Journal of Earth Science, *Vol. 29*, *No. 4*, *p. 745–754*, *August 2018* *ISSN 1674-487X*
Printed in China
https://doi.org/10.1007/s12583-018-0791-7

Sequence Stratigraphic Model of Middle Permian Barakar Formation from a Marginal Gondwana Basin, India

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ABSTRACT: Gondwana deposits are extensively found across the continents. Here we study the Middle Permian Barakar Formation from the marginal Gondwana Basin, eastern India, being deposited in a normal fault setting. Availability of extensive cores as well as geophysical log suites (gamma-resistivity-density from drilled wells) from the study area helped us achieving high resolution interpretation. Core study identifies fluvial sedimentary architectures, which were correlated with the geophysical logs and modeled field-wide to understand vertical and horizontal facies disposition. The facies analysis has been used to establish a sequence stratigraphic model of the cyclic Barakar deposition. Four major fining upward depositional sequences were identified, each sequence comprises of low accommodation system tract (LAST) at base and high accommodation system tract (HAST) at top. LAST is characterized by vertically stacked, multistory amalgamated channel sandstone dominated facies, while floodplain dominated facies characterizes HAST, reflecting a gradual shift from braided to meandering depositional system from bottom to top of each cycle. Study reveals depocenter to be in the western part, supported by eastward thinning of sediment packets, all being deposited in a half-graben setting.
KEY WORDS: fluvial sequence stratigraphy, Gondwana sediment, Middle Permian, Barakar Formation.

0 INTRODUCTION

Sequence stratigraphy is a methodology/tool that provides a process oriented stratigraphic framework to interpret depositional system and stratal stacking pattern/architecture through space and time on a basin scale as well as reconstruct paleogeography. Sequence stratigraphy studies the genetically related strata, bounded by unconformities or their correlative conformities. The objective of this study was to decipher a sequence stratigraphic model of Middle Permian Barakar formation, a major economic coal-bearing unit of the North Karanpura Coal Field, a westernmost member of the large east-west trending Damodar Valley Basin, eastern Gondwana, India. Core holes have been studied in detail to investigate the sedimentary structures and infer the possible depositional processes. The facies assemblages, inferred from the core analysis, had been correlated to the available geophysical logs field wide. Interpretations from cores as well as geophysical logs have been integrated to decipher sedimentary architectural elements and depositional model of the Barakar Formation of eastern Gondwana succession (Damodar Valley Basin), which then has been used to construct a fluvial sequence stratigraphic model. Study from this eastern Gondwana Basin provides an excellent opportunity to establish the regional sequence stratigraphic model integrating core and geophysical logs from hundreds of drilled wells, yielding greater degree of confidence.

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Manuscript received March 24, 2018.
Manuscript accepted April 12, 2018.

1 GEOLOGY OF THE STUDY AREA

Karanpura Coal Field, one of the major coal bearing Gondwana basins in India Peninsular is situated about 60 km north-west of Ranchi and 20 km south-west of Hazaribagh, forms part of Ranchi, Hazaribagh and Palamau districts of Jharkhand State. It extends for about 38 km in north-south direction and 75 km in east-west direction encompassing an area of about 2 280 km^2. The Ashwa Pahar hill ranges divide the area into North Karanpura Coal Field (NKF) and South Karanpura Coal Field (SKF). The North Karanpura Coal Field, a westernmost part of the vast east-west chain of Damodar Valley Basin (Fig. 1), constitutes a large expanse of coal-bearing Lower Gondwana sediments deposited mostly in the tectonic trough (approx. 1 230 km^2). It is a saucer shaped basin, having a maximum length of 64 km in the east-west direction and a width of about 36 km in the north-south direction and spreads over Hazaribagh, Ranchi and Palamau districts of Jharkhand State, India (Priyadarshi, 2004).

Stratigraphy of the North Karanpura Coal Field consists of thick sedimentary succession from Carboniferous to Cretaceous; Lower to Middle Gondwana Group of rocks from Talchir to

Dey, J., Sen, S., 2018. Sequence Stratigraphic Model of Middle Permian Barakar Formation from a Marginal Gondwana Basin, India. *Journal of Earth Science*, 29(4): 745–754. https://doi.org/10.1007/s12583-018-0791-7. http://en.earth-science.net

