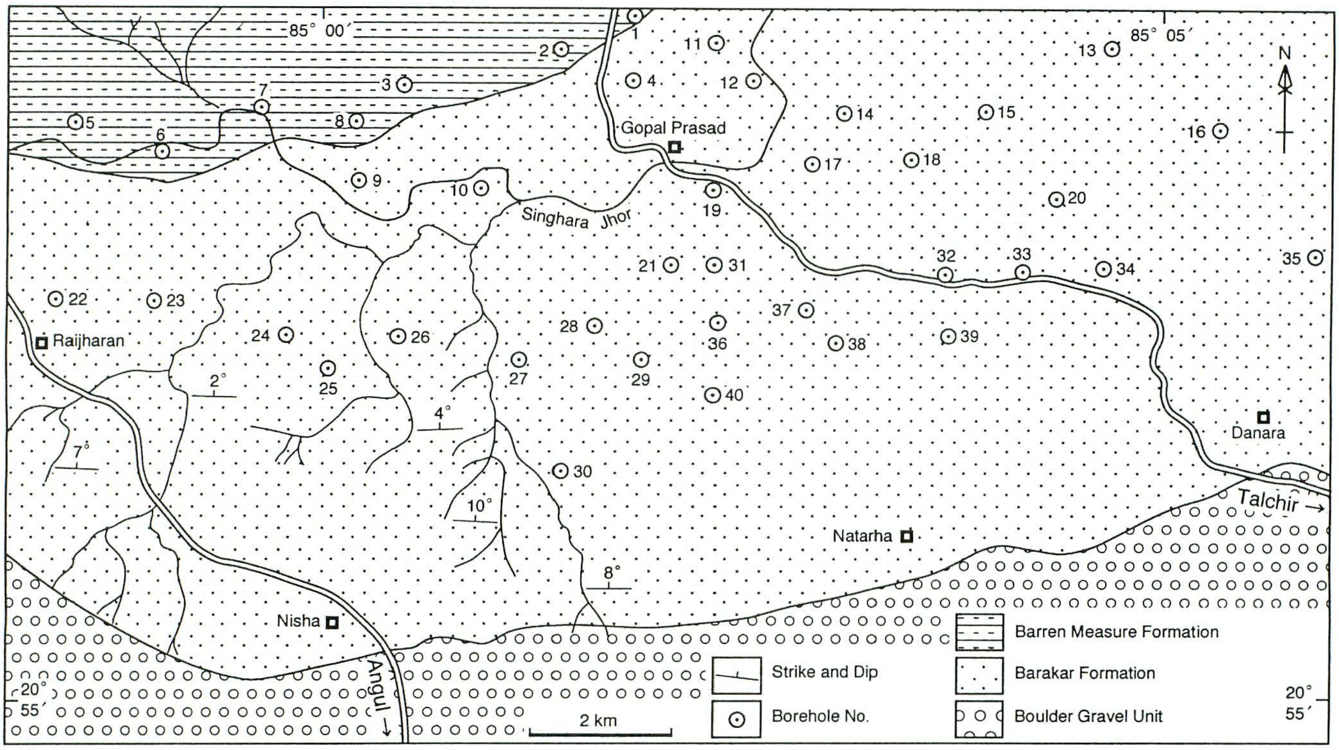

Fig. 2 Geological map of the study area showing location of boreholes, data of which used in Markov chain and entropy analyses.

identified on the basis of their geometry, gross lithology and sedimentary structure. Due to paucity of exposures, vertical relationship between various lithofacies could not be established from surface studies. The lithofacies observed in surficial study were condensed into a smaller number of facies states in conformity with the borehole record. The facies transition data of forty borehole logs were subjected to Markov chain analysis following the procedure outlined by Miall (1973) and Casshyap (1975). The data were processed into transition count (f_{ij}), transition probability (p_{ij}), random probability (e_{ij}) and difference (d_{ij}) matrices (Table 1). A facies relationship diagram (Fig. 3) was constructed on the basis of difference matrix results to arrive at the preferred upward transition of facies states. The cyclicity of facies states was tested by chi-square statistic proposed by Billingslay (1961) and Harbaugh and Bonham-Carter (1970). The extent and nature of ordering of facies states was further investigated by the concept of entropy (Hattori, 1976) to the embedded Markov probability matrices drawn up for the Barakar Formation. Entropy before and after deposition ($E^{(pre)}$ and $E^{(post)}$) of each facies state as well as the maximum entropy ($E_{(max)}$) and the entropy of the sedimentation system ($E_{(system)}$) were computed following the procedure outlined by Hattori (1976). As the pre- and post-depositional entropies are dependent upon the number of states under consideration, they were normalised by dividing the respective values by the maximum entropy (Table 2).

