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Cyclic Sedimentation of the Barren Measures Formation (Damuda Group), Talchir Gondwana Basin: Statistical Appraisal from Borehole Logs

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Abstract: The succession of lithofacies of a part of the Barren Measures Formation of the Talchir Gondwana basin has been studied by statistical techniques. The lithologies have been grouped under five facies states viz coarse-, medium-, and fine-grained sandstones, shale and coal for statistical analyses. Markov chain analysis indicates the arrangement of Barren Measures lithofacies in the form of fining upward cycles. A complete cycle consists of conglomerate or coarse-grained sandstone at the base sequentially succeeded by medium-and fine-grained sandstones, shales and coal at the top. The entropy analysis puts the Barren Measures cycles into A-4 type cyclicity, which consists of different proportions of lower, upper and side truncated cycles of lithologic states. Regression analysis indicates a sympathetic relationship between total thickness of strata (net subsidence) and number of cycles and an antipathic relationship between average thickness and number of sedimentary cycles. The cyclic sedimentation of the Barren Measures Formation was controlled by autocyclic process which occurred due to the lateral migration of streams triggered by intrabasinal differential subsidence. In many instances, the clastic sediments from the laterally migrating rivers interrupted the cyclic sedimentation resulting in thinner cycles in areas where the number of cycles are more. Principal component and multivariate regression analyses suggest that the net subsidence of the basin is mostly controlled by the thickness of sandstones, shale beds and coal stringers.

Keywords: Cyclic sedimentation, Markov chain analysis, Entropy analysis, Regression analysis, Principal component analysis, Barren Measures Formation, Talchir Gondwana basin.

INTRODUCTION

Out of eight Gondwana basins in Orissa, the Talchir Basin (Figs.1 and 2) is the main coal bearing sedimentary succession in the state. Due to its vast coal resources, it has been extensively explored generating voluminous data on the subsurface geology. Examination of borehole logs indicates the repetition of different lithologies. Statistical methods like Markov chain and entropy analyses reveal the cyclic arrangement of lithofacies and their degree of ordering (Billingsley, 1961; Harbough and Bonham Carter, 1970; Hattori, 1976). These methods have been extensively used for analysis of coal measure cyclothems as well as alluvial, deltaic and marine successions of various periods throughout the world (Miall, 1973; Casshyap, 1975; Kumar, 1990; Shukla et al. 1996; Hota et al. 2003). Quantitative relationship between net subsidence and sedimentary cycles may reveal the cause of cyclic sedimentation (Duff, 1967; Johnson and Cook, 1973; Casshyap, 1975; Read and Dean, 1976). Earlier, Hota and Maejima (2004) studied the cyclicity of the Barren Measures Formation with eight borehole sections and revealed only the cyclic arrangement of Barren Measures strata. They did not study the relationship between net subsidence and parameters of sedimentary cycles, most of which do not contain coal. In the present study a segment of the Barren Measures Formation of the Damuda Group located in the south-eastern part of the Talchir Gondwana basin (Fig.2) has been selected. The aims of the present study are:

(a) to study the cyclic arrangement of various lithofacies by Markov chain analysis;
(b) to evaluate the degree of ordering of lithofacies using entropy functions;
(c) to establish the relationship between net subsidence (total thickness of strata) and number and average thickness of sedimentary cycles using bivariate regression analysis;
(d) to establish the relationship between net subsidence of the depositional basin and different parameters like

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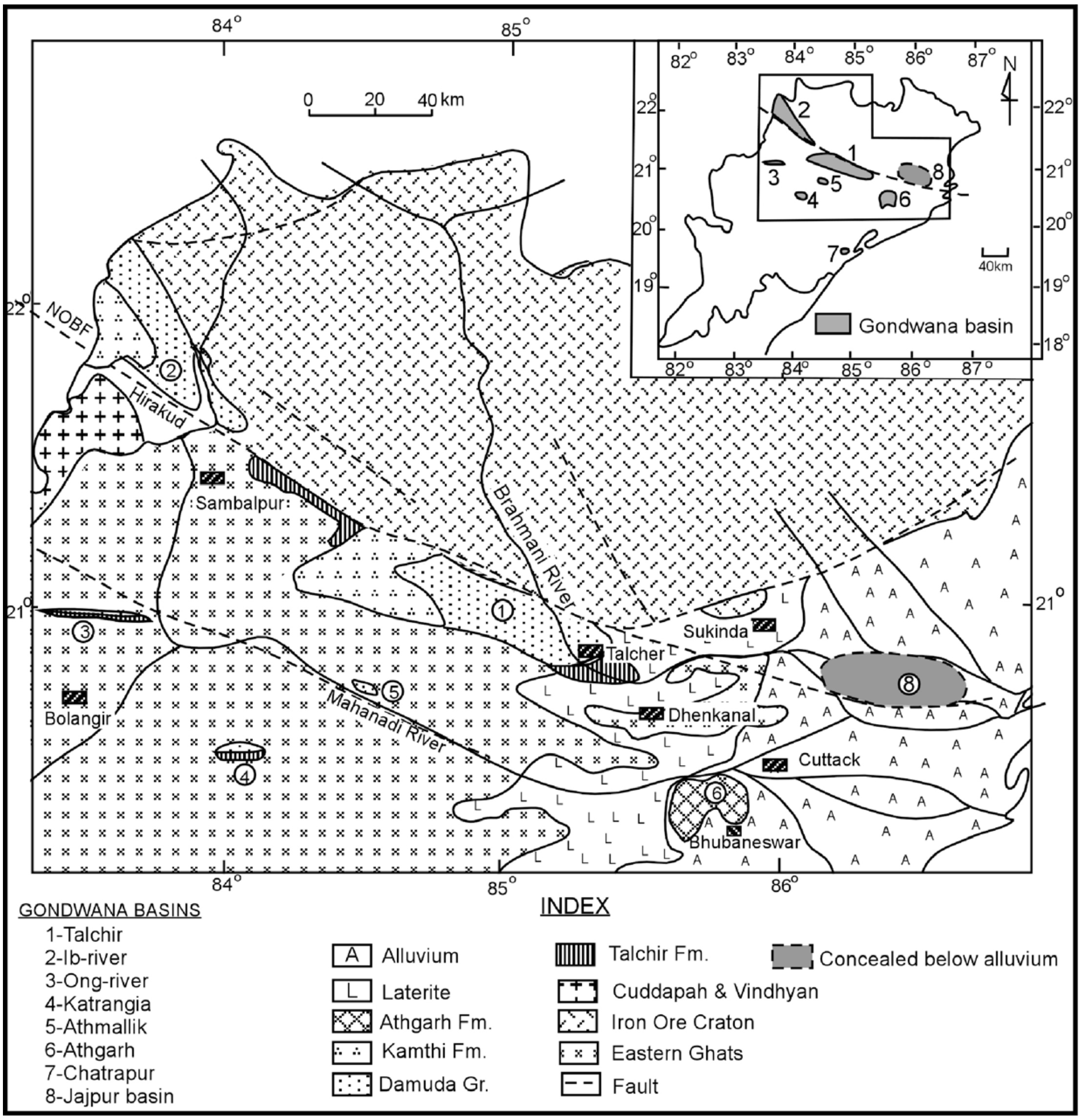