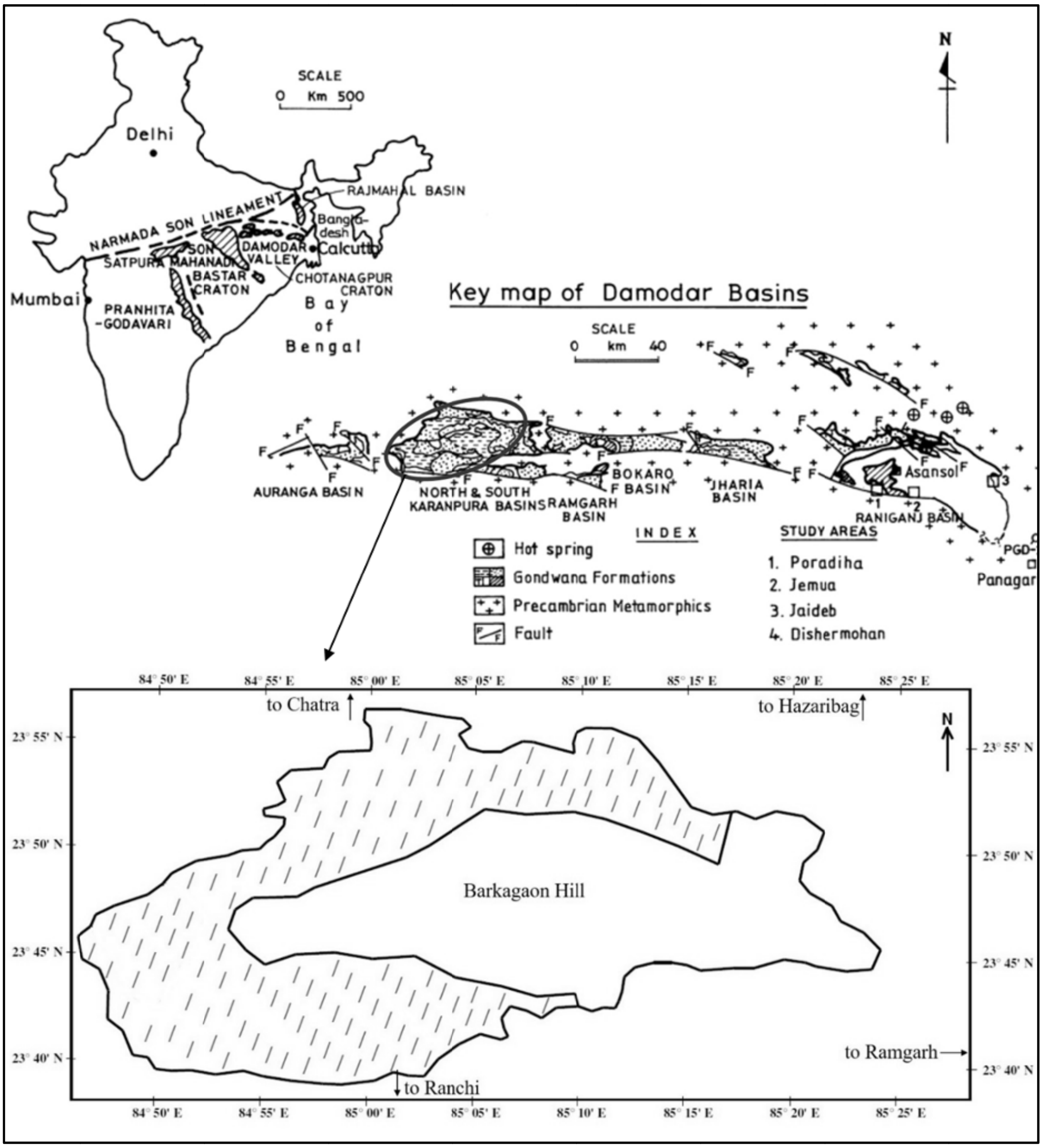

Figure 1. Gondwana basins in India Peninsular. The basins along the Damodar Valley trend are shown enlarged (modified after Ghosh, 2002). Study area—North Karanpura Coal Field marked by ellipse with detailed map location.

Mahadeva Formation (Ghosh et al., 1996). Karharbari, Barakar, Barren Measures and Panchet formations with thick shale beds with cumulative thickness of about 500–800 m are present in the North Karanpura Coal Field (Mendhe et al., 2016). In the easternmost part of this coalfield, Precambrian basement rocks (metamorphic rocks) and small patchy occurrence of Talchir Formation is noted. Barakar Formation occurs in northern, southern and Western parts of the basin with patchy occurrence in eastern part. Barren Measure Formation is exposed mainly in north and west parts of the basin. Central part of the basin is occupied with Panchet Formation. Our study area lies between 23°43'N to 23°47'N and 84°47'E to 84°53'E (Fig. 1), falls under the CCL (Central Coal Fields Limited) command area of Palamau District and lies in the westernmost sector of the North Karanpura Coal Field (NKF). The whole area (approx. 26.11 km^2) has a fairly rugged topography bounded by large hillocks and elongated ridges in the western and north-western part, whereas the southern and eastern region is covered by fairly dense forest. The average ground level (GL) above mean sea level (MSL) varies from 412–508 m. The block is mostly covered by layers of soil and alluvium, where the average thickness of soil varies from 8–10 m, measured from the surface and weathered brownish loose sandstone persists up to a depth of 14–17 m. The Barren measure comprises a thick column of fresh medium to fine grained sandstone and pebble beds (rarely) (approx. 180–200 m in thickness) overlying the coal bearing formation of Barakar. The major part of Barakar Formation consists of buff or dull brownish medium to coarse grained compact feldspathic sandstone with interbedded clay bands, grey shale and coal seams, the average thickness of coal seam varies from 1–20 m and has its dip towards SE. The occurrence of *Glossopteris*, *Gangamopteris* and *Cyclopteroids* fossil leaves were also observed in their usual state of preservation from the carbonaceous shale and clay band of Barakar Formation. The coal bearing Gondwana Formation was deposited unconformably over the Archean basement of quartzite and quartz mica schists. Where the Karharbari Formation is faulted and Talchir is seen very rarely. The regional stratigraphic sequence of North Karanpura Coal Field is presented in Table 1.

Table 1 Stratigraphic sequence of North Karanpura Coal Field (modified after Sen and Banerjee, 2015; Ghosh et al., 1996)

Geological Age	Formation	Thickness (m)
Tertiary	Clay, sand	8–17
Unconformity		
Permian	Barren measure/iron stone shale	20–200
	Barakar	400
	Talchir	Rarely encountered
Unconformity		
Precambrian	Quartzite, mica schist	

2 METHOD APPLIED

Detailed core analysis has been performed to identify sedimentary architectures and facies interpretation. These have been identified in the well logs to establish facies disposition vertically in the drilled wells. Regional correlation helped to distribute sedimentary facies horizontally field wide. Correlated facies distribution has been used to identify various sequences to interpret depositional cycles as an effect of changing basinal accommodation, which defined a high resolution sequence stratigraphic model for the study area.