Lithofacies Analysis

The term lithofacies used in the present wok is synonymous with the usage of Walker (1984), Selley (1985) and Reading (1986) but it does not include the biological aspect of the rocks. On the basis of geometry, gross lithology and sedimentary structure, nine lithofacies were identified in the Barakar Formation of the present area. These are:

Thin conglomerate (facies A_1)

This facies is locally developed as small and discontinuous bodies having an erosional basal surface. It is lensoidal, 10 cm–1 m thick, massive and pinches out laterally within a few metres. It is poorly sorted and composed of pebble- and cobble-sized clasts of vein quartz, quartzite, mica-schist, charnockite and khondalite held in a medium to coarse-grained sandy matrix. In most instances, it is overlain by pebbly to coarse-grained sandstone and underlain by interbedded sandstone–shale or a coal seam. This facies represents the channel lag and scour fill deposits formed in the deepest part of the stream (Allen, 1970).

Flat-bedded, very coarse-grained to pebbly sandstone (facies A_2)

Representatives of this facies are widespread in the succession and generally overlie thin conglomerate or coal seam. It is represented by yellowish buff and gray coloured, very coarse-grained to pebbly sandstone characterised by horizontal bedding with a thickness rarely greater than a metre and laterally persistent up to tens of metres. It often exhibits a scoured and channelised base. This facies represents channel floor deposits veneering lags and scours (Casshyap, 1970).

Trough cross-bedded, coarse- to very coarse-grained sandstone (facies A_3)

This facies is widely distributed in the succession and generally occurs above facies A_2. It is coarse- to very coarse-grained, gray, white, and pink in colour and profusely cross-bedded. The cross-bed units are of large scale, mostly trough type and occur as solitary or grouped sets. This facies occurs as small (~50 cm) and large (1-3 m) multistory and multilateral coalescing bodies with scoured base. The sandstones of this facies are attributed to in-channel deposition and bar development within channel (Miall, 1977; Cant and Walker, 1976, 1978). Abundant erosional scours, cosets of trough cross beds and their occurrence as multistory and multilateral channel bodies are suggestive of frequent lateral shifting of channels and bars in the low flow regime of moderate to high intensity (Allen, 1968).

Trough cross-bedded, medium- to coarse-grained sandstone (facies B)

This facies is characterized by erosional base and flat top as well as sheet like bodies with flat base, and appear as continuous beds for several metres. It is common throughout the sandy horizons of the formation. Individual sandstone bodies of this facies are a few tens of centimetres in thickness, gray, yellow and pink in colour and show profuse development of cosets of large-scale cross-beds with occasional interbeds of planar foresets. This facies may be attributed to down current migration of sand dunes, sand waves, transverse/linguoid bars in shallow water in lower flow regime of moderate to high intensity (Casshyap, 1970). Sheet-like cross-bedded sandstone bodies with flat base may be attributed to lateral accretion in sinuous stream channels (Allen, 1970). Planar foresets may be attributed to mid-channel bar development (Miall, 1977)

Trough cross-bedded, fine- to medium-grained sandstone (facies C_1)

This facies is constituted of fine- to medium-grained, trough cross-bedded, pink and yellow coloured sandstone bodies with erosional to gradational base. It is more common in the upper part of the formation. The cross-bedded units are of small scale and occur as solitary and grouped sets. The facies is commonly thin (< 50 cm) and extend as continuous bed for several metres because of lateral coalescence. This facies may be attributed to lateral accretion on point bar in low flow regime of moderate to high intensity (Casshyap, 1970) or bar aggradation (Cant and Walker, 1976).

Ripple-drift cross-laminated, fine-grained sandstone (facies C_2)

This facies is relatively scarce in comparison to other facies developed in the Barakar succession of the present area. It is fine-grained, gray to yellow in colour and occurs as thin prism-like bodies lensing out laterally within a few metres. This facies shows straight parallel laminations alternating with ripple-drift cross laminations. This may be attributed to down current migration of sinuous trains of asymmetrical ripples under controlled conditions of sediment supply in a lower flow regime of low intensity (Allen, 1963) or inactive channel-fill deposit (Miall, 1977).

