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Net subsidence and evolution of coal swamps in Early Permian coal measures of eastern India Gondwana basins using principal component analysis

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Abstract

Principal component analysis is applied to explain variation in net subsidence (i.e. total thickness) in the Karharbari and Barakar coal measures, respectively of Giridih and Korba coalfields of eastern India Gondwana basins. Results suggest that total thickness of sandstone and number of sandstone beds are largely responsible for variation in net subsidence in the Karharbari coal measures of Giridih, whereas total thickness of sandstone, number of sandstone and number of coal beds mainly control variation in net subsidence in the Barakar Formation of Korba coalfield.

The greater degree of relationship between the total thickness of coal with total thickness of shale and total thickness of sandstone in the Karharbari implies the development of peat swamps in distal flood plains and also in abandoned channels. In the Barakar, the close association of total thickness of coal with total thickness and number of sandstone beds indicates formation of peat swamps largely in abandoned channels.

Key-words : principal component analysis, net subsidence, Gondwana, coal measures.

Introduction

The early Permian fluvial Gondwana coal measures of peninsular India exhibit variation in total thickness and number and thicknesses of constituent lithologies of sandstone, shale and coal in different Gondwana basins (Casshyap and Tewari, 1984). These variations are the result of complex geological processes including depositional environment, tectonic setting and differential subsidence and therefore require special attention. Besides field studies as summarized elsewhere (Veevers and Tewari, 1995), the litho sequences from these coal measures have been statistically analysed for cyclicity using Markov chain and Entropy Function (Tewari and Casshyap, 1983; Casshyap and Tewari, 1984; Hota et al., 2003; Hota and Maejima, 2004) and Cluster Analysis (Tewari, 1997). Casshyap et al. (1988) using linear regressions and product moment correlations established statistical relationship between various lithologic variables of sandstone, shale and coal from different Gondwana coalfields of peninsular India. Khan and Tewari (1991) analysed quantitative relationships between the number of coal bearing cycles and total thickness of strata (net subsidence) in a number of Gondwana coalfields of eastern India. However, the phenomenon of variation in net subsidence (total thickness) of early Permian Gondwana coal measures with respect to constituent lithologies has not yet been quantitatively documented and interpreted. Thus it would be meaningful to evaluate such relationships and their contribution in the variation of total thickness i.e. net subsidence of early Permian Gondwana coal measures of peninsular India. The study may also have significant bearing on the evolution of peat swamps in fluvial system.

The present study therefore aims at (1) analysing variations in total thickness (net subsidence) of Karharbari coal measures of Giridih and Barakar coal measures of Korba coalfields; and (2) analysing and interpreting the development of coal swamps.

Geology, Sedimentary Characters and Nature of Data

The Permian Gondwana sediments of peninsular India enclose coal beds at three stratigraphic horizons: the Karharbari, Barakar and Raniganj Formations. These sequences are characterised by fining upward fluvial cycles deposited by northwesterly flowing braided and meandering streams (Tewari, 1997; Tewari and Casshyap, 1983; Casshyap and Tewari, 1984). The present study includes Karharbari Formation of Giridih and Barakar Formation of Korba coalfields, respectively (Fig. 1). Talchir, Karharbari and Barakar Formations represent the Gondwana stratigraphy of these coalfields in ascending order (Table 1). The Giridih coalfield is a small graben-like isolated basin of the Koel-Damodar-basin of eastern India, whereas the Korba coalfield represents a half graben within the fairly continuous Son-Mahanadi Gondwana basin of the eastern part of Central India (Fig. 1). Although, the given coalfields exhibit different tectonic settings, the Karharbari Formation of Giridih and Barakar Formation of Korba are quite similar in sedimentary characters and depositional environment (Casshyap and Tewari, 1984).

The study is based on 33 and 32 borehole logs, respectively for Karharbari Formation of Giridih and Barakar Formation of Korba coalfield. The borehole logs used in the present study were used earlier for Markov chain analysis (Tewari and Casshyap, 1983; Casshyap and Tewari, 1984), linear regression and correlation coefficients (Casshyap et al., 1988), cycles and subsidence (Khan and Tewari, 1991) and cluster analysis (Tewari, 1997). In view of the gentle dip of 3°–8°, the strata intersected in the borehole represents near-true thickeness of the sequence. Fig. 2 illustrates part of Karharbari and Barakar stratigraphy reproduced from borehole logs. The total thickness of Karharbari Formation of Giridih varies from 16–305 m, and that of Barakar of Korba coalfield from 750–900 m. The number and thicknesses of three constituent lithologies of sandstone, shale and coal also vary throughout the two coalfield areas. The following stratigraphic and lithologic variables are computed from 33 and 32 borehole logs, from the Karharbari and Barakar Formations from Giridih and Korba coalfields, respectively.