3 SEDIMENTARY FACIES, ARCHITECTURAL ELEMENTS AND DEPOSITIONAL ENVIRONMENT OF BARAKAR FORMATION

Barakar Formation is a common formation found to be in all of the Gondwana basins in India. This Lower Permian Formation comes after basal Talchir and Karharbari formations in almost all of the basins. The basement rock for Gondwana sedimentation was Precambrian gneisses. The immediately overlying Talchir Formation comprises muddy massive boulder bed, laminated diamictite and rhythmites, khaki green needle shale and light green sandstone. Overall Talchir Formation is of glaciogene origin. The dominant facies interpreted from core analysis from the Barakar Formation are classified as sandstone dominated facies, sandstone-shale heterolith facies, shale facies and coal facies. Graphic logs from few of the studied core holes are presented in Fig. 2.

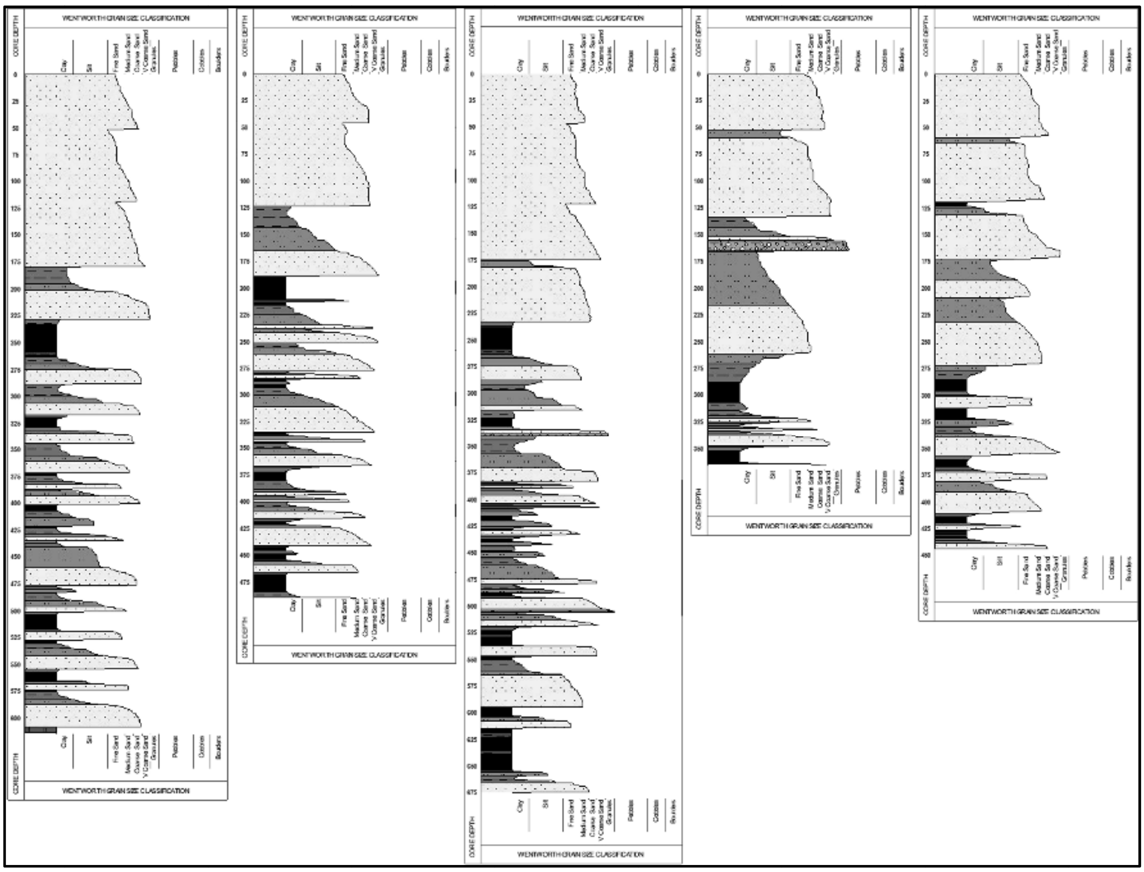

Figure 2. Graphic logs of five core holes, drilled in Middle Permian Barakar Formation, North Karanpura Coal Field. Output taken from core log module, GEO suite of software. All the graphic logs display a general fining upward trend.

Sandstones of varied grainsizes are extensively found in all the core holes. Most of them show cross stratification with sharp erosive base indicating unidirectional current flow, i.e., channel deposits. Presence of coarse basal lags (Fig. 3a) records the cessation of rolling bed due to drop in flow velocity (Sen et al., 2016; Allen, 1970). Trough cross stratification (Fig. 3b) and planar cross beds both can be identified in the cores. Trough cross beds represent migrating channel bed forms (Collinson, 1978), while planar cross beds are formed due to channel aggradation (Cant and Walker, 1976). Some channel sands are massive in nature, devoid of any primary sedimentary structure, deciphering planar sheet transport in upper flow regime (Rust, 1972). Fine grained sandstones in the cores have been interpreted as the low energy deposits (Sen et al., 2016) and associated flat laminations, current ripple laminations with silty intercalations indicate minor flow velocity fluctuations within the channel (Fig. 3c) (Opluštil et al., 2005).

Second type of dominant lithology in all the cores is laminated shale (Fig. 3e), which are carbonaceous, micaceous and ferruginous in nature at different horizons. This shale facies overlies the channel sandstones and thus defines the top of fining upward cycle. These shales indicate deposition occurring from suspension in the floodplain settings (Casshyap and Tewari, 1984).

Coal seams (Fig. 3f) occur with close association with floodplain shales. Limited/restricted clastic influx (other than flood waters/splays), floodplain is the ideal place for uninterrupted vegetation growth and reducing swamp environment for extensive peat accumulation (Leeder, 1996; Johnson and Murphy, 1984; Jackson, 1978). Some coal seams are shaley in nature (Fig. 3g). Cleats of few coal seams have calcite mineralization. Eight major groups of coal seams are identified in the studied Barakar Formation (Fig. 4), demarcated as S-1 to S-8 from top to bottom. Seams are laterally continuous and easily correlatable. Coal seams show very prominent splitting-merging behavior, as interpreted from geophysical logs and correlated across the study area.