Fig.1. Gondwana basins of Orissa (modified after Pandya, 2006).

number and thickness of sandstone, shale and coal, which constitute the Barren Measures Formation by principal component and multiple regression analysis methods.

(e) to analyse the cause of cyclicity vis-à-vis Barren Measures sedimentation during Middle Permian.

GEOLOGICAL SETTING

The study area is located in the southeastern part of the Talchir Gondwana basin (Fig. 2). The Gondwana sediments of the study area (Fig. 3) represent a part of Barakar and Barren Measures Formations. The Barakar Formation comprises cyclothemic succession of sandstonse, shales and coal seams. The Barren Measures Formation comprises pebble beds, fine- to coarse-grained sandstones, shales and coal stringers. The sandstones and the shales are often ferruginous and workable coal seams are absent. The Barren Measures rocks are disposed in a homoclinal trend striking east-west and dipping towards north at low angles ranging from 4 to 8 degrees (Fig. 3). The average thickness of Barren Measures strata is about 150 m and are composed of thin conglomerates and sandstones of different textures (80.87%), grey and ferruginous shales (18.68%) with subordinate carbonaceous shale and coal stringers (0.45%). Predominance of coarse clastics and abundance of tabular and trough cross beddings suggest a possible braided stream origin of the Barren Measures Formation (Pettijohn, 1984; Tewari, 1995; Prothero and Schwab, 1996 and Nichols, 1999). This is supported by the

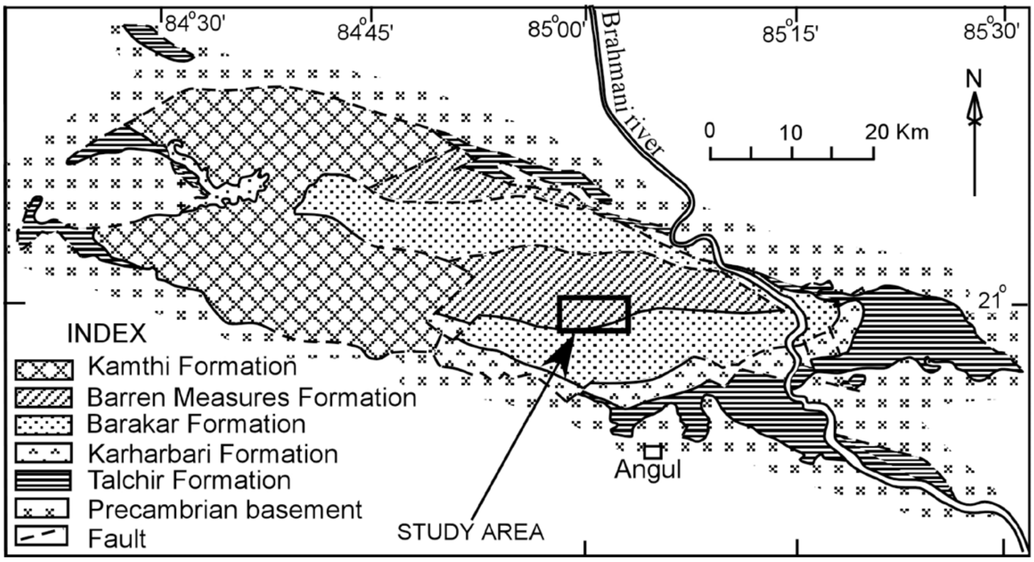

Fig.2. Geological sketch map of the Talchir Gondwana basin showing the study area (modified after Raja Rao, 1982).