Interbedded fine-grained sandstone and shale (Facies D_1)

This facies is discontinuous, pinches out laterally within a few tens of metres. The sandstones within the facies are thin (5-10 cm), fine-grained, gray and pink in colour and exhibit parallel lamination with occasional sets of cross lamination. The shales are gray in colour, thin (2-10 cm) and parallel and occasionally wavy laminated. Thin and discontinuous beds of fine clastics correspond to deposition on the top of sandy bars and in abandoned flood plains of sinuous rivers during periods of reduced discharge (Allen, 1964).

Gray shale (facies D_2)

This facies is extensive in the middle and upper parts of the succession and occurs at the base and top of the coal seams exposed in the area and intersected by boreholes. The shale is gray with occasional yellow bands, mostly thick (50 cm-2 m), massive and at times laminated. It contains impressions of plant fossils like Glossopteris, Gangamopteris and Vertebraria species. Thick and persistent beds of shale are attributed to deposition through vertical accretion on stable and extensive over banks of moderately sinuous to meandering streams during periods of greater discharge and overflow (Allen, 1970). Gray colour may be attributed to persistent reducing conditions due to high water table close to or even above the depositional surface of a lake or back swamp (Reading, 1978).

Interbanded carbonaceous shale, shaly coal and coal (facies E)

The coal seams of the Barakar Formation are constituted of interbanded carbonaceous shale, shaly coal and coal. They generally occur above gray shale and are succeeded by gray shale, sandstone or thin conglomerate. Lateral and vertical gradation between carbonaceous shale and coal are common. Bands rich in coal are generally bright, pitch black and break with vertical fracture, whereas bands rich in shaly matter are dull, brownish and break with horizontal splitting. This facies is laterally extensive for several hundred metres and depending upon their thickness may be classified into thin to moderately thick (up to 4m) and thick (4 to 30m). The impersistent thin seams may be attributed to their formation in abandoned flood plains and/or distal crevasse splays following vertical accretion in low-sinuous, multichannel streams, whereas extensive thicker seams may be attributed to accumulation of vegetal debris in large and small, low-lying over bank and inter-channel coal swamps and locally protected lakes of meandering streams (McCabe, 1984; Belt et al., 1984). The carbonaceous shale probably was a more proximal floodplain deposit than coal, as evidenced by lateral and vertical gradation from carbonaceous shale to coal and back to carbonaceous shale. These gradations could be due to progradation and abandonment of clastic sources such as crevasse splays into the flood basins (Diemer and Belt, 1991; Diemer et al., 1992).

Markov Chain and Entropy Analyses

In conformity with borehole records and to avoid the risk of error, which may occur if the facies states are divided into larger numbers (Cashyap, 1975), the lithofacies observed in the outcrop were condensed into five groups. These are:

Table 1 Markov matrices and chi-square statistics of facies states in the Barakar Formation.

Transition count matrix (f_{ij})

	A	B	C	D	E
A	0	151	131	114	13
B	93	0	202	137	18
C	75	92	0	313	92
D	122	101	167	0	700
E	107	91	64	555	0

Random probability matrix (e_{ij})

	A	B	C	D	E
A	0	0.15	0.2	0.37	0.28
B	0.14	0	0.2	0.38	0.28
C	0.15	0.16	0	0.39	0.3
D	0.18	0.2	0.25	0	0.36
E	0.16	0.18	0.23	0.43	0

Transition probability matrix (p_{ij})

	A	B	C	D	E
A	0	0.37	0.32	0.28	0.03
B	0.21	0	0.45	0.3	0.04
C	0.13	0.16	0	0.55	0.16
D	0.11	0.09	0.16	0	0.64
E	0.13	0.11	0.08	0.68	0

Difference matrix (d_{ij})

	A	B	C	D	E
A	0	0.22	0.12	-0.09	-0.25
B	0.07	0	0.25	-0.08	-0.24
C	-0.02	0	0	0.16	-0.14
D	-0.07	-0.11	-0.09	0	0.28
E	-0.03	-0.07	-0.15	0.25	0

Test of significance

Test equation	Computed value of χ^2	Degree of freedom	Limiting value of χ^2 at 0.5% significance level
Billingslay (1961)	1189.46	15	32.8
Harbaugh and Bonham-Carter (1970)	2232.64	11	26.76