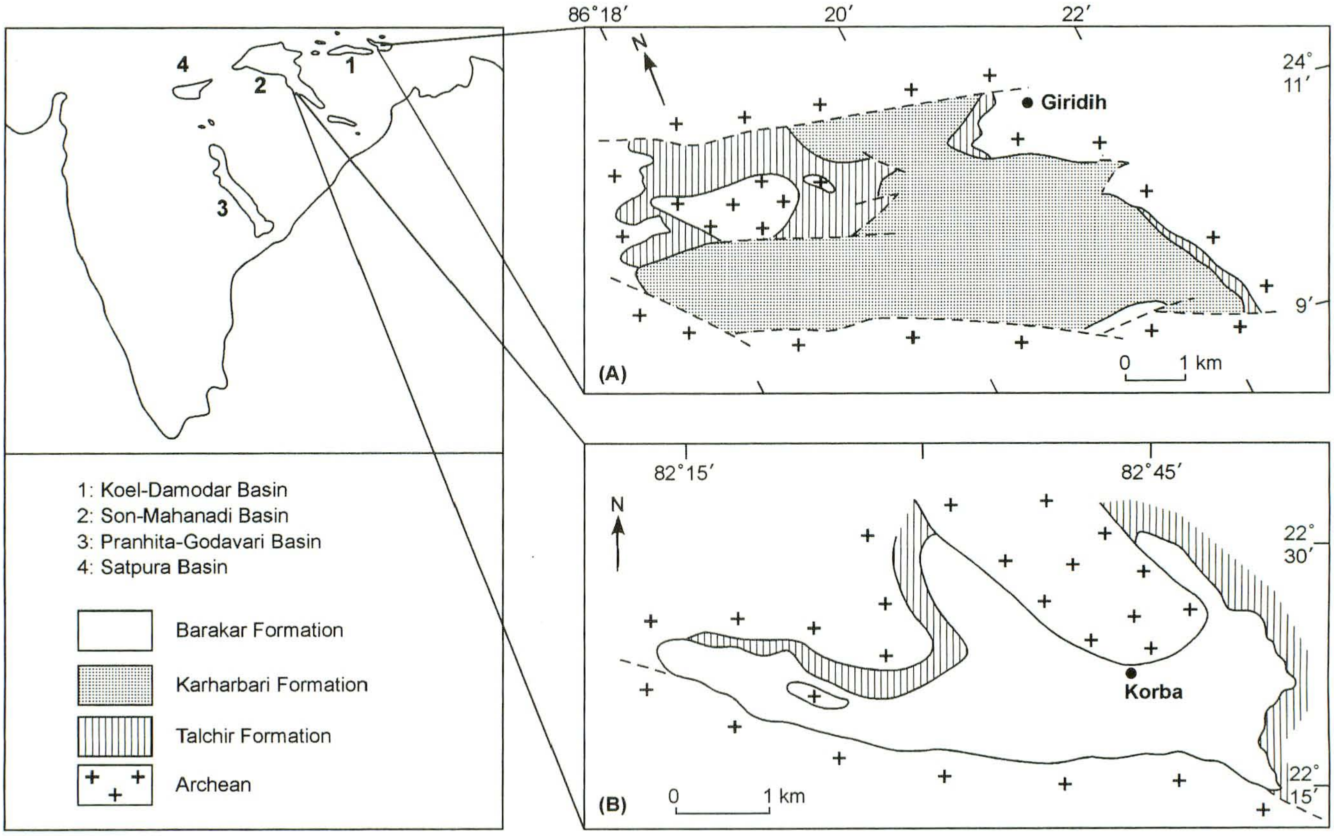

Fig. 1 Location and geological maps of (A) Giridih and (B) Korba coalfields.

Table 1 Stratigraphy and lithologic characters of Gondwana rocks of Giridih and Korba coalfields of eastern India (Based on Raja Rao, 1983, 1987).

Giridih Coalfield	Korba Coalfield	Lithologic Characters
–	Barakar Formation (750-900 m)	Fining upward cycles of coarse to medium grained sandstone interbedded with fine-grained sandstone or siltstone, carbonaceous shale and coal. In Korba area thick beds of conglomerate occur in association of very coarse grained sandstone in the middle part.
Karharbari Formation (165-305 m)	–	Top: Fining upward cycles surmounted by coal ; middle: multistory and multilateral coalescing channel shaped sandstone bodies; base: clast supported conglomerate.
Talchir Formation (15-90 m)	Talchir Formation (200 m)	Stratified tillite, congomerate, cross-bedded sandstone, interbedded with rhythmite with or without dropstones and greenish shale.