Along with sandstones, shales and coals, fourth dominant lithofacies is heterolith, as seen in all the cores and commonly occur as intercalation of shale and fine-medium grained sandstone. Sandstones within some heterolith (Fig. 3d) have been seen with well-developed ripple laminations, which normally occur as a result of vertical accretion in fluvial overbank setups (Sen et al., 2016; Casshyap and Tewari, 1984; Allen, 1970) and interpreted as levee deposits. Another kind of heterolith has been reported from many of the core holes, where fine grained sands with sharp bottoms are sandwiched between shales and carbonaceous shales/coals. This happens when relatively high energy flood water breaks the levees and enters in the low energy floodplain environment (Knightonn, 1998; Murray and Paola, 1994; Reading, 1986). These are interpreted as crevasse-splays (Sen et al., 2016; Galloway and Hobday, 1996).

The observations and interpretations from cores have been integrated with geophysical logs of more than hundreds of wells available from the study area. Geophysical log suite had gamma, resistivity (shallow, medium and deep resistivities), density and sonic data. Gamma ray signature has been used as

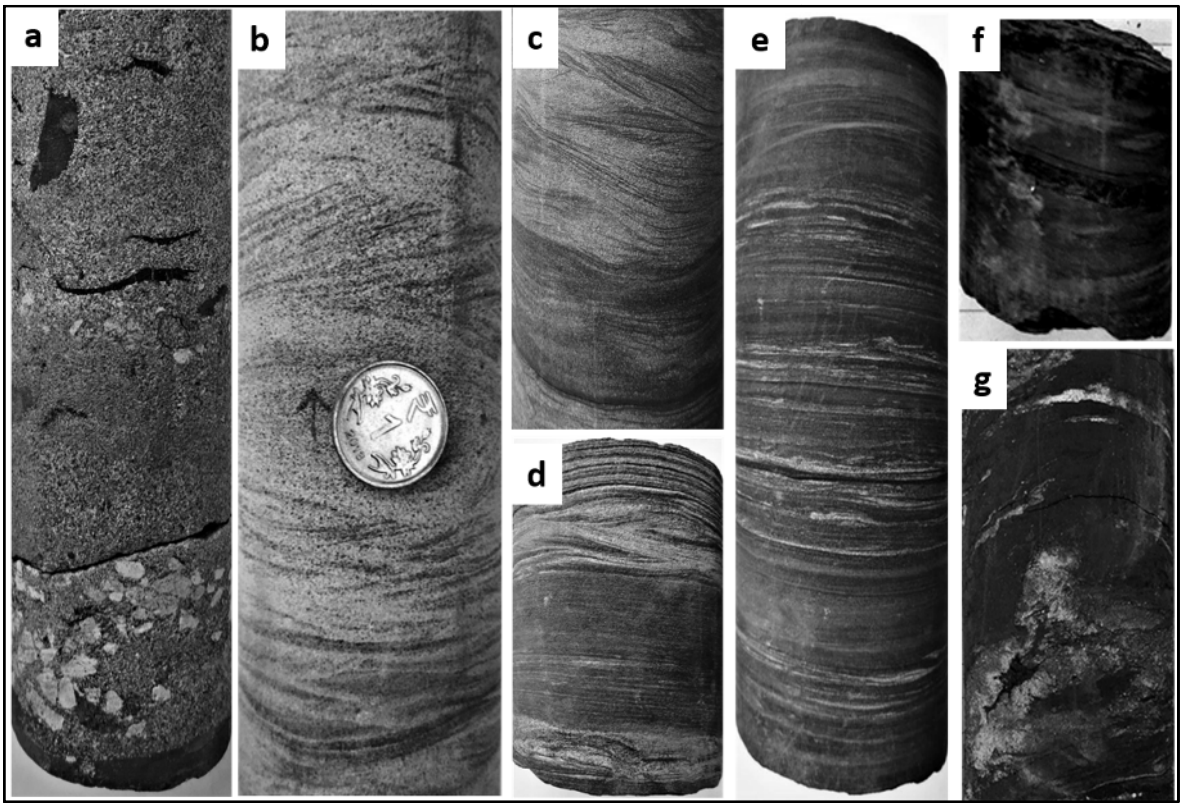

Figure 3. Core photographs of various sedimentary architectural elements, as interpreted from the cores of study area. (a) Channel sand with sharp base and basal feldspathic lags; (b) trough cross stratification in channel sand body; (c) current ripple laminations with silty intercalations within channel; (d) heterolith facies—levee; (e) laminated shale—floodplain/overbank deposits; (f) coal; (g) shaley coal.