A: Coarse-grained sandstone
B: Medium-grained sandstone
C: Fine-grained sandstone
D: Gray shale
E: Coal

1. Coarse-grained sandstone (facies A): thin conglomerate, flat and trough cross-bedded coarse-grained to pebbly sandstones.
2. Medium-grained sandstone (facies B): trough cross-bedded medium- to coarse-grained sandstone.
3. Fine-grained sandstone (facies C): trough cross-bedded, fine- to medium-grained sandstone and ripple-drift cross-laminated fine-grained sandstone.
4. Gray shale (facies D): interbedded sandstone-shale and gray shale.
5. Coal (facies E): interbanded carbonaceous shale, shaly coal and coal (coal seam).

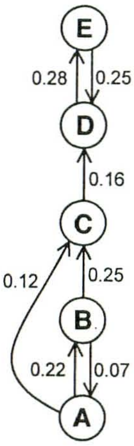

Fig. 3 Facies relationship diagram showing upward transition of facies states (based on d_{ij} values) of the Barakar Formation. A: coarse-grained sandstone; B: medium-grained sandstone; C: fine-grained sandstone; D: gray shale; E: coal.

The upward facies transition data of forty borehole logs (Fig. 2) were subjected to Markov chain and entropy analyses. The computed values of chi-square exceed the limiting value at the 0.5% significance level (Table 1) suggesting the Markovity and cyclic arrangement of facies states. The facies relationship diagram (Fig. 3) drawn up from the difference matrix shows that the Barakar cycles are a fining-upward asymmetric type. Each complete cycle starts with a thin conglomerate or pebbly to coarse-grained sandstone (facies A) at the base and is succeeded by medium- to fine-grained sandstone (facies B and C), interbedded sandstone-shale and gray shale (facies D) and terminates with a coal seam (facies E) at the top. Alternation existing between coarse-grade members (sandstones) may be due to the predominance of truncated cycles developed by sidewise migration of stream (meandering or braided) channels; alternation of shale and coal may be attributed to frequent over-flooding of rivers and consequent deposition of fine clastics over accumulating peat in a swamp environment (McCabe, 1984). Initiation of second and subsequent fining-upward cycles in the Barakar succession commonly starts with the deposition of coarse-grained sandstone (facies A). Such a change does not occur in the facies relationship diagram even though such transitions do exist in the borehole data. This may be attributed to random change in the depositional mechanism (Miall, 1973) manifested by the development of some sort of channel system after phases of peat accumulation.

The entropy analysis (Table 2) shows that both pre-

Table 2 Calculated values of entropy sets for the Barakar Formation.

Facies states	$E^{(Pre)}$	$E^{(Post)}$	$R^{(Pre)}$	$R^{(Post)}$	Relationship
Coarse-grained sand stone (A)	1.977	1.73	0.989	0.865	$E^{(Pre)} > E^{(Post)}$
Medium-grained sand stone (B)	1.965	1.697	0.983	0.849	$E^{(Pre)} > E^{(Post)}$
Fine-grained sand stone (C)	1.895	1.708	0.948	0.854	$E^{(Pre)} > E^{(Post)}$
Gray shale (D)	1.722	1.497	0.861	0.749	$E^{(Pre)} > E^{(Post)}$
Coal (E)	0.766	1.402	0.383	0.701	$E^{(Pre)} < E^{(Post)}$

$E_{(max)} = 2.00$, $E_{(system)} = 3.799$

$E^{(Pre)}$: Entropy before deposition

$E^{(Post)}$: Entropy after deposition

$R^{(Pre)}$: Normalised entropy before deposition

$R^{(Post)}$: Normalised entropy after deposition

$E_{(max)}$: Maximum possible entropy for every state in the system

$E_{(system)}$: Entropy of the sedimentation process for every state in the system

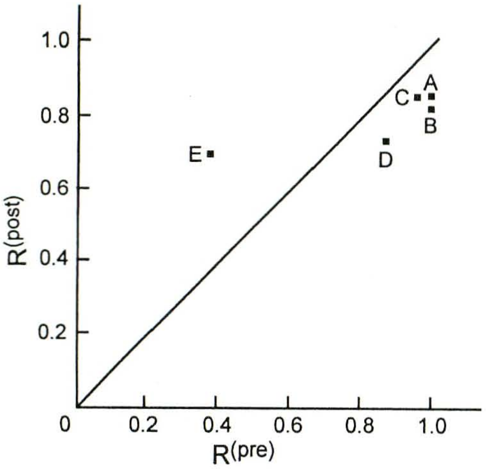

Fig. 4 Entropy sets for facies states of the Barakar Formation. A: coarse-grained sandstone; B: medium-grained sandstone; C: fine-grained sandstone; D: gray shale; E: coal.