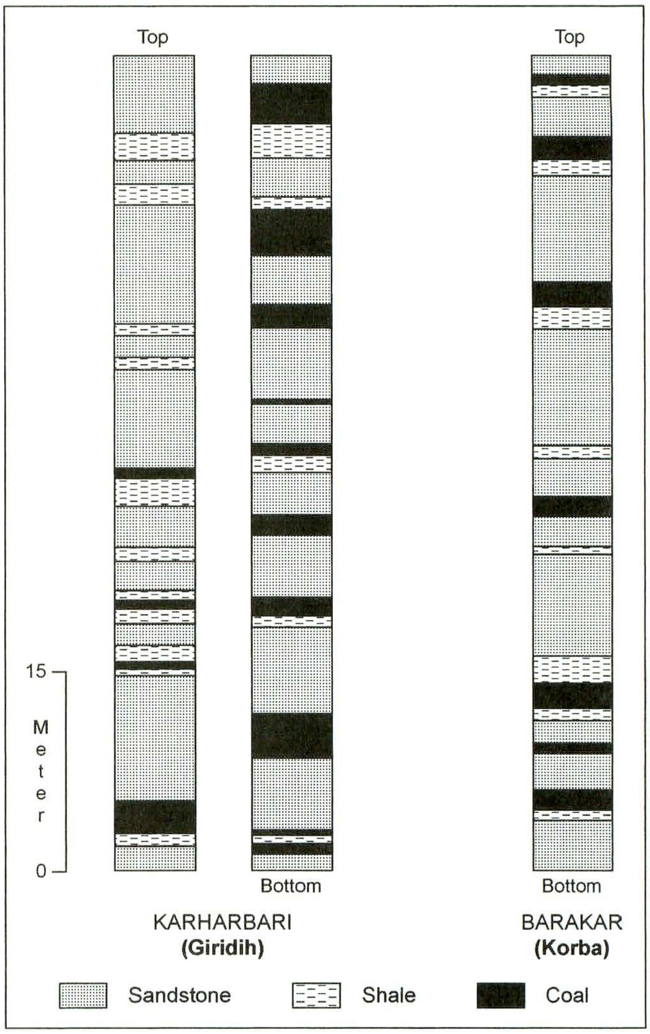

Fig. 2 Parts of stratigraphic sections of Karharbari and Barakar Formations.

Stratigraphic Variable

1. Total thickness

Lithologic Variables

2. Total thickness of sandstone beds
3. Total thickness of shale beds
4. Total thickness of coal beds
5. Total Number of sandstone beds
6. Total Number of shale beds
7. Total Number of coal beds
8. Sandstone / shale ratio
9. (Sandstone + shale) / coal ratio

These variables are formally designated as K_1-K_9 for Karharbari Formation and B_1-B_9 for Barakar Formation.

Principal Component Analysis

The simple approach of analysing and interpreting stratigraphic and lithologic variations of a given basin is to document contour facies maps (Krumbein and Sloss, 1963). The quantitative approach to analyse such variations is to compute linear regressions and corresponding correlation coefficients (Casshyap et al., 1988). It would result in a large number of correlation coefficients but may provide simple statistical relationship between the two variables. However, the simultaneous interrelationships of a number of variables from a fairly large number of localities cannot be analysed by the above approach. The Principal component analysis is a multivariate statistical technique, which has been recommended to analyse interrelationships of several variables simultaneously (Davis, 1986). It has been used to demonstrate quantitative variation in litho-fill thickness of a given basin through space (Read and Dean, 1972). In addition to statistical interrelationships, the Principal component analysis precisely leads to pick out those variables, which are statistically significant and account for variation in litho-fill thickness such as net subsidence.

Detailed computational procedure of Principal component analysis is given in Davis (1986) and summarized as follows. The first step in this analysis is to arrange the data in the form of matrix where rows correspond to localities and columns represent variables (Tables 2 and 3). The basic data is then log normalised (log Xi, i = 1 to 9) so as to give equal weights to all variables

(Tables 4 and 5). Using the normalized data matrix, the correlation coefficients are computed for each pair of variables. Finally eigenvalues and eigenvectors are computed from the correlation matrix. The eigenvalues are roots of correlation matrix, and the corresponding eigenvectors are referred to as principal components. It has been recommended that only those principal components, which are greater than unity, are statistically significant and

Table 2 Stratigraphic and lithologic variables of Karharbari Formation, Giridih coalfield.

	K 1	K 2	K 3	K 4	K 5	K 6	K 7	K8	K 9
1	550.00	527.17	9.80	12.50	10.00	6.00	4.00	53.78	43.01
2	500.00	475.40	11.00	13.80	7.00	4.00	3.00	43.21	35.24
3	425.41	359.20	23.60	42.80	14.00	8.00	7.00	15.22	8.94
4	293.00	245.40	26.60	21.20	5.00	5.00	5.00	9.22	12.83
5	499.00	434.70	27.90	36.80	7.00	9.00	5.00	15.58	12.56
6	521.00	446.20	46.90	28.10	7.00	7.00	8.00	9.51	17.51
7	451.80	386.10	15.20	50.50	6.00	4.00	7.00	25.40	7.94
8	339.00	260.40	32.80	46.00	8.00	8.00	3.00	7.93	6.36
9	501.00	458.40	16.30	26.50	10.00	9.00	10.00	28.12	17.91
10	317.00	294.00	13.90	9.30	5.00	3.00	5.00	21.15	33.10
11	500.00	443.90	17.80	38.70	9.00	7.00	6.00	24.93	11.92
12	470.00	412.70	13.90	43.80	8.00	7.00	9.00	29.69	9.73
13	465.60	426.11	21.30	17.40	5.00	5.00	4.00	20.00	25.75
14	472.60	393.80	24.70	54.30	8.00	6.00	7.00	15.94	7.70
15	493.00	421.50	25.60	46.00	9.00	9.00	6.00	16.46	9.71
16	373.00	281.00	50.00	42.00	11.00	10.00	9.00	5.62	7.88
17	125.00	72.60	24.60	28.00	4.00	8.00	3.00	2.95	3.46
18	181.00	152.10	12.20	16.00	7.00	3.00	4.00	12.46	10.31
19	388.90	315.20	32.20	41.50	8.00	12.00	6.00	9.78	8.37
20	508.00	417.00	50.00	41.00	8.00	15.00	11.00	8.34	11.39
21	328.30	269.10	17.60	40.80	8.00	4.00	7.00	15.28	4.02
22	430.00	361.90	28.60	39.90	9.00	7.00	7.00	12.65	9.78
23	537.00	477.60	17.10	41.80	9.00	12.00	13.00	27.92	11.85
24	354.00	305.00	14.90	34.30	8.00	4.00	7.00	20.46	9.32
25	257.00	212.40	12.60	32.20	9.00	6.00	4.00	16.85	6.98
26	529.00	448.10	44.10	35.40	10.00	10.00	7.00	10.16	13.94
27	312.00	255.10	36.50	20.50	3.00	9.00	6.00	6.98	14.15
28	515.00	438.80	59.50	16.80	5.00	8.00	4.00	7.20	29.64
29	409.00	349.90	60.30	30.00	4.00	6.00	2.00	5.80	13.36
30	507.50	391.50	79.30	86.90	10.00	8.00	10.00	4.93	5.41
31	137.90	70.90	35.50	21.70	4.00	5.00	2.00	1.99	4.89
32	502.00	480.20	15.30	6.70	8.00	9.00	5.00	31.39	73.95
33	451.00	406.40	28.10	16.70	7.00	10.00	4.00	14.46	24.01