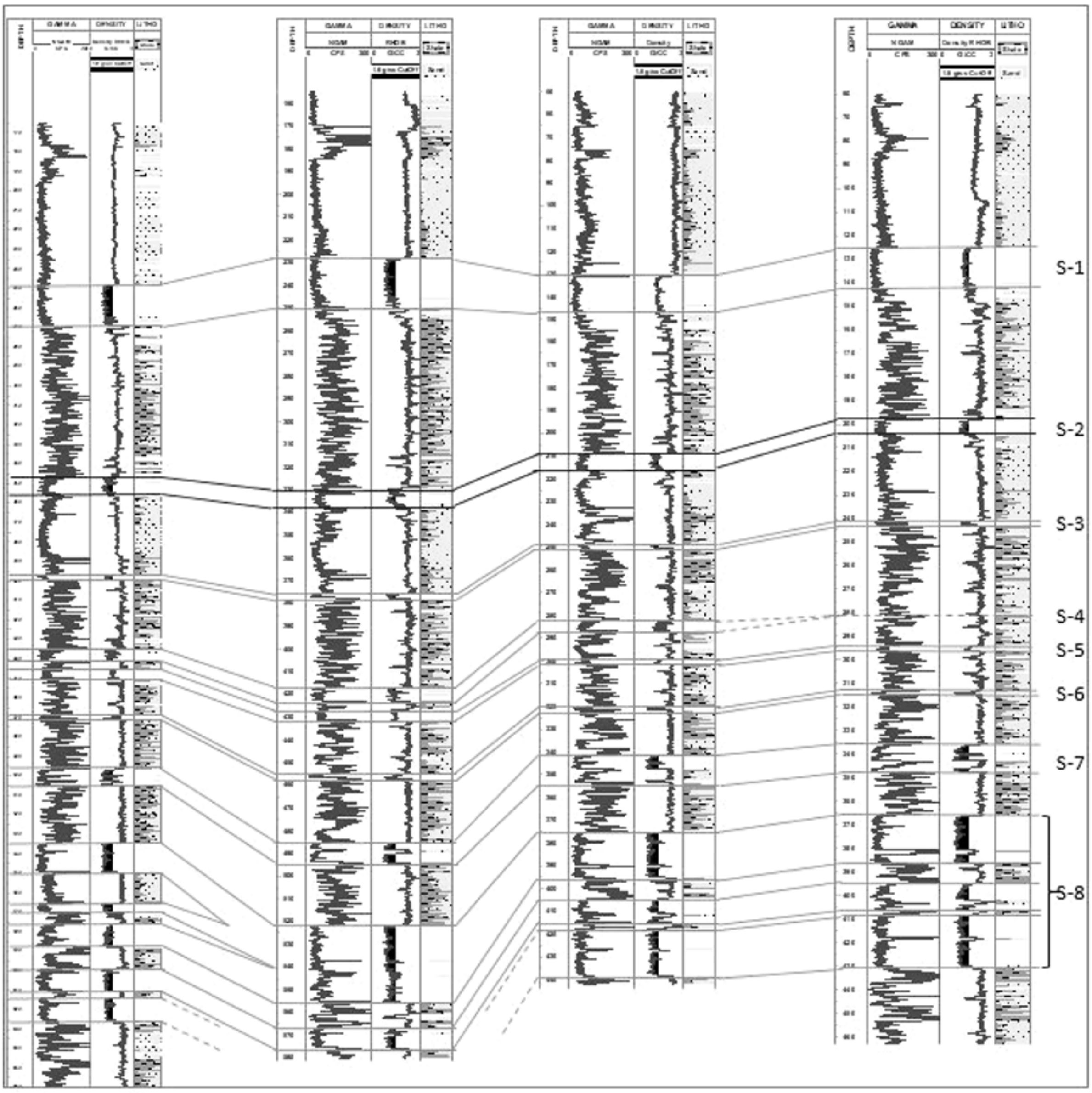

Figure 4. Geophysical log correlation amongst four studied wells, Barakar Formation. Left to right, the wells (Well-A, B, C and D respectively) display west to eastward facies disposition vertically and horizontally. Well-A (west/left most) being drilled in the deeper section of the study area. Each well contains gamma ray log, density log with coal marked in black based on 1.6 g/cc density cutoff and volume lithology (computed from gamma ray log). Plot shows sandstone-shale-coal bearing sequences, 8 major coal seams demarcated as S-1 to S-8 from top to bottom.

basic curve for calculating shale volumes and identifying fining/coarsening upward cycles (Yang et al., 2006). Lithofacies interpreted from cores, have been identified in logs, correlated with all the available wells and extrapolated field wide to model the lateral and vertical distribution of all the lithofacies, which then used as a basis of depositional framework for the whole study area (Mackey and Bridge, 1995).

Channel, floodplain, crevasse-splays, levees are the main sedimentary architectures as interpreted in the cores and correlated in geophysical logs. And this, as an assemblage, deciphers a meandering fluvial depositional environment (Dey et al., 2017, in press). Cyclic deposition is common in fluvial settings and found globally across geological timescales. Each succession normally starts with a high energy phase followed by fine sediment deposition in lower energy condition (Catuneanu et al., 2011).

4 AVAILABLE FLUVIAL SEQUENCE MODELS

The main controlling factors which governs the fluvial dynamics and fluvial architectural distributions are channel pattern, avulsion-aggradation rates, hinterland characteristics, gradient, sediment budget and influx, transportation capacity, preservation potential, effective accommodation space, tectonics (uplift/subsidence) and climate (Rhee, 2006). Several researchers have tried to fit the shoreline sequence stratigraphic model to interpret fluvial deposits. Allen (1978) tried to relate the fluvial aggradation and sedimentation cycles with base level changes. Wright and Marriott (1993) provided a sequence stratigraphic model for nonmarine deposits, where the two controlling factors were rate of sedimentation and the rate at which accommodation space is being generated. As per this model, sequence boundaries (subaerial unconformities) are developed by forced regression. Lowstand and Transgressive system tracts (LST and TST) are represented as amalgamated channel sands and thick floodplain dominated sections respectively. These marine sequence model terminologies being used in fluvial sequences may be inappropriate and questionable, as it has no connection to the sea (Rhee, 2006). Currie (1997) suggested analogous terms like 'degradational system tract' for LST and 'transitional system tract' for TST in fluvial sequence model. This model is exactly the same as Wright and Marriott (1993), the nomenclature had been just modified.