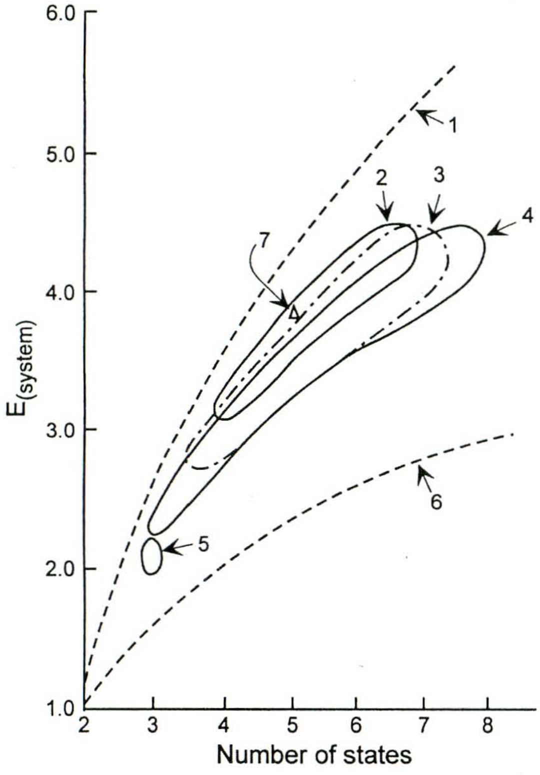

Fig. 5 Relationship between entropy and depositional environment of lithological sequences (after Hattori, 1976). 1: maximum entropy; 2: entropies for coal-measure successions; 3: entropies for fluvial–alluvial successions; 4: entropies for neritic successions; 5: entropies for flysch sediments; 6: minimum entropy; 7 (triangle): entropy for the Barakar succession.

and post-depositional entropies ($E^{(pre)}$ and $E^{(post)}$) for sandstone facies are large, which in turn suggests the occurrence of sandstone as the most random event in the Barakar Formation of the Talchir basin. $E^{(pre)}>E^{(post)}$ relationship in case of sandstone and shale facies indicates that these facies exert strong influence on their successors but are relatively uninfluenced by their precursors. In other words, lithologies that follow sandstone and shale facies can be conjectured with more certainty than those preceding them. Markov matrices (Table 1) and a facies relationship diagram (Fig. 3) support this view. Coarse-grained sandstone (facies A) is succeeded by medium- and fine-grained sandstones (facies B and C) with d_{ij} values of 0.22 and 0.12, respectively. Medium-grained sandstone (facies B), fine-sandstone (facies C) and gray shale (facies D) are succeeded by fine-grained sandstone (facies C), gray shale (facies D) and coal (facies E) with d_{ij} values of 0.25, 0.16 and 0.28 respectively. For coal, the relationship between pre- and post-depositional entropies is strikingly different. $E^{(pre)}<E^{(post)}$ relationship in case of coal suggests that coal does not show strong memory for any succeeding lithological state but is dependent on the preceding state in the succession. In the present study, the probabilities of coal proceeded by coarse-, medium-, fine-grained sandstones and gray shale are 0.02, 0.02, 0.11 and 0.85, respectively.

The nature of cycles of the Barakar sediments is asymmetric and truncated. However, the entropy sets for facies states are not compatible with those for any possible types of asymmetric cycles (A-1 to A-4 of Hattori, 1976). Rather, the $R^{(pre)}-R^{(post)}$ plots of the facies states (Fig. 4) resemble closely the corresponding plots for the New Castle Coal measures of New South Wales (Hattori, 1976, Fig. 15). The latter has been assigned to the D-type cyclicity, which has entropy sets difficult to explain clearly in the sense of cyclic sedimentation (Hattori, 1976). The entropy of the Barakar sedimentation system as shown in Fig. 5 plots in the coal measure field of the succession discrimination diagram of Hattori (1976, Fig. 16).