Table 3 Stratigraphic and lithologic variables of Barakar Formation, Korba coalfield.

	B 1	B 2	B 3	B 4	B 5	B 6	B 7	B 8	B 9
1	62.79	27.28	1.06	34.45	3.00	1.00	2.00	25.74	0.82
2	83.45	44.19	6.00	33.26	5.00	4.00	27.00	7.37	1.34
3	53.99	21.03	6.77	26.10	3.00	4.00	9.00	3.11	1.06
4	54.33	22.17	4.35	27.81	2.00	4.00	3.00	5.10	0.95
5	45.52	16.60	3.60	25.32	2.00	4.00	4.00	4.61	0.80
6	167.94	115.10	8.81	44.03	11.00	10.00	6.00	13.06	2.81
7	210.89	158.18	12.01	40.70	7.00	11.00	9.00	13.17	4.18
8	188.01	138.61	14.41	34.99	6.00	11.00	5.00	9.62	4.37
9	89.34	53.50	13.90	21.94	7.00	11.00	2.00	3.85	3.07
10	229.18	214.52	10.11	4.55	4.00	10.00	2.00	21.22	49.37
11	124.74	85.99	8.99	30.64	9.00	7.00	4.00	9.57	3.10
12	191.21	129.88	9.58	51.25	5.00	5.00	6.00	13.56	2.69
13	250.77	195.16	10.65	44.96	7.00	13.00	8.00	18.32	4.58
14	101.79	62.85	5.67	33.27	6.00	6.00	3.00	11.08	2.06
15	145.72	106.74	9.50	29.48	6.00	10.00	4.00	11.24	3.94
16	90.74	56.57	1.97	32.20	4.00	1.00	2.00	29.72	1.82
17	126.00	122.45	1.77	1.78	9.00	2.00	1.00	69.18	69.79
18	39.93	16.86	5.15	17.92	4.00	5.00	9.00	39.27	1.23
19	125.88	82.01	3.05	40.82	4.00	10.00	9.00	26.88	2.08
20	95.37	78.48	5.75	11.14	8.00	6.00	5.00	13.65	7.56
21	19.51	4.57	9.67	5.27	3.00	2.00	2.00	0.47	2.70
22	44.06	27.89	14.60	1.57	6.00	6.00	2.00	1.91	27.06
23	135.95	106.17	19.41	10.37	11.00	8.00	7.00	5.47	12.11
24	176.39	144.02	14.31	18.06	16.00	13.00	9.00	10.06	8.77
25	147.52	52.50	68.53	26.49	13.00	40.00	18.00	0.77	4.57
26	234.84	174.53	30.28	30.03	6.00	20.00	23.00	5.76	6.82
27	239.41	90.58	110.63	38.20	11.00	63.00	34.00	0.82	5.27
28	177.89	116.32	27.96	33.61	10.00	18.00	13.00	4.16	4.29
29	295.99	153.10	94.46	48.43	21.00	74.00	31.00	1.62	5.11
30	684.09	591.02	31.45	61.62	28.00	24.00	12.00	18.79	10.10
31	162.43	100.10	4.66	57.67	7.00	5.00	7.00	21.48	2.16
32	46.78	20.42	3.27	23.09	2.00	4.00	2.00	6.24	1.03

Table 4 Log normalized data of Karharbari Formation, Giridih coalfield.