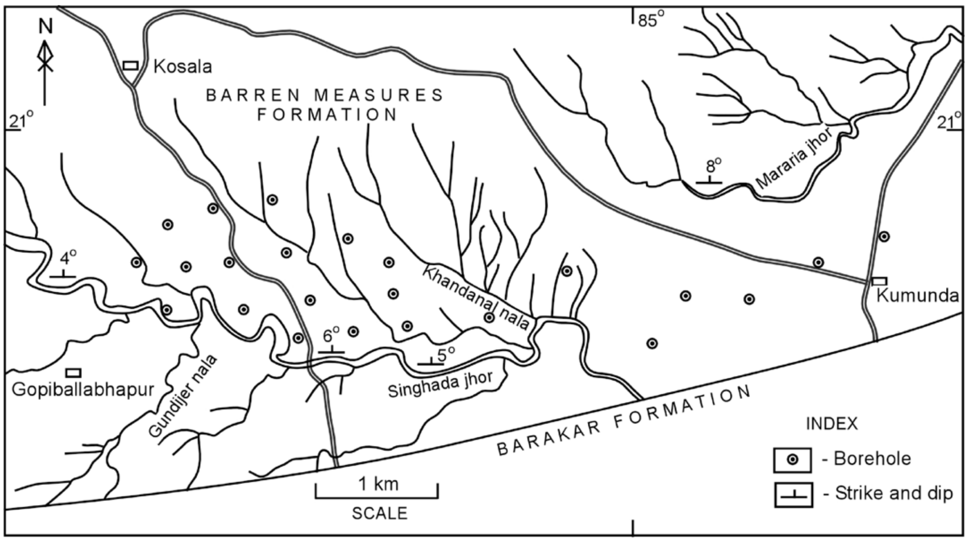

Fig.3. Geological map of the study area with location of boreholes.

presence of cut and fill structures, channeling and lenticular beds.

METHODS OF STUDY

Fieldwork was carried out to study the Barren Measures rocks exposed in the sections of the easterly and north-easterly flowing streams. Due to erratic nature and discontinuous exposures, vertical relationship between different lithofacies could not be ascertained from surficial studies. Twenty three borehole sections (Fig.3) drilled and logged by Central Mining Planning and Design Institute and Directorate of Geology, Govt. of Orissa are used in the present study.

There is disagreement among different workers regarding the scale and boundary of a sedimentary cycle. While Udden (1912) advocated a cycle to commence from the base of coal seam, Weller (1930) opined that each cycle starts with sandstone at the base. Read and Dean (1967 and 1976) suggested the minimum thickness of a cycle to be 0.3 m and Casshyap (1975) put it to be 1 m. In the present study, the sequence of strata of more than 1 m thickness with basal coarse member (conglomerate or sandstone) and terminating with shale bed or coal seam has been considered to constitute a cycle. This is in conformity with the definition of fining upward cycle of Allen (1965a) for the alluvial sediments and coal cycle of Casshyap (1970). Both types correspond to complete cycles of stream system in fluvial environment in accordance with the concept of Strahler (1963) that the coal-forming environment is apparently not a normal feature of the alluvial flood plain.

To make the data analysis simple and to avoid the risk of error the lithologies observed in the surface exposures were condensed into five facies states on the basis of lithology and texture as observed in the borehole records (Miall, 1973 and Casshyap, 1975). These are:

Facies-A: Coarse-grained sandstones that include massive conglomerates, pebbly sandstones, flat-bedded pebbly and coarse-grained sandstones, trough- and tabular cross-bedded coarse-grained sandstones.

Facies-B: Medium-grained sandstones that include trough- and tabular cross-bedded coarse to medium- and medium-grained sandstones.

Facies-C: Fine-grained sandstones that include parallel and ripple-drift cross-laminated medium to fine- and fine-grained sandstones.

Facies-D: Shales that include interbedded sandstone-shales and grey and ferruginous shales.

Facies-E: Coal that includes carbonaceous shale, shaly-coal and coal, which commonly constitute a coal seam in Talchir coalfield.

Concept of five lithofacies seems reasonable as A and B represent mid- and distal-channel bar deposits respectively; C is characteristic of bar-top and abandoned-channel deposits; D represents proximal flood plain, abandoned channel fill and over bank deposit and E is the deposit in the peat swamps (Allen, 1965b; Casshyap, 1970; Miall, 1977; Cant and Walker, 1978 and Sengupta, 2007).

The upward facies transition data of twenty three boreholes (Fig. 3) were added to form a transition count matrix (f_{ij}), which was processed into transition probability (p_{ij}) independent trial/random probability (r_{ij}) and difference (d_{ij}) matrices by the methods outlined by Miall (1973) and Casshyap (1975). The cyclicity (Markovian property) of facies states was tested by chi-square statistics proposed by Billingsley (1961) and Harbaugh and Bonham-Carter (1970). The degree and nature of ordering of facies states were investigated by the concept of entropy (Hattori, 1976). The entropies of each facies states after deposition $E^{(post)}$ were computed from the Markov matrix (p_{ij}).The entropies of each facies states before deposition $E^{(pre)}$ were computed from the probability matrix (Q) obtained from the frequency matrix (f_{ij}) by dividing each transition frequency by the corresponding column total. Since the entropy values are dependent on the number of states under consideration, they were normalised before plotting in the graph. Entropy of the sedimentation process was computed to know the depositional environment of the Barren Measures Formation.