Ethridge et al. (1998) proposed a fluvial sequence model in LST, TST and HST based on the relative proportion of channel fills. As per this model, fluvial sequences show overall fining upwards characteristics with amalgamated channel sands at bottom, thus defining LST and interpreted as a product of braided depositional system. TST stays in the middle, characterized by high sinuosity meandering channel deposits within floodplain dominated successions. The transition from LST to TST is gradational. HST stays at the top part, here proportion of floodplain deposits decrease, channel fills become laterally interconnected due to increasing degree of lateral channel avulsion. This model was again a manifestation of marine sequence framework onto fluvial deposits.

Marine sequences are commonly presented in dip section and fluvial sequences are illustrated in strike section (Rhee, 2006). Therefore interpreting strike oriented fluvial successions using dip oriented marine sequence models might be problematic (Rhee, 2006; Adams and Bhattacharya, 2005). A full cycle of accommodation variation results in a genetic sequence. During negative accommodation periods, sequence boundaries are formed. But it is not always necessary, as we get parasequences, T-R sequences of Johnson and Murphy (1984). System tracts are deciphered on the basis of stacking pattern, type of bounding surfaces and relative positions within a sequence (Catuneanu, 2006; Posamentier and Allen, 1999; Van Wagoner, 1995; Van Wagoner et al., 1990, 1988, 1987; Posamentier et al., 1988). Considering shoreline dependency as a playing factor, there can be two types of systems—shoreline dependent system tracts, where sedimentation and accommodation are the outcomes of shoreline trajectories. Second one is the shoreline independent system, where sedimentation remains unaffected by relative positions of shoreline (Catuneanu et al., 2011; Holbrook et al., 2006) and this scenario happens in upstream controlled fluvial depositional settings. Shanley and McCabe (1994), Boyd et al. (2000), Catuneanu et al. (2011) interpreted these shoreline independent fluvial sequences to be consisting of low- and high-accommodation system tracts based on the varied degrees of channel amalgamations. Blum and Törnqvist (2000) suggested that these types of sequences commonly have time offset to the shoreline dependent sequences. As per Catuneanu et al. (2009), low accommodation system tract (LAST) is characterized by channel dominated facies, while high accommodation system tract (HAST) is defined by floodplain/ overbank dominated facies.

5 SEQUENCE STRATIGRAPHIC MODEL OF BARAKAR FORMATION

We have followed the model of fluvial sequence stratigraphy by Catuneanu et al. (2009) in our study area. Our study identifies four major fining upward depositional cycles in Barakar Formation in the studied Gondwana Basin, these are named as Cycle-1, 2, 3 and 4 (Figs. 5 and 6, prepared using X-section module of GEO suite of software). Each depositional sequence consists of LAST at bottom and HAST on top of it, bounded by sub-aerial unconformities. LAST is characterized by erosional based, vertically stacked, amalgamated multistory channel sandstone dominated facies and scarcely preserved floodplain facies (light shaded areas in Figs. 5 and 6) indicating a braided river system (Sen et al., 2016). HAST is characterized by overbank dominated facies (dark shaded areas in Figs. 5 and 6). HAST segments of the marked cycles are characterized by more cumulative coal thickness with respect to the LAST segments, indicating HAST periods are favorable for yielding calm and quiet floodplains of vegetation growth, i.e., peat, in a meandering river system (Sen et al., 2016).

Sequence stratigraphic model of west and eastern part of the study area have been presented in Figs. 5 and 6 respectively. Four distinct depositional cycles have been demarcated in the western part of the study area, represented as Cycle 1 to 4 (Fig. 5), details of which are as below.

(1) Cycle-1: the bottommost cycle. HAST of Cycle-1 consists of S-8 group of seams. Well-B was not drilled/logged till Segment-E of S-8 group of coal seam, hence HAST-LAST boundary could not be picked in this well. The bottom of LAST in Cycle-1 has been demarcated at the end depth of logs of the studied wells, as those were not drilled further, so it was beyond the scope of study. S-8 group of seams reveal splitting tendency towards west (Fig. 5).

(2) Cycle-2 is characterized by a thinner LAST (30–35 m) and a HAST of good thickness of 90–100 m in all the four wells (Fig. 5). This is characterized by serrated gamma ray response of frequent sand/silt-shale-coal intercalation, indicating higher accommodation space with a good pace of sedimentation. It consists of four major coal seams (S-3, S-4, S-5 and S-6) and minimum three shaley coals/carbonaceous shale units, which are laterally continuous. Seams encountered in Cycle-2 HAST are relatively thinner, when compared to other coal seams (i.e., S-1, S-2 and S-8). Cycle-2 LAST consists of a fining upward cycle ending up in S-7 coal seam. S-7 seam can be divided in 3 units, as can be seen in density logs of all the four wells.

(3) Cycle-3 again has a thicker HAST (75–100 m, with thickness increasing from east to westward) at top and a relatively thin LAST (35–45 m) at base. Cycle-3 LAST is very distinguishable in logs with 25 m thick sand showing cylindrical gamma signature and it ends up with S-2 coal seam at top. This multi-storey channel sand (amalgamated) indicates channel accretion. Cycle-3 HAST consists of thick S-1 seam, being the top most coal seam of Barakar Formation in the study area. HAST is characterized by frequent silt-shale intercalations, similar to Cycle-2 HAST.

(4) Cycle-4 is the top most depositional cycle with LAST defined by a clean thick sandstone (cylindrical gamma response) of 35–45 m thickness, while HAST is only 8–15 m thick. HAST top of Cycle-4 demarcates the Barakar-Barren Measure boundary, clearly distinguishable in logs with a very high gamma spike. This cycle does not consist of any coal

seam. Thickness of this cycle is lowest in Well-C, possibly because of fault.