	K 1	K 2	K 3	K 4	K 5	K 6	K 7	K 8	K 9
1	2.74	2.72	0.99	1.09	1.0	0.77	0.60	1.73	1.63
2	2.69	2.67	1.04	1.14	0.84	0.60	0.47	1.63	1.54
3	2.62	2.55	1.37	1.63	1.14	0.90	0.84	1.18	0.95
4	2.46	2.39	1.42	1.32	0.95	0.70	0.70	0.96	1.17
5	2.69	2.63	1.44	1.56	0.84	0.95	0.70	1.19	1.17
6	2.71	2.64	1.67	1.44	0.84	0.84	0.90	0.97	1.24
7	2.65	2.58	1.18	1.70	0.77	0.60	0.84	1.40	0.90
8	2.53	2.41	1.11	1.66	0.90	0.90	0.47	0.90	0.81
9	2.70	2.66	1.21	1.42	1.0	0.95	1.0	1.45	1.25
10	2.49	2.47	1.14	0.96	0.69	0.47	0.70	1.32	1.52
11	2.69	2.64	1.25	1.58	0.95	0.84	0.77	1.39	1.07
12	2.67	2.61	1.14	1.64	0.90	0.84	0.95	1.47	0.98
13	2.66	2.63	1.32	1.23	0.90	0.70	0.60	1.30	1.41
14	2.67	2.59	1.39	1.73	0.90	0.77	0.84	1.20	0.88
15	2.69	2.62	1.40	1.66	0.95	0.95	0.77	1.21	0.98
16	2.59	2.44	1.70	1.62	1.04	1.0	0.95	0.74	0.89
17	2.09	1.86	1.39	1.44	0.60	0.80	0.47	0.47	0.54
18	2.25	2.18	1.08	1.20	0.84	0.47	0.60	1.09	1.01
19	2.59	2.49	1.50	1.62	0.90	1.07	0.77	0.99	0.92
20	2.70	2.62	1.70	1.61	0.90	1.17	1.07	0.92	1.05
21	2.51	2.42	1.24	1.61	0.90	0.60	0.84	1.18	0.60
22	2.63	2.55	1.29	1.60	0.95	0.84	0.84	1.10	0.99
23	2.72	2.67	1.23	1.62	0.95	1.07	1.17	1.44	1.07
24	2.55	2.48	1.17	1.53	0.90	0.60	0.84	1.31	0.96
25	2.40	2.32	1.09	1.50	0.95	0.77	0.60	1.22	0.84
26	2.72	2.65	1.64	1.54	1.0	1.0	0.84	1.0	1.14
27	2.49	2.40	1.56	1.30	0.47	0.95	0.77	0.84	1.14
28	2.71	2.64	1.77	1.22	0.70	0.90	0.60	0.85	1.47
29	2.61	2.54	1.78	1.47	0.60	0.77	0.30	0.76	1.18
30	2.70	2.49	1.89	1.93	1.20	0.90	1.0	0.69	0.73
31	2.14	1.85	1.19	1.33	0.60	0.70	0.30	0.29	0.68
32	2.70	2.68	1.18	0.82	0.90	0.95	0.70	1.49	1.86
33	2.65	2.61	1.44	1.22	0.84	1.0	0.60	1.16	1.38

Table 5 Log normalized data of Barakar Formation, Korba coalfield.

	B 1	B 2	B 3	B 4	B 5	B 5	B 6	B 8	B 9
1	1.79	1.43	0.02	1.53	0.47	0.0	0.30	1.41	0.00
2	1.92	1.64	0.78	1.52	0.69	0.60	1.43	0.86	0.12
3	1.73	1.32	0.83	1.41	0.47	0.60	0.95	0.49	0.02
4	1.74	1.34	0.64	1.44	0.30	0.60	0.47	0.70	-0.03
5	1.65	1.22	0.53	1.40	0.30	0.60	0.60	0.66	-0.10
6	2.23	2.07	0.94	1.64	1.04	1.00	0.77	1.11	0.44
7	2.33	2.20	1.07	1.61	0.84	1.04	0.95	1.11	0.62
8	2.27	2.14	1.15	1.54	0.77	1.04	0.69	0.98	0.63
9	1.96	1.72	1.14	1.34	0.84	1.04	0.30	0.58	0.47
10	2.36	2.34	1.04	0.65	0.60	1.00	0.30	1.32	1.69
11	2.09	1.93	0.95	1.48	0.95	0.84	0.60	0.98	0.49
12	2.28	2.11	0.98	1.71	0.69	0.69	0.77	1.13	0.41
13	2.40	2.29	1.02	1.65	0.84	1.11	0.90	1.25	0.65
14	2.01	1.89	0.75	1.52	0.77	0.77	0.47	1.04	0.30
15	2.16	2.03	0.99	1.47	0.77	1.00	0.60	1.04	0.59
16	1.96	1.76	0.29	1.50	0.60	0.0	0.30	1.47	0.26
17	2.10	2.08	0.24	0.24	0.95	0.30	0.0	1.83	1.84
18	1.60	1.25	0.71	1.25	0.60	0.69	0.95	1.59	0.09
19	2.09	1.91	0.48	1.61	0.60	1.00	0.95	1.42	0.30
20	1.98	1.89	0.76	1.04	0.90	0.77	0.69	1.13	0.87
21	1.29	0.66	0.98	0.72	0.47	0.30	0.30	-0.33	0.43
22	1.65	1.44	1.16	0.19	0.77	0.77	0.30	0.27	1.43
23	2.13	2.06	1.38	1.02	1.04	0.90	0.84	0.73	0.08
24	2.25	2.15	1.15	1.25	1.20	1.11	0.95	1.00	0.94
25	2.16	1.72	1.82	1.42	1.11	1.60	1.25	-0.12	0.65
26	2.37	2.24	1.48	1.47	0.77	1.30	1.36	0.76	0.83
27	2.38	1.95	2.06	1.58	1.04	1.79	1.53	-.09	0.71
28	2.25	2.06	1.44	1.52	1.00	1.25	1.11	0.62	0.63
29	2.47	2.18	1.97	1.68	1.32	1.86	1.49	0.21	0.70
30	2.84	2.77	1.49	1.79	1.44	1.38	1.07	1.27	1.00
31	2.26	2.00	0.66	1.76	0.84	0.69	0.84	1.33	0.33
32	1.67	1.31	0.51	1.44	0.30	0.60	0.30	0.79	0.08

can be used for geological interpretations (Jeffers, 1965; Read and Dean, 1972).