Relationship between total thickness of strata (net subsidence), number and thickness of sedimentary cycles were studied by regression analysis. Since the dip of the Barren Measures Formation is very low, there is not perceptible difference between the strata cut by bore and their true thickness. The data of 23 boreholes shown in Fig. 3 were used in the present case. The length of each borehole section was taken into consideration for the calculation of total thickness of strata and number of cycles. Total thickness of strata (x in m), number of cycles (y) and average thickness of cycle (z in m) were computed for all the twenty three sections. The methods of linear and curvilinear regression analysis outlined by Davis (2002) were used in the present case. First- and second-degree polynomial regression lines were fitted to the data sets by least-square criteria. Percentages of goodness of fit of each regression line and 95% confidence (fiducial) limits were calculated. Analysis of variance was performed using the F-test to verify the significance of each regression line and whether each second-degree polynomial line is making a significant additional contribution to the regression variance already explained by the first degree line or not. Correlation coefficients between pairs of variables were computed. Their significance was tested by the Student's t-test. The principal component and multiple regression analyses have been done by SPSS and Statistica software.

RESULTS AND DISCUSSION

Markov Chain Analysis

The transition count (f_{ij}), transition probability (p_{ij}), random probability (r_{ij}) and difference (d_{ij}) matrices of the Barren Measures Formation facies states are summarised in Table 1. The computed values of chi-square exceed the limiting value at the 0.1% significance level suggesting the presence of Markovity and cyclic arrangement of facies states. The facies relationship diagram (Fig. 4) is constructed from the difference matrix results. It suggests that the Barren Measures cycles are fining-upward asymmetric type. Each complete cycle starts with a 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 grey and/or ferruginous shales (facies D) and in some cases terminates with a carbonaceous shale or coal stringers (facies E) at the top. Predominance of truncated fining upward cycles with abrupt changes in lithology at the top suggests deposition of Barren Measures sediments by rapidly shifting braided

Table 1. Markov matrices and χ^2 test statistics of facies states of the Barren Measures Formation

Transition count matrix (f_{ij})						Transition probability matrix (p_{ij})					
	A	B	C	D	E		A	B	C	D	E
A	0	15	17	4	0	A	0.00	0.42	0.47	0.11	0.00
B	7	0	37	15	0	B	0.12	0.00	0.63	0.25	0.00
C	15	32	0	161	5	C	0.07	0.15	0.00	0.76	0.02
D	14	16	163	0	34	D	0.06	0.07	0.72	0.00	0.15
E	0	0	5	33	0	E	0.00	0.00	0.13	0.87	0.00
Random probability matrix (r_{ij})						Difference matrix (d_{ij})					
	A	B	C	D	E		A	B	C	D	E
A	0.00	0.11	0.40	0.42	0.07	A	0.00	0.31	0.07	-0.31	-0.07
B	0.07	0.00	0.41	0.44	0.07	B	0.05	0.00	0.22	-0.19	-0.07
C	0.10	0.16	0.00	0.63	0.11	C	-0.03	-0.01	0.00	0.13	-0.09
D	0.10	0.17	0.62	0.00	0.11	D	-0.04	-0.10	0.10	0.00	0.04
E	0.07	0.11	0.40	0.42	0.00	E	-0.07	-0.11	-0.27	0.45	0.00

Test of significance

Test equation	Computed value of χ^2	Degrees of freedom	Limiting value of χ^2 at 0.1% significance level
Billingslay (1961)	136.54	15	37.70
Harbaugh and Bonham-Carter (1970)	376.78	11	31.26

Legend: A: Coarse-grained sandstone, B: Medium-grained sandstone, C: Fine-grained sandstone, D: Shale, E: Coal. For each transition pair, the row letter represents the lower facies and the column letter, the upper facies.

streams. Had the deposition been in meandering stream depositional environment, then the cycles would have been gradually fining upward as in case of Barakar Formation (Prothero and Schwab, 1996; Hota and Maejima, 2004).

The excess of probability of transition of A to B and B to A over random transition are 0.31 and 0.05 respectively, which indicate frequent braiding of the stream channels that lead to the superposition and interfingering of proximal channel facies by distal channel facies and *vice versa* as visualized by Das and Pandya (1995). The excess of probability of bar-top and abandoned-channel deposits (facies C) overlying facies A and B are 0.07 and 0.22 respectively, which suggest that the channels were more frequently abandoned, a feature generally common in braided streams than sidewise migration of meandering stream and deposition of fine-grained sandstones. This indicates dominance of braided stream regime during Barren Measures sedimentation. The fine-grained sandstones (facies C) are succeeded by interbedded sandstone-shale and/or grey and/or ferruginous shales (facies D) with difference probability of 0.13. In many instances, the cycles terminate with facies D at the top. In a few cases, thin carbonaceous shale or coal stringer (facies E) are present at the top of the cycles. In the later case, the facies E is overlain by facies D with a relatively larger value of difference probability (0.45), which is succeeded by facies C by difference probability of 0.10. These features suggest that many of the abandoned channels received fine clastics during the periods of greater discharge while a few of them were converted to short lived peat swamps for temporary period. The peat swamps were quickly covered by sidewise migrating over bank (D) and bar top (C) facies.

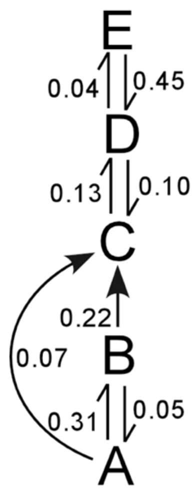

Fig.4. Facies relationship diagram of the Barren Measures Formation of the study area.