Discussion

Integrated surface and subsurface studies of lithofacies as well as Markov chain and entropy analyses indicate preferential arrangement of lithofacies states, suggesting existence of fining-upward cycles in the Barakar Formation of the Talchir basin. A complete cycle displays all the nine lithofacies with thin conglomerate (facies A_1) at the bottom and coal seam (facies E) at the top (Fig. 6). These lithofacies exhibit a systematic variation in texture and bedding types. There is a vertical fining of grain size from pebbly, very coarse-grained sandstone (conglomerate in a few instances) at the base through coarse- and medium-grained sandstone and shale at the top. The associated bedding types usually change from massive flat bedding, large scale cross bedding, small scale cross bedding to parallel lamination. The complete cycle also includes a carbonaceous shale-coal sequence at the top. The vertical sequence of lithologic units and associated bedding types by and large imply a steady upward decrease in the intensity of flow from an upper flow regime in the lower part to a lower flow regime of high to moderate intensity in the middle part and a low to very low intensity in the upper part. Complete cycles are not frequently developed and the constituent lithologies seldom occur together; rather, most of the cycles examined in the borehole record are truncated with one or more lithologic states missing.

The bedding types exhibited by coarse grade members (sandstones) are characteristic of braid bar, side bar and point bar sands of many modern streams (Allen, 1965). These might have resulted from the lateral accretion of stream bed-load by sidewise migration of braiding or meandering channels. The palaeohydrologic studies indicate the low to moderate sinuous nature of the Barakar streams, with sinuosity ranging from 1.31 to 1.36 (Hota et al., 2001). The palaeodrainage parameters are closely comparable with those of braided streams (Miall, 1976; Casshyap and Khan, 1982 and Reddy and Prasad, 1988). Though a meandering stream depositional environment has been argued for the continental fining-upward cycles (Allen, 1965), sedimentation in a braided system can give rise to fining-upward sequences as well (Cant and Walker, 1976, 1978). Thick accumulation of a carbonaceous shale-coal sequence is, however, suggestive of relatively high stability of channels compared with typical braided rivers. On the other hand, braid bars (channel bars) can also develop in some meandering rivers transporting coarse materials. Thus, the fining-upward cycles of the Barakar Formation of the Talchir basin might have been deposited by braid channels within a meandering fluvial systems, which were transformed into purely meandering systems with the advancement of sedimentation.

The lithofacies observed in the Barakar fining-upward cycles can be linked with various sub-environments of a meandering stream depositional environment (Fig. 6). The sandstone assemblages comprising coarse-grade members (facies A and B) are the deposits, which, in texture and sedimentary structure, compare very closely with the channel sediments of modern rivers (Sarkar and Basumallick, 1968). Their extensive development in the Barakar cycles indicate that the growing channel bar deposits migrated sidewise as the meandering (braiding) river channels wandered (anabranched) through the slowly subsiding flood plain (Casshyap, 1970). The upper part of the coarse-grade member commonly comprises a thin sequence of fine-grained sandstone unit (Facies C), which may be attributed to lateral accretion of a point bar or channel bar deposit and more likely refers to a stage when the water discharge and velocity dropped to a minimum in a steadily shoal-

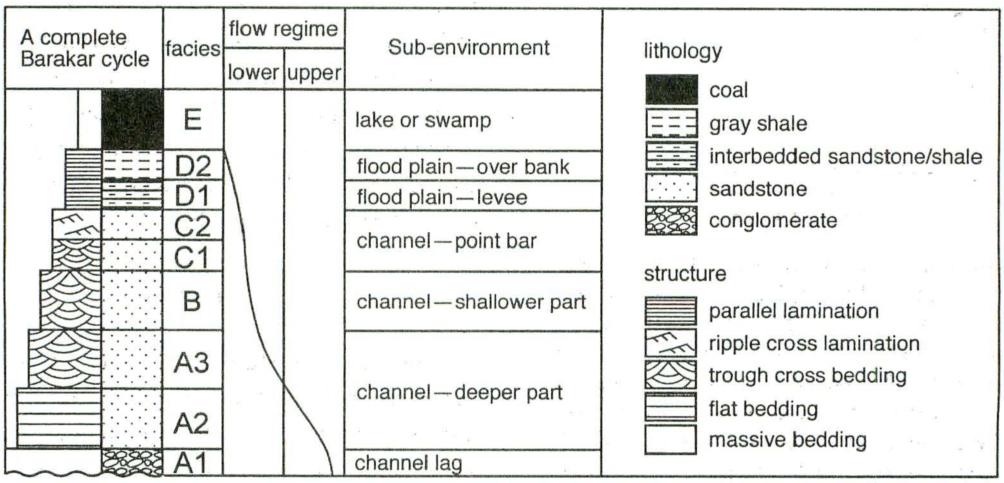

Fig. 6 Bar diagram showing the vertical arrangement of lithofacies in a complete cycle of the Barakar Formation; the flow regime and sub-environments are recorded in vertical sequence (no vertical scale implied).