Detailed correlation establishes the presence and continuity of bottom two cycles, i.e., Cycle-1 and 2 in the eastern part of the study area, directly underlying the Barren Measure Formation (Fig. 6). These two cycles consist of well correlated coal seams from S-8 to S-5. HAST top of Cycle-2 defines the boundary of Barakar Formation and Barren Measure Formation in the eastern part. It reveals basin shallowing in the northeast direction, supported by eastward stratigraphic pinching of two shallower cycles as well as thinning of cumulative sedimentary packet from Well-E to Well-J (Fig. 6).

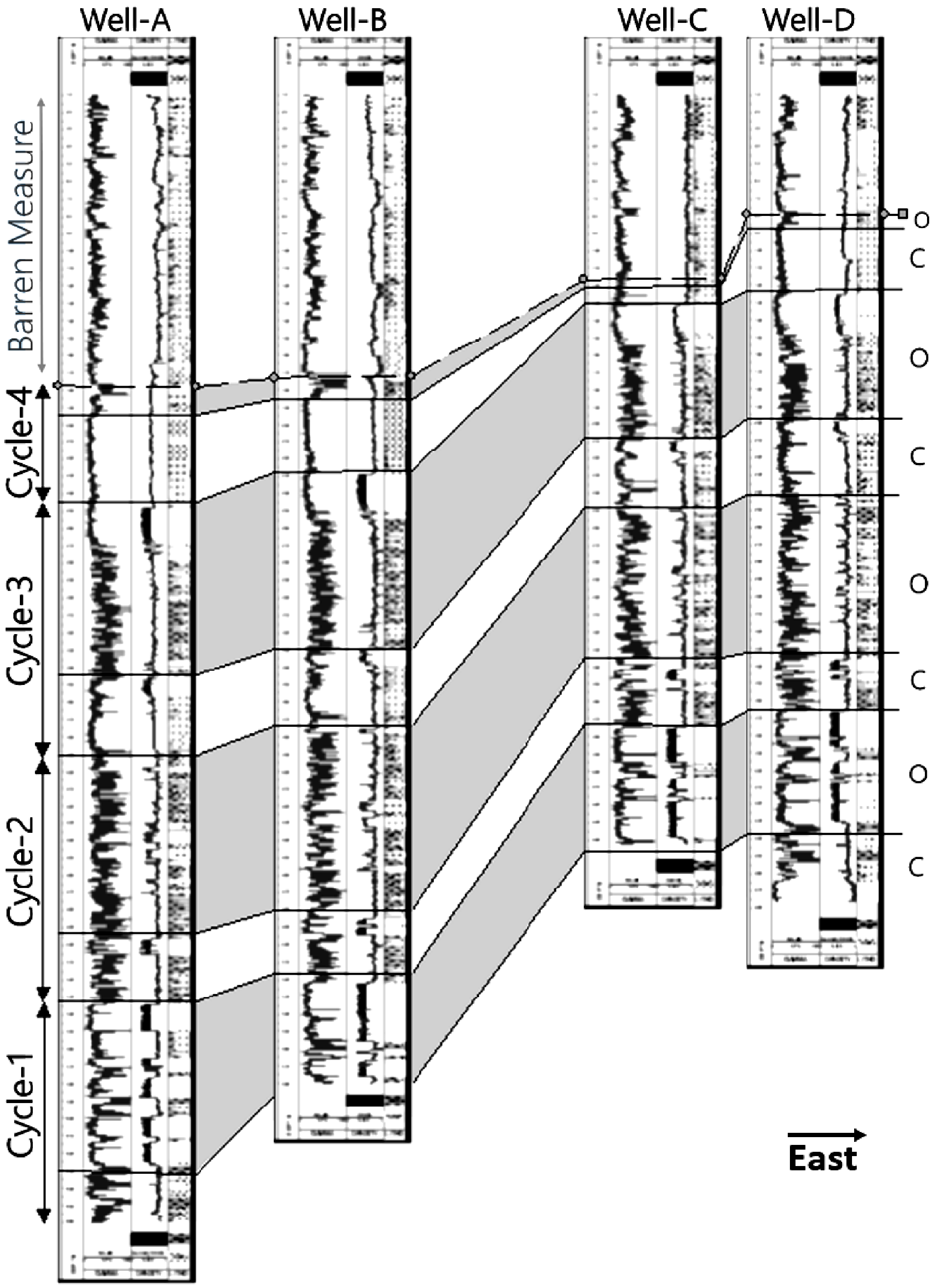

Figure 5. Correlated well section (Well-A to Well-D—west to east) in the west of study area showing stratal stacking pattern of four major cycles of fluvial succession; demarcation of channel-dominated and overbank-dominated sections (C and O respectively) in Barakar Formation from studied area. HAST top of Cycle-4 defines Barakar-Barren Measure boundary