Results and Sedimentological Interpretation

The basic data computed from borehole logs were arranged into two separate matrices of 33x9 (Karharbari) and 32x9 (Barakar), where 33 and 32 are the number of borehole logs used and 9 refers to the number of variables listed above. The data was normalized and correlation coefficients were computed between each pair of variables separately for the two data sets . In cases of both the formations, correlation coefficients between 22 pairs out of 36 pairs show fairly good positive correlation (Tables 6 and 7). The ratio variables 8 and 9 (sandstone/shale ratio and (sandstone+shale)/coal ratio) record less degree of correlation in both cases in view of their dependency on other lithologic variables. All the lithologic variables from 2 to 7 exhibit positive correlation with total thickness (variable 1) in both the formations implying that an increase in total thickness i.e. net subsidence is due to increase in the thickness and number of constituent lithologies. However, it cannot be said precisely at this stage, which variable contribute more towards the net subsidence of the Karharbari and Barakar Formations. The two correlation matrices are then used to calculate eigenvalues and eigenvectors separately for the two formations. The cumulative variance of three eigenvalues, which are greater than unity, is 92.46 % in the Karharbari (Table 8) and 86.1% in the Barakar (Table 9); the corresponding three eigenvectors representing principal components are therefore statistically significant and considered for geological interpretation.

Figures 3 and 4 show projections of nine variable vectors of unit length of the planes defined by three combinations of eigenvectors (principal components), which are also of unit length. Geological significance of these components is as follows:

Karharbari Formation

In Fig. 3A referring to vectors I and II, the total thickness (K_1), total sandstone (K_2), total shale (K_3), total coal (K_4), number of sandstone (K_5), number of shale (K_6) and number of coal (K_7) are closely clustered around vector I. The ratio variables of (sandstone / shale) (K_8) and (sandstone + shale) / coal (K_9) occurring remotely from other variables are not independent as they are derived from total sandstone (K_2), total shale (K_3) and total coal (K4). In Fig. 3B, vectors II and III are taken as reference axes; the total thickness (K_1), total sandstone (K_2), number of sandstone (K_5) and number of shale (K_6) exhibit a closer interrelationship. Greater degree of association of total

Table 6 Correlation coefficients between lithologic variables of Karharbari Formation Giridih coalfield.

Variables	K1	K2	K3	K4	K5	K6	K7	K8	K9
Total thickness of strata (K1)		0.981	0.687	0.761	0.843	0.844	0.793	-0.13	-0.29
Total thickness of sandstone (K2)			0.552	0.659	0.76	0.747	0.720	0.037	-0.18
Total thickness of shale (K3)				0.690	0.793	0.819	0.616	-0.68	-0.43
Total thickness of coal (K4)					0.801	0.824	0.928	-0.44	-0.61
Total number of sandstone (K5)						0.885	0.751	-0.3	-0.34
Total number of shale (K6)							0.828	-0.41	-0.36
Total number of coal (K7)								-0.27	-0.43
Sandstone/shale ratio (K8)									0.708
Sandstone + shale/coal ratio (K9)									

Table 7 Correlation coefficients between lithologic variables of Barakar Formation, Korba coalfield.

Variables	B1	B2	B3	B4	B5	B6	B7	B8	B9
Total thickness of strata (B1)		0.966	0.405	0.562	0.805	0.473	0.365	0.023	0.099
Total thickness of sandstone B2)			0.187	0.442	0.736	0.258	0.170	0.132	0.207
Total thickness of shale (B3)				0.232	0.558	0.972	0.803	-0.370	-0.064
Total thickness of coal (B4)					0.358	0.318	0.362	-0.102	-0.522
Total number of sandstone (B5)						0.616	0.435	-0.061	0.083
Total number of shale (B6)							0.801	-0.324	-0.072
Total number of coal (B7)								-0.317	-0.022
Sandstone/shale ratio (B8)									0.575
Clastic ratio (B9)									

coal (K_4) and number of coal (K_7) implies an increase in coal due to number of coal beds. The ratio variables K_8 and K_9, likewise, occur remotely. Taking vectors I and III as reference axes (Fig. 3C), the picture is almost similar to that of Fig. 3A, where all the variables from K_1 to K_7 are clustered in a zone showing closer interrelationship than variables K_8 and K_9, which are ratios and occur remotely.

Evidently, the increase in total thickness of Karharbari Formation, i.e. net subsidence, is largely due to total sandstone and number of sandstones, whereas shale and

Table 8 Matrix of three principal components for the 9 variables of Karharbari Formation.