ing channel (Barrett, 1965). The succeeding fine grade members, i.e., interbedded sandstone and gray shale (facies D) characterise proximal (levee) and distal (over bank) flood plain deposits, respectively. The carbonaceous shale-coal sequence (facies E) at the top of each complete cycle implies a depositional environment, which could favor accumulation and growth of vegetal material, which is more likely, a lake or swamp. The coal-forming environment whether a lake or swamp (marsh) is apparently not a normal feature of the alluvial flood plain (Strahler, 1963); probably this may be the reason why a carbonaceous shale-coal sequence does not occur regularly with each fining-upward cycle. The occurrence of coal seams at the top of the fining-upward cycle, therefore, suggests cessation of fluvial sedimentation and conversion of the flood plain into lake or swamp. The coal-forming environment could have occupied small areas or the entire basin. The former situation should yield a local coal seam, whereas the latter case may give rise to an extensive coal seam covering the entire basin (Casshyap, 1970). Thus, it is very likely that an extensive coal seam shows floor and roof of variable lithologies in different parts of the basin (Hota, 2000). This interpretation is supported by Markov chain and entropy analyses results. Barakar coals mostly occur depending upon the preceding facies states but are independent in some degrees with the overlying states. The coal seams developed in the swamps located in the distal part of the flood plain and, due to differential subsidence of the basin, the coal-forming environment gradually encroached other parts of the depositional area. The Barakar cycles belong to the D-type cyclic sequence of coal measure succession (Hattori, 1976) and the deposition of sandstones represents the most random event which was possibly brought about by random change in the depositional mechanism triggered by the differential subsidence of the depositional area. Differential subsidence or upliftment of the basin and landmass (source area) might have been responsible for the rejuvenation of the river system, which appeared in the depositional area and initiated a new cycle with freshly transported sediments. Each complete cycle, with basal sandstone and terminating with a coal seam, records the establishment of some kind of channel system and then its abandonment and burial beneath a swamp or lake. The borehole data records repeated cyclic occurrence of sandstone-shale-coal facies, testifying that channel establishment and abandonment was repeated many times at a given site during Barakar sedimentation. As the Barakar sediments are non-marine and alluvial in nature, the fining-upward coal cycles might have been generated by sediment control theory (Duff et al., 1967) in the form of sedimentary distributive mechanism by way of lateral migration of streams (Pettijohn, 1984) or drainage diversion (Belt et al., 1992) caused in response to intrabasinal differential subsidence.

Summary and Conclusions

Nine lithofacies have been identified in the Barakar Formation of the Talchir Gondwana basin. These are thin conglomerate, flat-bedded pebbly to coarse-grained sandstone, trough cross-bedded coarse-, medium- and fine-grained sandstones, ripple-drift cross-laminated fine-grained sandstone, interbedded sandstone and shale, gray shale and interbanded carbonaceous shale, shaly coal and coal. For statistical analyses these lithofacies can be conveniently grouped into five facies states viz. coarse-, medium-, fine-grained sandstones, shale and coal. Markov chain analysis suggests the preferential arrangement of facies states and their organisation in form of fining-upward coal cycles. Each complete cycle exhibits vertical fining of grain size and decrease in the flow intensity and current velocity during deposition of each cycle. The lithofacies constituting the fining-upward cycles can be linked with various sub-environments of braid channels and bars within a meandering fluvial system and their organization may be attributed to lateral migration of streams caused in response to intrabasinal differential subsidence. Each complete cycle, with basal sandstone and terminating with coal seam, records the establishment of some kind of channel system and then its abandonment by stream and burial beneath a swamp or lake. The Barakar cycles belong to the D-type cyclic sequence of Coal measure succession (Hattori, 1976) and the deposition of sandstones represents the most random event which was possibly brought about by random change in the depositional mechanism triggered by the differential subsidence of the depositional area. Intrabasinal differential subsidence might have been responsible for the rejuvenation of the river system and the consequent initiation of a new cycle with freshly transported sediments.

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