Entropy Analysis

$E^{(pre)} > E^{(post)}$ relationship (Table 2) in case of sandstone

Table.2. Entropy values of facies states of the Barren Measures Formation

Facies	$E^{(Pre)}$	$E^{(Post)}$	$R^{(Pre)}$	$R^{(Post)}$	Relationship
Coarse-grained sandstone (A)	1.51	1.38	0.76	0.69	$E^{(Pre)} > E^{(Post)}$
Medium-grained sandstone (B)	1.49	1.29	0.74	0.64	$E^{(Pre)} > E^{(Post)}$
Fine-grained sandstone (C)	1.17	1.09	0.59	0.55	$E^{(Pre)} > E^{(Post)}$
Shale (D)	1.09	1.26	0.55	0.63	$E^{(Pre)} < E^{(Post)}$
Coal (E)	0.56	0.56	0.28	0.28	$E^{(Pre)} = E^{(Post)}$
	$E_{(Max)} = 2.00$		$E_{(System)} = 3.08$		

$E^{(Pre)}$: Entropy before deposition $R^{(Pre)}$: Normalised entropy before deposition
$E^{(Post)}$: Entropy after 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 the Barren Measures Formation

facies indicates that these facies exert strong influence on their successors but are relatively uninfluenced by their precursors. Coarse-grained sandstone (facies A), medium-grained sandstone (facies B) and fine-grained sandstone (facies C) are succeeded by medium-grained sandstone (facies B), fine-grained sandstone (facies C) and shale (facies D) with d_{ij} values of 0.31, 0.22 and 0.13 respectively. $E^{(pre)} < E^{(post)}$ relationship in case of shale (facies D) suggests that this facies does not show strong memory for succeeding lithological state but is dependent on the preceding state in the succession. In the present study, the difference probabilities of facies D underlain by fine-grained sandstone and overlain by coal are 0.13 and 0.04 respectively (Fig. 4). The $E^{(pre)} = E^{(post)}$ relationship in case of coal suggests that this facies is equally influenced by its successor and precursor. The probability of coal underlain and overlain by shale is 0.87 (p_{ij} and q_{ij}). The Barren Measures cycles are asymmetric and truncated. The entropy sets for facies states (Fig. 5) belong to the A-4 of Hattori, 1976, which consists of different proportions of lower, upper and side

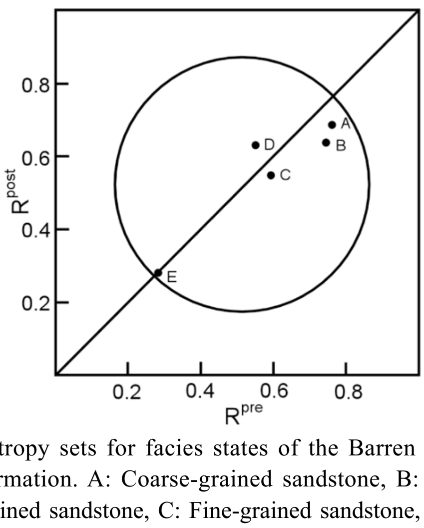

Fig.5. Entropy sets for facies states of the Barren Measures Formation. A: Coarse-grained sandstone, B: Medium-grained sandstone, C: Fine-grained sandstone, D: Shale, E: Coal.

truncated cycles of lithologic states. The facies relationship diagram (Fig.4) suggests that very often the Barren Measures cycles terminate with a shale facies at the top and thus are upper truncated. Some of the cycles which develop in abandoned channel areas start with fine-grained sandstone and are C – D – E type i.e. bottom truncated. Though the facies A, B, C and D are overlain by these facies in different frequencies (Table 1), they are not represented in the facies relationship diagram (Fig. 4) excluding A – C transition, which occur in very low frequency.

The entropy of the Barren Measures sedimentation system as shown in Fig.6 plots below the coal measure and alluvial-fluvial successions fields in the succession

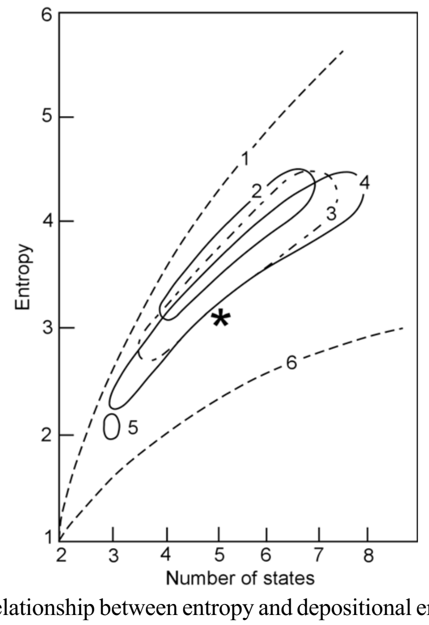

Fig.6. Relationship between entropy and depositional environment of lithological sequences (after Hattori, 1976). 1-Maximum entropy, 2-Entropies for the coal-measure successions, 3-Entropies for fluvial-alluvial successions, 4-Entropies for neritic successions, 5-Entropies for flysch sediments, 6-Minimun entropy, *: Entropy for the Barren Measures Formation.