Variables	Principal Components		
	(1)	(2)	(3)
Eigenvalues 3.845	2.752	1.224	
% of total variance	67.27	18.27	6.912
Cummulative % of total variables	67.276	85.552	92.464
Total thickness of strata (K_1)	0.366	0.366	-0.140
Total thickness of sandstone (K_2)	0.328	0.387	-0.0793
Total thickness of shale (K_3)	0.345	-0.187	0.547
Total thickness of coal (K_4)	0.375	-0.066	-0.332
Total number of sandstone (K_5)	0.371	0.113	0.202
Total number of shale (K_6)	0.382	0.055	0.216
Total number of coal (K_7)	0.362	0.090	-0.337
(Sandstone/Shale) ratio (K_8)	-0.188	0.658	-0.271
Classic (sand + shale)/coal ratio	-0.216	0.522	0.554

Table 9 Matrix of three principal components for the 9 variables of Barakar Formation.

Variables	Principal Components		
	(1)	(2)	(3)
Eigenvalues 4.212	2.127	1.410	
% of total variance	46.8	23.6	15.670
Cummulative % of total variables	46.80	70.43	86.100
Total thickness of strata (B_1)	0.398	-0.346	-0.177
Total thickness of sandstone (B_2)	0.318	-0.457	-0.206
Total thickness of shale (B_3)	0.396	0.231	0.357
Total thickness of coal (B_4)	0.286	0.022	-0.572
Total number of sandstone (B_5)	0.405	-0.226	0.033
Total number of shale (B_6)	0.418	0.190	0.304
Total number of coal (B_7)	0.370	0.261	0.200
(Sandstone/Shale) ratio (B_8)	-0.137	-0.493	0.132
Classic ratio (B_9)	-0.068	-0.466	0.564

coal contribute subordinately. The total coal (K_4) showing greater degree of interrelationship with total shale (K_3) (Fig. 3A) and total sandstone (K_2) (Figs. 3A and C) indicates that peat swamps developed in distal flood planes and also in the areas of abandoned channels, supporting the independent inferences based on cluster analysis of vertical facies transitions (Tewari, 1997).

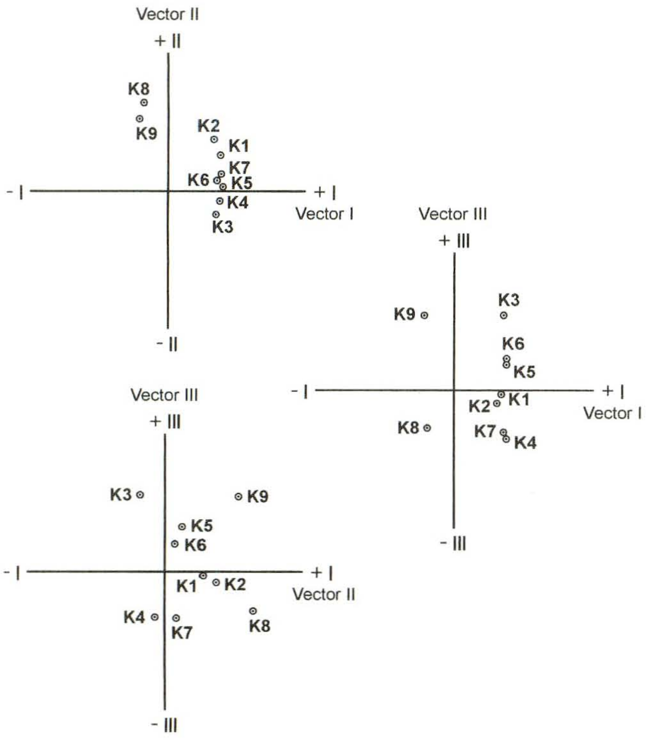

Fig. 3 Graphic plots of three Principal Components (vectors) of Kharharbari Formation.

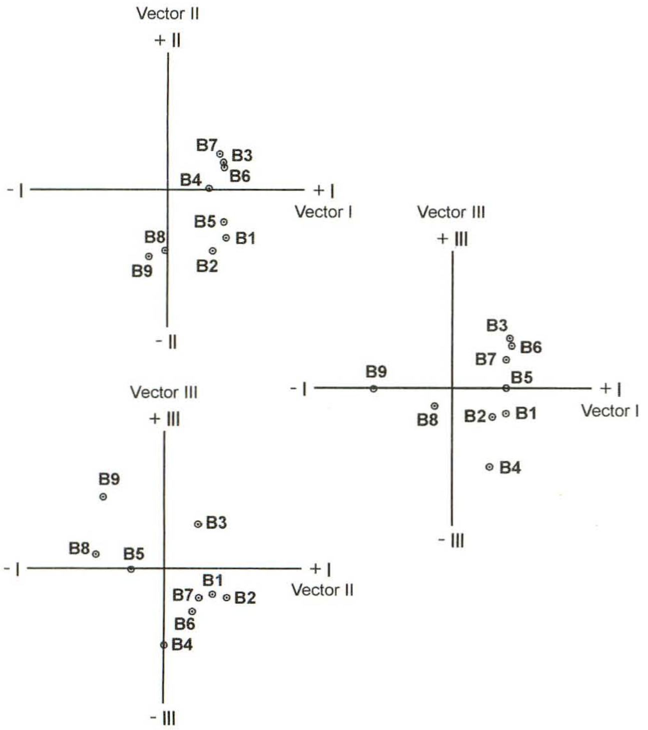

Fig. 4 Graphic plots of three Principal Components (vectors) of Barakar Formation.