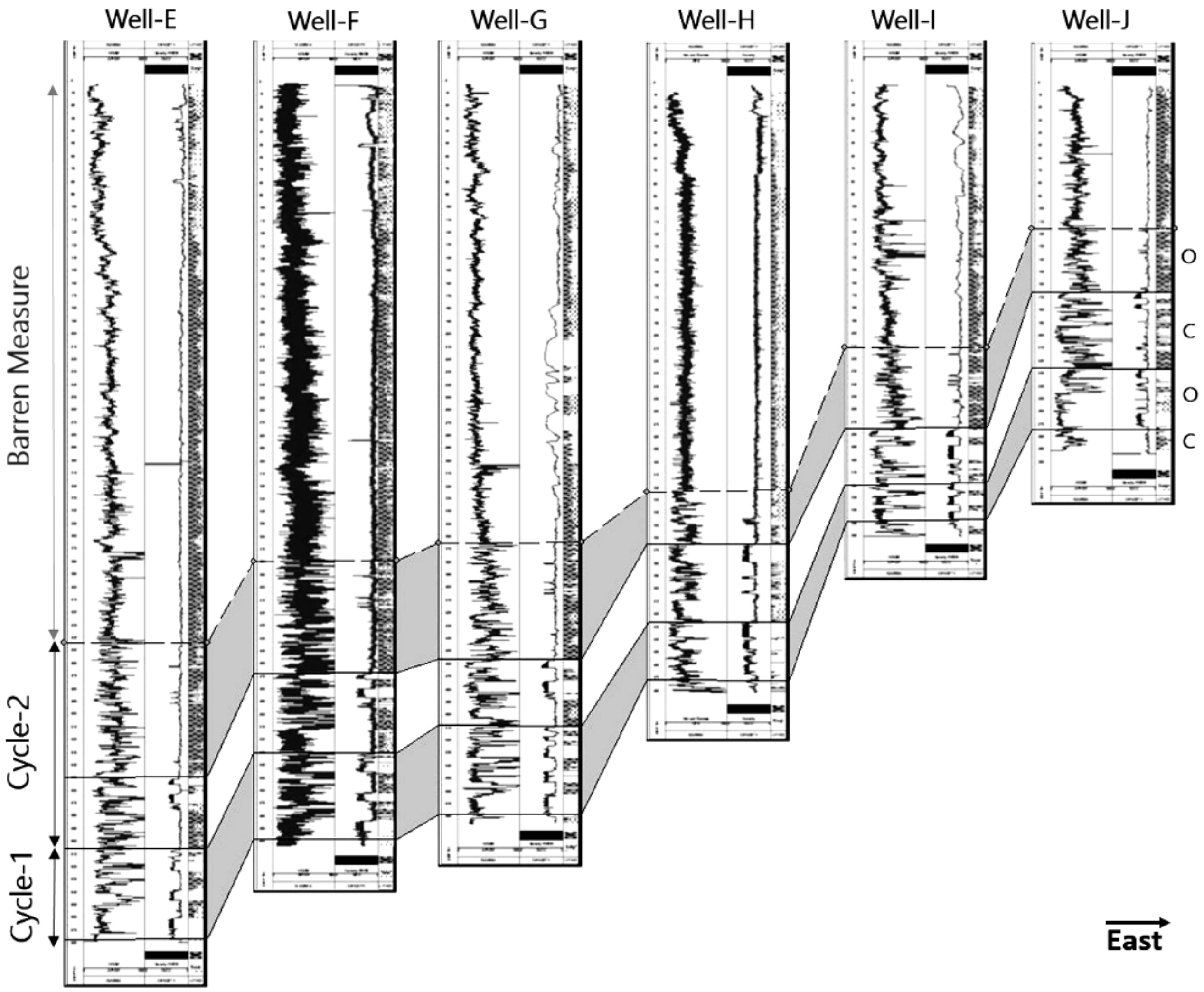

Figure 6. Correlated well section (Well E to J—west to east) in the east of study area with bottom two depositional cycles.

6 DISCUSSION

Analysis of sedimentary facies and architectural elements from this integrated study of cores and geophysical logs, indicates a meandering depositional system for the Barakar Formation in the study area. This is characterized by several fining upwards sequences with channel belt sandstones-levees-overbanks deposits. Identified sedimentary architectures are channels, back swamp-floodplains, crevasse splays and levee. Laterally continuous coal seams were deposited in the calm and quiet environment of extensive floodplains. Channel sinuosity and lateral channel migration/avulsion results in lateral facies heterogeneity and coal splitting. Overall Barakar Formation can be subdivided in maximum to four major depositional cycles in western part and bottom, two cycles are correlated in east, each consisting of low-accommodation system tract (LAST) at base and high-accommodation system tract (HAST) above it. LAST is channel dominated facies and HAST is overbank dominated facies, reflecting a gradual shift from braided to meandering depositional system from bottom to top of each cycle. HAST segments show greater cumulative coal thickness with respect to the LAST sections. Stratigraphic pinching of two shallower cycles in the eastward part of the studied marginal North Karanpura Coal Field of Gondwana Basin defines it as a half graben with depocenter in the west.

7 CONCLUSION

Gondwana deposits are found across continents depicting similar sedimentation pattern before the continental breakup (barring the stratigraphic anomalies occurring in local scales). Study of Middle Permian Barakar Formation thus becomes an ideal geo-horizon or rather a type section to analyze the vertical and lateral distribution of various fluvial lithofacies. Availability of huge volume of exploratory and development well data in the form of cores and geophysical logs make this a perfect place to understand the depositional processes, facies distribution, identify high frequency depositional cycles field wide, which all resulted in a fluvial sequence model. This work establishes Middle Permian Barakar Formation as a perfect analog not only to the Gondwana sediments across Africa-India-Australia, but also to the fluvial deposits from varied geological timescale across the globe, as the principals and idea of the sequence manifestation and their field outcomes remain on the same line.

ACKNOWLEDGMENTS

Authors thank Dr. Jun Xiao, editor and Ge Yao from editorial office, *Journal of Earth Science* for their timely communication and support. Constructive reviews and suggestions by two anonymous reviewers are greatly appreciated, as it helped in the betterment of the manuscript. Authors would like to express their sincere gratitude to Coal India Ltd., for providing the core and geophysical log dataset and permission to publish this work. Authors are thankful to Geologix Limited for providing access to core log and X-section modules, GEO Suite of software which has been instrumental in preparing the graphic logs and well correlation plots. JD expresses his sincere gratitude to Sabur Ali (Deputy Manager, CIL) and Priyankar Upadhyay (Assistant Manager, CIL) for their suggestions and help while preparing this manuscript. The views and interpretations presented in this paper are solely of authors' and do not necessarily reflect those of Coal India Limited and Geologix Limited. The final publication is available at Springer via https://doi.org/10.1007/s12583-018-0791-7.

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