Table 3. Equations of first- and second-degree polynomial regression lines and F-test results

First-degree polynomial	F-test result	Second-degree polynomial	F-test result
(a) Total thickness of strata (x in m) versus number of cycles (y)			
y = - 0.0009 + 0.0784x (± 1.47)[Y]	214.10*	y = - 0.5076+ 0.0954x – 0.0001x^2 (±0.85)	321.36§
(b) Total thickness of strata (x in m) versus average thickness of cycles (z in m)			
z = 14.834 - 0.0213x (± 5.06)	1.31*	z = 18.81 - 0.1548x + 0.0009x^2 (± 4.83)	1.71§
(c) Number of cycles (y) versus average thickness of cycles (z in m)			
z = 16.087 - 0.5011y (± 4.29)	6.98*	z = 20.862 – 2.6912y + 0.1987y^2 (± 3.65)	8.38§

[Y]95% confidence (fiducial) limits are given in brackets; $*F_{[(n1 = 1, n2 = 21), a = 0.05]} = 4.32$; $^{\S}F_{[(n1 = 2, n2 = 20), a = 0.05]} = 3.49$

discrimination diagram of Hattori (1976, Fig.16). This is due to lower degree of randomness of the Barren Measures sedimentation system as indicated by lower value of $E_{(System)}$ (3.08) (Table 2) in comparison to the Barakar sedimentation system (3.799 in Hota et al. 2003) and Barren Measures Formation (3.567 in Hota and Maejima, 2004). This may be due to congregation of both coal and non-coal cycles in the present study.

Regression Analysis

The equations of first- and second-degree polynomial regression lines along with the 95% confidence (fiducial) limits and F-test results are given in Table 3 and the corresponding lines are plotted in Figs.7a-c. The lines are comparable with each other and with those given by Duff (1967), Read and Dean (1967, 1976), Johnson and Cook (1973), Casshyap (1975) and Hota and Pandya (2002). It is interesting to note that the second-degree polynomial regression lines are divisible into two categories. In case of x versus y, (Table 3a) the coefficient of the first-degree term is positive and that of second-degree term is negative. This line (Fig. 7a) shows upward convexity. In the remaining two cases (x versus z and y versus z, Table 3b and c) the coefficient of the first-degree terms are negative and that of the second-degree terms are positive. Such curves (Figs.7b and 7c) when superimposed on the first-degree lines, display upward concavity. It is to be noted that the second-degree line is a parabola with general regression equation "$y = a + bx + cx^2$" the second derivative (d^2y/dx^2) of which is 2c. Depending on the positive or negative sign of c (the coefficient of second-degree term), the curve shows upward concavity or convexity with base line (X-axis). The computed values of 'F' in case of first- and second-degree lines (x versus y and y versus z) exceed the critical value at the 5% significance level (Table 3). Thus, the null hypothesis (H_0) that the variance about the regression line is not different from the variance in the observation is rejected and the alternate hypothesis (H_1) that there is significant difference of variance about the regression line and the variance in the observation is accepted. These four lines are statistically significant at the 5% significance level. The computed values of 'F' in case of first- and second-degree lines of x versus z are less than the critical value at the 5% significance level (Table 3). Thus, the null hypothesis (H_0) that the variance about the regression line is not different from the variance in the observation is accepted.

The percentage of total sum of squares satisfied (percentage of goodness of fit) by first- and second-degree lines in case of x versus y are reasonably high, moderate in case of y versus z, and low in case of data sets x versus z (Table 4). The computed values of 'F' to test the significance of increase of fit of second-degree line over the first-degree line in former two cases are greater than the critical values at the 5% significance level (Table 4). In these two cases, the null hypothesis (H_0) that the added term in the regression equation does not make a significant contribution to the

Table 4. Correlation coefficients between variable pairs, percentages of goodness of fit of regression lines and F-test results of increase of fit of 2nd degree line over 1st degree line

Variables	Correlation coefficient (r)	Computed value of 't'	Percentage of goodness of fit of		Test of significance of increase of fit of 2nd degree line over 1st degree line (F-test result)
			1st degree line	2nd degree line	
x vs y	0.954	14.607*	91.04	91.17	39.36§
x vs z	-0.245	-1.156*	5.98	13.14	2.00§
y vs z	-0.492	-2.593*	24.24	44.43	7.60§

Legend: x = Total thickness of strata in m, y = number of cycles and z = average thickness of cycle in m.
$*t_{(n = 21, a = 0.05)} = 1.721$; $^{\S}F_{[(n1 = 1, n2 = 20), a = 0.05]} = 4.35$