Barakar Formation

In Fig. 4A, where vectors I and II are taken as reference axes, variables B1 and B7 are clustered into two zones close to vector I. It implies that total thickness of Barakar (B_1), total sandstone (B_2) and number of sandstone (B_5) are more closely linked. On the other hand, total shale (B_3), total coal (B_4), number of shale (B_6) and number of coal (B_7) show greater degree of interrelationship. The ratio variables (B_8 and B_9) occurring remotely from others are not independent variables. In fig. 4B, based on vectors II and III, total thickness (B_1) shows close association with total sandstone (B_2), though number of shale (B_6) and number of coal (B_7) are also close to total thickness (B_1) as compared to number of shale (B_6) implying that coal contribute more in net subsidence than shale. Fig. 4C based on vectors I and III is quite similar to that of Fig. 4A, in which all the variables except ratio variables are clustered close to vector I.

It is evident from the above plots that total sandstone, number of sandstone beds and number of coal beds have greater control over an increase in total thickness and hence net subsidence of Barakar Formation. A close association of number of coal beds with total sandstone and number of sandstone beds further suggests that peat swamps developed largely in the areas of abandoned channels.

Conclusions

The early Permian Karharbari and Barakar coal measures of Giridih and Korba coalfields of eastern India are composed of repetitive fining upward fluvial cycles of sandstone, shale and coal. These coal measures exhibit variations in total thickness i.e. net subsidence throughout the respective coalfields.

The multivariate principal component analysis is applied to explain the variation in net subsidence of the two coal measures sequences with respect to lithologic variables. The greater degree of association of total thickness with total sandstone and number of sandstone beds in Karharbari Formation suggests that net subsidence of the Karharbari coal measures is largely controlled by the increase in thickness and number of sandstone beds. In comparison, close association of total thickness with total sandstone, number of sandstone and number of coal beds indicate that these lithologic variables contribute more towards net subsidence during Barakar sedimentation. Based on the close interrelationship of total coal with total sandstone and total shale in the Karharbari, and total sandstone and number of sandstone in the Barakar, it is further suggested that peat swamps were mainly developed in distal flood planes and abandoned channels during Karharbari and largely abandoned channels during the deposition of Barakar sediments.

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References

Casshyap, S. M. and Tewari, R. C. (1984) Fluvial models of the lower Permian Gondwana coal measures of Koel-Damodar and Son-Mahanadi basins, India. In: Rahmani, R.A. and Flores R.M., (eds.), *Sedimentology of Coal and Coal bearing Sequences* Spe. Pub. Intern. Asso. Sediment., **7**, 121-147.

Casshyap, S. M., Tewari, R. C. and Khan, Z. A. (1988) Interrelationships of stratigraphic and lithologic variables in Permian fluviatile coal measures of aestern India. In *Recent Researches in Geology*, Hindustan Pub. Corp., Delhi, **12**, 111-125.

Davis, J. C. (1986) *Statistics and Data Analysis in Geology.* John Wiley and Sons, New York, 646 p.

Hota, R. N., Pandya, K. L. and Maejima, W. (2003) cyclic sedimentation and facies organization of the coal-bearing Barakar, Talchir Gondwana basin, Orissa, India: a statistical analysis of subsurface logs. *Jour. Geosciences, Osaka City University*, 46, 1-11.

Hota, R. N. and Maejima, W. (2004) Comparative study of cyclicity of lithofacies in Lower Gondwana formations of Talchir Basin, Orissa, India: A statistical analysis of subsurface logs. *Gondwana Research*, 7, 353-362.

Jeffers, J. N. R. (1965) *Principal Component Analysis in Taxonomic Research.* Statist. Sect. Pap. For. Comm. London, No.83.

Khan, Z. A. and Tewari, R. C. (1991) Net subsidence and number of cycles; their interrelationship in different Permian Gondwana basins of Peninsular India. *Sed. Geology*, 73, 161-169.

Krumbein, W. C. and Sloss, L. L. (1963) *Stratigraphy and Sedimentation.* W.H.Freeman and Co. San Francisco, 660 p.

Raja Rao, C. S. (ed.) (1983) *Coalfields of India: Coal Resources of Madhya Pradesh, Jammu and Kashmir.* Bull. Geol. Surv. India, Series A, No. 45, 3, 204 p.

Raja Rao, C. S. (ed.) (1987) *Coalfields of India: Coal Resources of Bihar (excluding Dhanbad District).* Bull. Geol. Surv. India, Series A, No. 45, 4, 336 p.

Read, W. A. and Dean, J. M. (1972) Principal component analysis of lithologic variables from some Namurian (E2) paralic sediments in central Scottland. *Bull. Geol. Surv. Great Britain*, No. 40, 83-99.

Tewari, R. C. (1997) Numerical classification of coal bearing cycles of early Permian Barakar coal measures of eastern-central India Gondwana basins using Q-mode cluster analysis. *Jour. Geol. Soc. India*, 50, 593-599.

Tewari, R. C. and Casshyap, S. M. (1983) Cyclicity in early Permian fluviatile coal measures: An example from Giridih and Saharjuri basins, Bihar, India. *Sed. Geology*, 35, 297-312.

Veevers, J. J. and Tewari, R. C. (1995) *Gondwana Master Basin of Peninsular India Between Tethys and Interior of the Gondwanaland Province of Pangea.* Mem. Geol. Soc. America, No. 187, 72 p.

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