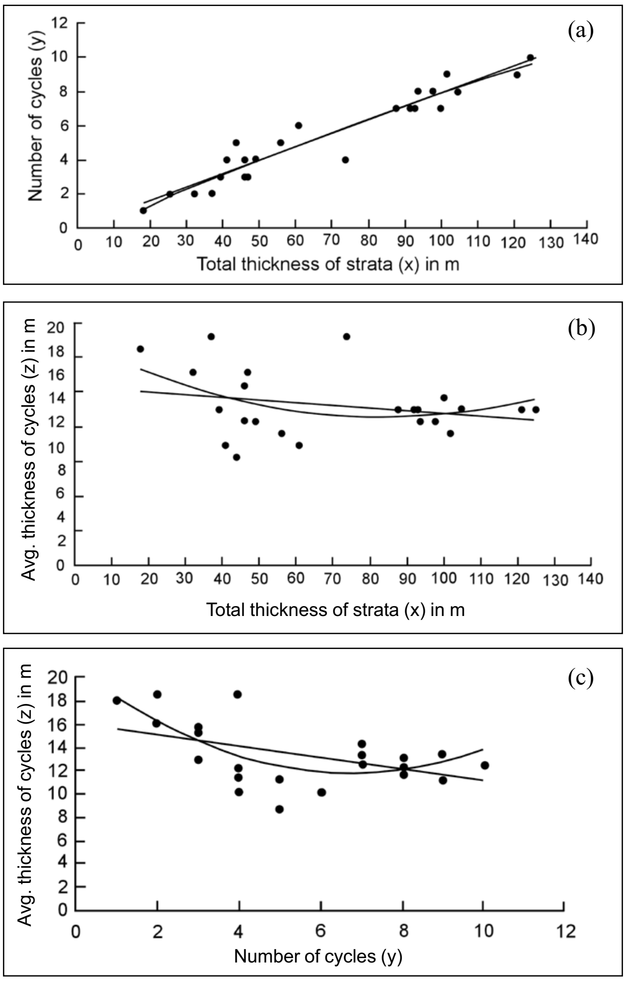

Fig.7. First- and second-degree lines showing statistical relationship between **(a)** total thickness of strata (x in m) and number of cycles (y), **(b)** total thickness of strata (x in m) and average thickness of cycles (z in m), **(c)** number of coal cycles (y) and average thickness of cycles (z in m) of the Barren Measures Formation of the study area.

regression variance is rejected. In these two cases attempt was made to fit the third-degree lines. In case of x versus y the third-degree line is "$y = -1.6139 + 0.1534x - 0.001x^2 + 0.000004x^3$" with goodness of fit of 91.38%. This line is almost coincident with the first- and second-degree lines and the increase of fit is not significant. In case of y versus z, the third-degree line is "$z = 23.77 - 4.9428y + 0.67y^2 - 0.0286y^3$" with goodness of fit of 47.58%. This line is almost coincident with the second-degree line. The second-degree lines are flat and closely follow the first-degree lines (Figs. 7a-c). The correlation coefficients, thus, adequately explain the relationship between the variables.

The computed values of 't' in x versus y and y versus z exceed the critical value (Table 4). This leads to the rejection of the null hypothesis (H_0) that the correlation coefficients are not significantly different from zero and acceptance of the alternative hypothesis (H_1) that the correlation coefficients are significantly different from zero. Thus, significant positive correlation (0.954, Table 4) between the total thickness of strata (x) and the number of coal cycles (y) and significant negative correlation (-0.492, Table 4) between the number of coal cycles (y) and their average thickness (z) exist. However, in case of x versus z, the correlation coefficient is negative (-0.245, Table 4) and not statistically significant

The first-degree polynomial regression line (Fig.7a) and the correlation coefficient value (r = 0.954, Table 4) demonstrate a direct relationship between the total thickness of strata (net subsidence) and the number of sedimentary cycles. This is in conformity with the findings of Duff (1967), Read and Dean (1967, 1976) Johnson and Cook (1973), Casshyap (1975) and Hota and Pandya (2002). The thicker the succession i.e. larger the subsidence of the depositional basin, greater is the number of cycles present. This direct relationship suggests that the cyclic sedimentation of the Barren Measures Formation was controlled by autocyclic process, which operated within the depositional basin rather than beyond the basin territory. A well known autocyclic process is the sedimentation that is caused by one or more of the factors like migration of delta, accumulation of peat, compaction of sediments and instability of channel development in the flood plain (Duff et al. 1967). Because the Barren Measures sediments are fluvial in nature (Hota et al. 2007) these might have been deposited by laterally migrating river channels and their associated deposits. Had the cyclic development been in response to allocyclic processes like extensive diastrophic movements, climatic control or eustatic rise in the sea level (Duff et al. 1967), then the number of cycles would have remained constant throughout the study area and the regression line would have been horizontal in Fig.7a. Thus, the Barren Measures sedimentation of the Talchir Gondwana basin is closely associated with the side-wise migration of streams or the drainage diversion (Belt et al. 1992) activated by intrabasinal differential subsidence.

Insignificant negative correlation (r = -0.245, Table 4) exists between total thickness of strata (net subsidence) and average thickness of sedimentary cycles (Table 4 and Fig.7b), which matches well with the findings of Johnson and Cook (1973) and Casshyap (1975). During Barren Measures sedimentation, the climate warmed up as a result of which the humid climate of Barakar Formation gradually changed over to semi-humid, semi-arid and finally to arid at the close of Damuda sedimentation. The changed climatic condition inhibited the growth of vegetation and also controlled the stream migration (Hota et al. 2007).

Significant negative correlation (r = -0.492, Table 4) exists between the number and average thickness of cycles (Table 4 and Fig. 7c). This inverse relationship matches well with the findings of Johnson and Cook (1973) and Casshyap (1975). This is attributed to the fact that the accumulation of fine-grained over bank and bar-top sediments as well as peat accumulations were disrupted by clastic sediments issued from the laterally migrating rivers that resulted in thinning of the coal and non-coal cycles and in increasing their number. Sporadic occurrence of coal stringers and abundance of truncated cycles support this conclusion.

Multivariate Analysis

The principal component and multiple regression analyses are multivariate statistical techniques, which have been recommended to find out interrelationships between several variables simultaneously (Davis, 2002). The first method has been used to quantify the variation of lithic fill of Scottish Namurian basin (Read and Dean, 1972, 1982) as well as interrelationship between lithologic variables of coal-bearing sediments of Indian coalfields (Tewari, 2008). The second method has been applied to know the role of different lithologic variables of coal and non-coal cycles in basin subsidence in the present work.

In the present study the sequence of strata comprising of a basal coarse member (conglomerate or sandstone) and terminating with a shale bed and / or coal stringer has been considered to constitute a cycle. The lithologic parameters are total thickness and number of constituent lithologies like sandstone, shale and coal stringers. It has been recommended that only those principal components, in which the eigen values are greater than unity, are statistically significant and can be used for geological interpretation (Read and Dean, 1972). The analytical results are presented in Table 5. It is seen that the communality of all the variables are appreciably high and only two of the principal components are statistically significant. The principal component – 1 with eigen value of 3.717 explains 53.107% of the total variance. It includes total thickness of strata as well as number and thickness of sand and shale beds. The principal component – 2 with eigen value of 1.672 explains 23.880 of total variance. It is strongly loaded on number and thickness of coal stringers. Thus, the number and thickness of sandstone and shale beds largely contribute to the total thickness of strata (net subsidence) during Barren Measures sedimentation.

Table 5. Matrix of the two components for the seven lithologic variables of the Barren Measures Formation of Talchir Gondwana basin

Lithologic variables	Principal components		Communality
	1	2	
Total thickness of strata	0.814*	-0.539	0.913
Total thickness of sandstone	0.744*	-0.594	0.651
Total thickness of shale	0.722*	-0.271	0.927
Total thickness of coal stringers	0.353	0.627*	0.838
Total number of sandstone bed	0.821*	0.267	0.989
Total number of shale bed	0.915*	0.285	0.776
Total number of coal stringers	0.586	0.639*	0.779
Eigenvalues	3.717	1.672	
Percentage of total variance	53.107	23.880	
Cumulative percentage of total variance	53.107	76.987	

* Highest positive value of principal component loading

While principal component analysis classifies the variables into different groups, the multiple regression analysis combines all the independent variables in a polynomial form to estimate the dependent variable quantitatively. In the present case total thickness of strata (net subsidence) of the basin has been taken as the dependent variable and the sedimentary cycle parameters (total thickness and number of sandstones, shales and coal stringers) as the independent variables. The F-test results are given in Table 6. The analysis of variance confirms the statistical significance of the regression equation (Total thickness of strata = - 0.212 + 1.002 thickness of sandstone + 0.995 thickness of shale + thickness of coal stringers + 0.0107 number of sandstone + 0.0256 number of shale – 0.0962 number of coal stringers) for the Barren Measures Formation at 0.05 significance level. The contributions of the thickness of sandstones, shales and coal stringers to the

Table 6. Completed ANOVA for testing the significance of regression of individual lithologic variables on the total thickness of strata of the Barren Measures Formation

Source of variation	Sum of squares	Degrees of freedom	Mean squares	F-Test
Regression	79144.81	6	13190.80	131908.02*
Total thickness of sandstone beds	34616.95	1	34616.95	346169.50*
Total thickness of shale beds	1042.80	1	1042.80	10428.00*
Total thickness of coal stringers	232.26	1	232.26	2322.60*
Total number of sandstone beds	0.01	1	0.01	0.10
Total number of shale beds	0.02	1	0.02	0.20
Total number of coal stringers	0.11	1	0.11	1.10
Deviation	1.63	16	0.10	
Total variation	79146.44	22		

*F values significant at 0.05 significance level; $F_{(6,16),\,0.05} = 2.74$; $F_{(1,16),\,0.05} = 4.49$

total thickness of strata are significant at 5% significant level (Table 6) and corroborate the results of principal component analysis.

CONCLUSIONS

Following conclusions have been drawn from the present study:

1. Markov chain analysis suggests the preferential arrangement of facies states and their organisation in the form of fining-upward cycles. Each complete cycle exhibits upward decrease of grain size, which is possibly due to decline of flow intensity and current velocity coupled with lateral migration of streams during deposition of each cycle.
2. The lithofacies constituting the fining-upward cycles can be linked with different sub-environments of braided channel fluvial system and their organization may be attributed to lateral migration of streams in response to intrabasinal differential subsidence. Each complete cycle with basal conglomerate or sandstone and terminating with shale or coal seam, suggest the establishment of some kind of channel system and subsequently its abandonment by stream and burial under peat swamp or freshly deposited coarse clastics.
3. The Barren Measures cycles belong to the A-4 type cyclic sequences of Hattori (1976), which consists of different proportions of lower, upper and side truncated cycles of lithologic states. The deposition of sandstones represents the most random event, which was possibly brought about by unsystematic change in the depositional mechanism activated by differential subsidence of the depositional area. Intrabasinal differential subsidence is responsible for the rejuvenation and lateral migration of the river system and consequent initiation of new cycles with freshly transported sediments.
4. Linear relationship between the total thickness of strata and sedimentary cycles worked out by different workers for the cyclic sedimentation at other places is also applicable to the fluvial sediments of Barren Measures Formation of Talchir Gondwana basin. The number of cycles closely relates to the total thickness of strata. Since the Barren Measures Formation is essentially fluvial and the cycles are autocyclic in nature, the sedimentary distributive mechanism, by lateral migration (or diversion) of streams, might have been the probable means for the development of sedimentary cycles. Thus, the cyclic sedimentation of Barren Measures Formation could have resulted due to intrabasinal differential subsidence of the depositional surface. Poor correlation between total thickness of strata and average thickness of cycle suggests inconsistent relationship between subsidence and vegetation growth in case of coal cycles and irregularity of channel migration in case of non-coal sedimentary cycles, which is due to changes in climate during Barren Measures sedimentation. The inverse relationship between number and average thickness of cycles might be due to frequent disruption of deposition of fine-grained over bank and bar-top sediments as well as peat accumulations by clastic sediments issued from laterally migrating streams.
5. The multivariate methods of principal component and multiple regression analyses suggest that thickness of sandstones and shale beds largely account for the subsidence of the basin during Barren Measures sedimentation.

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